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Interactions between Vegetation, Roots, and Soil Stability in Restored High-altitude Ski Runs in the Alps

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Abstract

Construction of ski runs has a very heavy impact on alpine ecosystems since it results in total destruction of the existing vegetation and profound alteration of the soil. Restoration work must thus set out to develop a protective plant cover immediately and promote re-establishment of a functional plant-soil system in the long term. The aims of the present study, conducted at the Monterosa ski resort (Val d'Ayas, Aosta, Italy) were to evaluate (1) how disturbance related to ski run construction at high altitude (2200–2600 m a.s.l.) has affected vegetation and soil properties compared to undisturbed sites, and (2) how vegetation and soil properties change in machine-graded ski runs with increasing time after hydroseeding. Herbaceous cover and specific composition, root density, physico-chemical soil properties, and aggregate stability were evaluated to determine the vegetation and soil dynamics of four runs constructed above timberline and hydroseeded 4, 6, 10, and 12 years ago, respectively, and of the adjacent undisturbed alpine pasture as control. The seeded species had quickly formed a cover that was still high even after 10 years. However, cover values were always extremely low for wild species, and this could be related to their strategies and to altered soil properties (higher pH, organic matter impoverishment, and loss of both fine particles and aggregates). The study indicated that more has to be done to conserve or restore physico-chemical soil properties as a decisive factor in establishing a self-sustaining native plant community.

Introduction

Winter sports have now become of prime importance in the mountain economy (Dinger, 1997; Urbanska, 1997; Bozzo et al., 2000). Construction of most recent European ski runs, particularly those above timberline, has a very heavy impact on all components of an alpine ecosystem (Schütz, 1988; Urbanska, 1989; Argenti et al., 2000): the natural vegetation cover and the organic topsoil are removed, most boulders are re-arranged to form the ski run bed, and coarse materials from lower horizons are mixed with finer upper soil and replaced to form the top layer. The outcome is a substrate with severely altered biotic, physical, and chemical properties (Gros et al., 2004; Freppaz et al., 2002) decidedly hostile to the establishment of plants and to their growth (Bradshaw, 1997). Besides this, the strategies that alpine species have elaborated to adapt to severe environmental constraints, i.e. slow and clonal growth, few seeds, and mechanisms for their release and dispersal in function of time rather than space (Chambers, 1997; Körner, 1999) result in very low resilience of alpine communities. In non-restored conditions the natural dynamism of the vegetation follows a primary succession pattern, with pioneer stages that develop very slowly and provide low cover (Urbanska, 1994; Urbanska and Chambers, 2002). Restitution of a stable grass cover under these conditions would take centuries (Cernusca, 1986) and be more likely in any event to be cut short by inevitable erosion.

The main aims in remediation of degraded alpine areas are thus two: (1) rapid establishment of a continuous plant cover that can protect and stabilize the substrate and hence minimize erosion (Delarze, 1994; Pardini et al., 1997; Argenti et al., 2000; Dinger, 2001; Tallarico and Argenti, 2001); and (2) re-establishment of

a functional plant-soil system to ensure the self-sustainability of the plant community and its ecological and visual integration with the adjacent undisturbed ecosystems (Bayfield, 1996; Conlin and Ebersole, 2001; Urbanska and Chambers, 2002). This second objective, which has been successfully achieved in many cases at low and medium altitude (Bayfield, 1996; Chambers, 1997; Siniscalco et al., 1997), is very hard to attain at higher altitudes (Van Ommen, 2001), in particular above timberline (Delarze, 1994; Klug-Pümpel and Krampitz, 1996; Urbanska, 1997; Wipf et al., 2005). Many studies have therefore been directed to several complementary aspects of the problem. Knowledge of the ecology of alpine species (Urbanska, 1986) and of the natural dynamism in disturbed environments (Chambers et al., 1984; Chambers, 1989, 1993; Chambers et al., 1990, 1991; Chambers 1995a, 1995b; Urbanska and Fattorini, 1998a, 1998b; Urbanska et al., 1998) is assumed as a base to identify the most appropriate plant materials and seeding techniques to obtain a continuous cover and increase floristic richness (Bozzo et al., 2000; Dinger, 1997, 2001; Urbanska and Chambers, 2002; Krautzer et al., 2004). Moreover, recent criteria of restoration ecology have been directed to the transplantation of single plants (Urbanska et al., 1988; Urbanska, 1994; Fattorini, 2001) or turf transplants of wild alpine species so as to create a wholly autochthonous community (Conlin and Ebersole, 2001; Urbanska, 1994, 1997; Ebersole et al., 2002).

The secure defense against erosion provided by a good and persistent plant cover is due to both its evident aboveground effects and its root systems. Roots not only stabilize the soil by simple mechanical effects, but the finer roots and root hairs together with fungal hyphae and the associated microflora (Tisdall, 1994) cause the aggregation of finer soil particles and

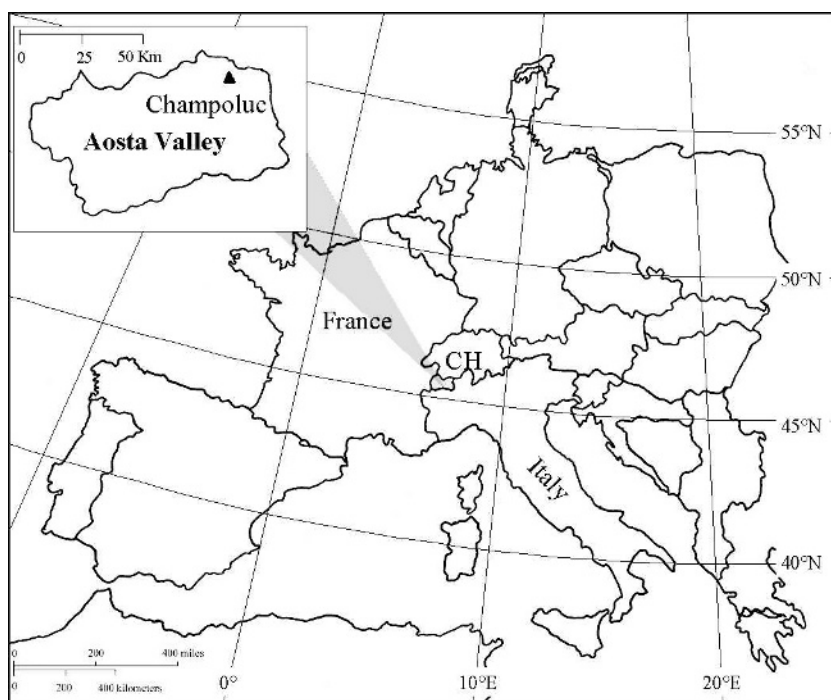


FIGURE 1. Location of the study area. CH = Switzerland.

organic components into soil aggregates by means of both physical action and the production of organic compounds (Tisdall and Oades, 1982; Oades, 1984; Miller and Jastrow, 1990; Scott, 1998). The binding of soil particles into stable aggregates of various size provides a range of pore sizes for storage of organic matter (OM) (Elliott and Coleman, 1988) and for available water, movement of water and air, and root growth. The soil is thus able to withstand water- and wind-induced erosion (Nearing et al., 1991).

Monitoring of results is an obvious requirement for any restoration program (Urbanska and Chambers, 2002; Dinger, 2001) and should provide a picture of both the dynamism of the plant community and the properties of the soil on which it depends. Nevertheless, few studies report on changes in both these factors through time after restoration of ski runs (Gros et al., 2004).

The aims of the present study, therefore, were to evaluate (1) how disturbance related to ski run construction at high altitude has affected vegetation and soil properties compared to undisturbed sites, and (2) how vegetation and soil properties change in machine-graded ski runs with increasing time after hydroseeding.

Dynamism was assessed in function of the cover and plant composition of runs seeded 4, 6, 10, and 12 years earlier by comparison with the undisturbed adjacent alpine pasture communities. The root-system dynamics and physico-chemical soil properties of the runs and their undisturbed adjacent communities were examined for interactions between these closely correlated parameters and development of the plant community.

Study Area

The study was conducted on ski runs at the Monterosa ski resort at Champoluc (Val d'Ayas, Aosta, Italy; Fig. 1) (45°50'N, 4°43'E) in the Monte Rosa massif (NW Alps) at 2200–2600 m a.s.l. on the left side of the valley and mainly facing WSW. The weather station records at Lago Gabiet (Gressoney La Trinité, 2430 m) show an alpine climate with a mean annual

temperature of 0.2°C and a pre-alpine precipitation pattern: main minimum in winter, main maximum in spring and secondary in autumn. The mean annual precipitation is 1084 mm yr⁻¹. Snow mostly falls between December and April. In some recent years, however, total snowfall has been well below average, and artificial snowguns have been installed beside all the ski runs.

Geologically the study area is in the Piedmontese Zone and composed of calcic schists with greenstones. The main lithotypes are prasinites, metagabbros, and serpentinites. The poorly developed soils bordering the ski runs are classifiable as Entisols and Inceptisols according to the USDA Soil Taxonomy (Soil Survey Staff, 2003).

The natural vegetation is typical of alpine pastures on acid or acidified substrates with *Carex curvula*, *Nardus stricta*, *Arnica montana*, *Pulsatilla alpina*, and *Trifolium alpinum* as dominant species. At the lower altitudes, pastures and rock outcrops alternate with alpine moorland composed of *Vaccinium uliginosum*, *Vaccinium myrtillus*, *Rhododendron ferrugineum*, and *Juniperus nana*. The plant cover is generally continuous. On the steeper slopes above 2500 m, however, the environmental conditions limit the formation of soil, and patches of alpine pasture alternate with debris where a scattered cover is provided by *Thlaspi rotundifolium*, *Erigeron alpinus*, *Achillea nana*, and *Veronica bellidioides*.

Method

SAMPLING STRATEGY

The study was conducted on four machine-graded ski runs located above timberline, ranging in altitude between 1990 and 2700 m (Table 1) and width between 12 and 15 m. They were hydroseeded with commercial mixtures 4, 6, 10, and 12 years earlier. Mineral fertilizer was supplied during hydroseeding (N/P/K 12/12/12, 30–40 g m⁻²), and manure was added once, usually during the second year. Cattle are pastured on all four ski runs. Five replicate plots and five control plots in the adjacent undisturbed alpine pasture were randomly chosen in each ski run. Control plots are assumed to represent both pre-disturbance

TABLE 1

Data on the ski runs (altitude, time after seeding, seed mixtures used) and plot characteristics (control plot data in italics).

Ski run	Ski run code	Altitude (m)	Years after seeding	Mean plot characteristics			Seed mixture
				alt.	asp.	slope	
Del Lago	1	1971–2449	4	2248 2255	W <i>W</i>	19 5	<i>Festuca rubra rubra</i> cv. Laxton (50%), <i>F. rubra commutata</i> cv. Medina (25%), <i>F. arundinacea</i> cv. Safari (10%), <i>Trifolium repens</i> cv. Huia (5%), <i>T. pratense</i> cv. Rajah (5%), <i>Lotus corniculatus</i> cv. Leo (5%)
Del Monte	2	1970–2440	6	2286 2290	W <i>W</i>	18 8	<i>Festuca rubra rubra</i> cv. Laxton (50%), <i>F. rubra commutata</i> cv. Medina (10%), <i>F. longifolia</i> (15%), <i>Phleum pratense</i> (10%), <i>Trifolium repens</i> cv. Huia (5%), <i>T. pratense</i> cv. Rajah (5%), <i>Lotus corniculatus</i> cv. Leo (5%)
Contenery	3	2214–2384	10	2320 2308	SW <i>SW</i>	20 12	<i>Festuca rubra</i> cv. Rubinba (35%), <i>Festuca pratensis</i> cv. Hounddog (10%) <i>Phleum pratense</i> cv. Climax (15%), <i>Lolium perenne</i> cv. Verna (15%), <i>Trifolium repens</i> cv. Huia (10%), <i>Agrostis tenuis</i> cv. Highland (5%), <i>Dactylis glomerata</i> cv. Prairial (5%), <i>Lotus corniculatus</i> cv. Leo (5%)
Du Col	4	2300–2700	12	2494 2506	W <i>W</i>	25 14	<i>Festuca rubra</i> cv. Rubinba (60%), <i>Poa pratensis</i> cv. Erte (10%), <i>Bromus inermis</i> (5%), <i>Trifolium repens</i> cv. Huia (15%), <i>Lotus corniculatus</i> cv. Leo (10%)

conditions and restoration target. Replicates did not differ significantly in altitude, inclination, aspect, and management. Since each ski run is relatively narrow, it was not possible to locate the replicates at the same altitude: in ski run 1, plots were between 2200 and 2300 m, in run 2 between 2260 and 2320 m, in run 3 between 2280 and 2360 m, and in run 4 between 2390 and 2550 m. The last run was included in this study, although located at higher altitude, because it is the oldest in this resort restored with modern techniques. In each plot, vegetation, root length, and physico-chemical soil properties were analyzed.

VEGETATION ANALYSIS

In the five 3 m × 3 m (9 m²) ski run plots and in the five 9 m² control plots the following parameters were monitored during the vegetative period: moss and total visually estimated herbaceous cover, presence and cover percentage of each vascular plant species. Cover values of 0.1% were assigned to plant species with few individuals. Nomenclature follows *Flora Europaea* (Tutin et al., 1964–1980).

ROOT LENGTH

Three root samples were taken from each ski run plot and three from each undisturbed plot, using 9-cm-long cylindrical corers (5.6 cm I.D.). Roots were separated from soil with an elutriating root washer device and stored in 50% ethanol-water at 4°C until processing. For each sample, total length of roots by five diameter classes (<0.5 mm, 0.5–1 mm, 1–1.5 mm, 1.5–2 mm, and >2 mm) was quantified using the Mac RHIZO v. 3.9 (Regent Instruments Inc., Canada) Images Analysis Program and reported as root density (cm_{root} cm_{soil}^{−3}).

SOIL ANALYSIS

Three 10-cm-deep topsoil samples were collected from each plot. Intact soil cores combined to form a single sample were analyzed after air drying and passage through a 2-mm sieve. pH was determined in a 1:2.5 soil:distilled water suspension (Conyers and Davey, 1988). Cation exchange capacity (CEC) was evaluated with the BaCl₂-triethanolamine method (Rhoades, 1982), and the exchangeable bases were measured by atomic absorption spectrophotometry (AAS). The Walkley-Black wet oxidation method was

used to determine organic carbon content (Nelson and Sommers, 1982). Particle size distribution was determined by the pipette method after dispersion of the sample with Na-hexametaphosphate (Indorante et al., 1990). All analyses were duplicated.

SOIL STABILITY

The stability of the soil aggregates (1- to 2-mm diameter) was evaluated after 5, 10, 15, 20, 40, and 60 min wet sieving. The loss of aggregates was determined from the initial aggregate weight, the weight retained, and the amount of coarse sand in the sample. The data were fitted to an exponential model shown to be successful for the evaluation of breakdown kinetics (Zanini et al., 1998):

$$y(t) = a(1 - e^{-t/c}) + b \quad (1)$$

where y is the aggregate breakdown or loss (%); t the wet-sieving time (abrasion) in minutes; a the maximum estimated abrasion loss of aggregates (%); b the incipient failure of aggregates when water-saturated (%); and c is a time-unit parameter that links the rate of breakdown to wet-sieving time.

DATA ANALYSIS

Plant cover, number of species, root length, and soil parameter values were tested statistically with one-way ANOVA comparing samples from ski runs of different age and comparing samples from runs and from natural vegetation. Analyses were carried out with SPSS 13.0.

Pearson's correlation was used to determine whether there were significant linear relationships between vascular plant vs. moss cover, between root density vs. loss of aggregates, and among measured physico-chemical soil properties. Soil stability parameters a , b , and c were estimated with the SPSS-PC iterative nonlinear regression procedure.

The entire data set comprising species cover percentages; altitude; slope; pH; sand, silt, and clay percentages; organic carbon; cation exchange capacity; and soil stability was analyzed by Canonical Correspondence Analysis (CCA) using CANOCO version 4.0 (ter Braak and Šmilauer, 1998). CCA is a direct ordination technique in which the species/sample data in the ordination are constrained to optimize their linear relationship to the environmental variables (ter Braak and Prentice, 1988). The

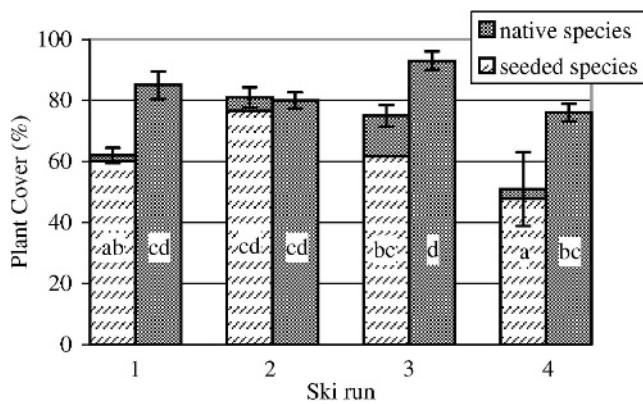


FIGURE 2. Mean native and seeded plant cover in the four ski runs compared to each adjacent natural vegetation. Different letters among columns represent significant difference of total cover at $P < 0.05$.

samples are plotted in an ordination diagram with the environmental variables shown by vectors (arrows). The statistical validity of the ordination was tested using an unrestricted Monte Carlo permutation test (ter Braak and Šmilauer, 1998). Species occurring in only one plot in the original matrix data set (32 species altogether) were discounted. The analyzed data set was of 90 species and 40 samples.

Results

DESCRIPTION OF VEGETATION

Total herbaceous cover in ski runs was generally lower than in adjacent natural vegetation (Fig. 2) although it was always higher than 50%. Only ski run 2 had mean cover values (80%) not different from undisturbed vegetation.

In ski run 1 total herbaceous cover was 62% after four years and was increased to 81% in ski run 2 six years after seeding. Values remained high on ski run 3 (75%) after 10 years. Ski run 4, hydroseeded 12 years earlier and located at the highest altitude, had the lowest mean cover with the highest variability among plots ($51 \pm 12.1\%$).

The seeded species (see Table 1) were always the main constituents of the cover. Even after 12 years, cultivars of the *Festuca rubra* group were always dominant. The legumes, especially *Trifolium repens* and *Trifolium pratense*, presented high cover variability with a maximum value of 35% after 12 years and up to about 2430 m, but fell to zero at higher altitudes. The cover values for the native species were always very low, except for *Trifolium pallescens*. This was the only native species able to attain appreciable mean percentage values ($9 \pm 5.5\%$ in ski run 3). The total cover of the native species on runs 1, 2, and 4 was always less than 5%, while on run 3 there was 13% cover (Fig. 2).

The total number of species was always consistently lower in ski runs than in the adjacent natural vegetation (9 vs. 25) and did not differ among the runs in relation to years from seeding.

The mean number of native species (Fig. 3) was five on the ski runs sown 4, 10, and 12 years earlier and rose to seven on that sown 6 years earlier. The most frequent species were *Trifolium pallescens*, *Poa alpina*, *Silene rupestris*, *Rumex acetosella*, *Polygonum viviparum*, *Erigeron alpinus*, and *Cardamine resedifolia*. Only in ski run 2 were species typical of lower altitude meadows found,

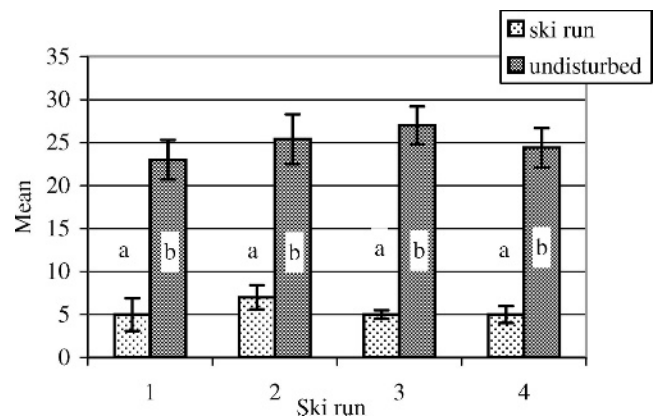


FIGURE 3. Mean number of native species in the four ski runs compared to each adjacent natural vegetation. Different letters among columns represent significant difference at $P < 0.05$.

such as *Achillea millefolium*, *Taraxacum officinale*, *Polygonum bistorta*, and *Dactylis glomerata*.

Exposure of the substrate by erosion and thinning of the herbaceous cover was associated with formation of a moss layer, a symptom of combined disturbance and stress too critical to allow establishment and spread of phanerogams. The moss cover percentage was nil in control plots and ranged from 5% in ski run 2 to 12% in ski run 4. Moss cover was inversely correlated to the herbaceous cover ($r = -0.709$, $P < 0.01$).

ROOT LENGTH

The root length densities displayed significant differences (Table 2). The values for ski runs 1 and 3 were higher than those for runs 2 and 4. The maximum length was found on run 1 sown four years earlier, and the lowest values on run 4. Length distribution by diameter classes was much the same in each ski run. Roots less than 0.5 mm in diameter represented about 75% of the total length in three ski runs, whereas in run 3 it was 66%, and there were more roots with greater diameters.

Comparison between the seeded areas and the adjacent natural vegetation shows that the root length density in three runs was significantly lower than in the nearby natural vegetation; only in run 1 were the values the same in the ski run and the natural vegetation. There was no particular tendency of certain diameter classes to be differently represented in the runs and their adjacent natural vegetation, though the mean values for diameters of more than 1 mm were always higher in the natural vegetation.

SOIL PROPERTIES

In all ski runs, except 3, soil pH was higher than in undisturbed areas (Table 3). Calcium carbonate was significantly present in ski runs 2 and 4, with a corresponding significant increase in pH.

The soils on all ski runs were sandy loam (Table 3), while the undisturbed sites were loamy sand. A significant inverse correlation was found between the silt and sand content for the ski runs ($r = -0.998$, $P < 0.01$) and for the entire set of samples ($r = -0.993$, $P < 0.01$).

The CEC and the organic C values were significantly lower in the ski runs, with a significant correlation between these two parameters ($r = 0.834$, $P < 0.01$) for the entire set of samples. A significant correlation was also found between the CEC and clay

TABLE 2

Root density values: total and divided in diameter classes in ski runs and in the adjacent natural vegetation.

Study area	Root density (cm/cm ³)	Run × contr.	Diameter class <0.5 mm	Run × contr.	Diameter class 0.5–1 mm	Run × contr.	Diameter class 1–1.5 mm	Run × contr.	Diameter class 1.5–2 mm	Run × contr.	Diameter class	
											>2 mm	Run × contr.
1 Ski run	59.4 ^b	n.s.	45.8 ^b	n.s.	9.4 ^{ab}	n.s.	2.5 ^{bc}	n.s.	1.1 ^b	n.s.	0.1 ^a	**
Control	59.6		43.3		10.9		3.1		1.5		0.6	
2 Ski run	42.7 ^a	*	32.5 ^a	*	6.9 ^a	*	1.9 ^{ab}	*	0.9 ^{ab}	*	0.1 ^a	**
Control	67.3		49.7		12.5		3.1		1.3		0.5	
3 Ski run	57.9 ^b	*	38.1 ^{ab}	n.s.	13.5 ^b	n.s.	2.7 ^c	*	1.0 ^b	n.s.	0.5 ^a	n.s.
Control	73.7		41.7		26.8		3.8		1.1		1.1	
4 Ski run	37.4 ^a	**	28.8 ^a	n.s.	6.2 ^a	**	1.5 ^a	**	0.5 ^a	*	0.1 ^a	n.s.
Control	46.7		32.6		9.2		2.9		1.3		0.3	

Different letters in columns represent significant differences among ski runs: ** $P < 0.01$; * $P < 0.05$; n.s. = not significant.

content for the runs ($r = 0.595$, $P < 0.05$) and for the entire set of samples ($r = 0.675$, $P < 0.01$).

The exchangeable Ca concentration was 2.18 cmol_c⁺ kg⁻¹ in run 1, 5.61 cmol_c⁺ kg⁻¹ in run 2, 1 cmol_c⁺ kg⁻¹ in run 3, and 5.61 cmol_c⁺ kg⁻¹ in run 4.

SOIL STABILITY

The averaged breakdown curves for the ski runs and their adjacent natural vegetation are shown in Figure 4. Topsoils from the run disintegrated more quickly and were more unstable in terms of total loss of aggregates. The averaged “a” parameter (%) of Equation 1 estimated from the wet-sieving data was 43.39 (±11.60) in the ski runs and 20.89 (±13.81) in the undisturbed sites. Table 4 shows the averaged parameters of Equation 1 estimated from wet-sieving data by age of sowing. The soil of the youngest run (4 years) was the most stable in terms of total loss of aggregates. The soil of the 6-year-old run was the most unstable. The oldest run displayed an intermediate total loss but with a “b” value significantly higher. The 12-year-old run also showed the highest “c” factor. Undisturbed soils showed lower “a” values for the controls of ski runs 1 and 3 compared to runs 2 and 4. A positive correlation ($r = 0.801$, $P < 0.01$) was found between the maximum loss of aggregates of ski run soils and of the relative control soils.

A significant inverse correlation between organic C and parameter “a” was found for the runs ($r = -0.998$, $P < 0.01$) and the entire set of samples ($r = -0.760$, $P < 0.05$).

No significant correlations were found between ski run ages and the physico-chemical soil properties.

RELATIONSHIPS BETWEEN VEGETATION AND ENVIRONMENTAL FACTORS

The eigenvalues of the first two axes of the CCA were 0.799 and 0.558 and accounted for 33.9 and 57.5%, respectively, of the explained species-environment relationships and for 46.9% of the total variation in the species data set itself (Table 5). The first two ordination axes of CCA had significant canonical eigenvalues ($P < 0.005$) as determined by the Monte Carlo permutation test. High significance for all the other canonical axes was also found ($P = 0.005$, and see Trace in Table 5).

The ordination diagram (Fig. 5) for the sample scores from the first two axes shows the ski run samples clustered together at the lower end of axis 1, while the samples from the adjacent natural vegetation corresponding to each ski run were clustered together further away from the ski run samples. The first axis, representing a gradient from highly altered to undisturbed conditions of the vegetation/soil system, especially separates ski run sites from control samples. The first axis is strongly correlated with increasing clay and sand (Table 5), and correlated with decreasing silt, slope, pH, and loss of aggregate; axis 2 was related to increasing altitude and organic C.

Discussion

In the areas we studied, the use of appropriate agronomic techniques, conservation of the topsoil, selection of suitable plant material, and manuring after sowing have led to establishment of a sufficiently dense plant cover, although it did not reach the cover values of the adjacent natural alpine pasture. These results, together with data recently collected in other resorts in the Alps

TABLE 3

Texture and main chemical properties of the soils (0–10 cm depth). CEC = cation exchange capacity, Org C = organic carbon.

Ski run	Study area	Age (years)	pH	CaCO ₃ (%)	Clay	Silt	Sand	CEC cmol _c ⁺ kg ⁻¹	Org C g kg ⁻¹
					g kg ⁻¹				
1	Ski run	4	6.1 ^a	0	32 ^a	306 ^a	662 ^a	12 ^a	26 ^a
	Control		4.8 ^b	0	63 ^b	154 ^b	783 ^b	14 ^b	38 ^b
2	Ski run	6	7.9 ^a	2.8	16 ^a	267 ^a	703 ^a	6.9 ^a	11 ^a
	Control		5.2 ^b	0	59 ^b	184 ^b	758 ^b	15 ^b	17 ^b
3	Ski run	10	6.0 ^a	0	23 ^a	342 ^a	634 ^a	14 ^a	15 ^a
	Control		5.9 ^a	0	60 ^b	240 ^b	700 ^b	29 ^b	57 ^b
4	Ski run	12	7.4 ^a	1.4	22 ^a	362 ^a	616 ^a	11 ^a	15 ^a
	Control		5.9 ^b	0	54 ^b	193 ^b	755 ^b	18 ^b	49 ^b

Different letters in columns represent significant differences at $P < 0.05$.

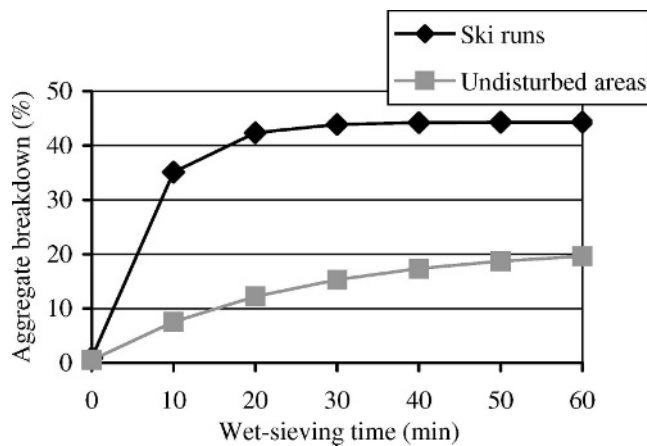


FIGURE 4. Comparison between average aggregate breakdown during wet-sieving in ski runs and in the natural vegetation.

(Bozzo et al., 2000; Argenti et al., 2000; Gros et al., 2004), show that progress in revegetation techniques has led to achievement of satisfactory results in terms of obtaining a protective cover even above timberline. Plant cover, after increasing over 4 to 6 years, maintained stable values for up to 10 years, while in the 12-year run local thinning was apparent, resulting in high variability; but

in this case cover reduction seems to be more a consequence of higher altitude than of time.

In spite of satisfactory plant cover values, species richness was always significantly lower on restored ski runs compared with control areas and did not show any positive trend as the years from seeding passed. Indeed, there was little evidence of significant re-establishment of native species in ski runs, and seeded species were dominant even after 12 years. *Festuca rubra* cultivars, extensively used in high-altitude restoration programs, provide rapid and long-lasting protective cover. It is often the only species that can tolerate extreme conditions above 2400 m, where other seeded species, in particular legumes such as *Trifolium pratense* and *T. repens* cannot survive (Argenti et al., 2000). *Festuca rubra*, on the other hand, produces excessively dense cover and copious litter which can reduce colonization by native species (Delarze, 1994; Bayfield, 1996; Argenti et al., 2000). Thus colonization by native species in ski runs was inconspicuous in terms both of species richness and plant cover; only *Trifolium pallescens*, an *r*-strategist, displays the characteristics of an invasive pioneer species such as high regeneration capacities due to high seed production and seed-bank reserves (Hillgardt, 1993a, 1993b), reached appreciable values. Its abundance seems mainly related to soil disturbance by snow-grooming vehicles. Pioneer species that colonize debris, such as *Silene rupestris*, *Polygonum viviparum*, and *Cardamine resedifolia*, were the only natives found on ski runs,

TABLE 4

Averaged parameters of Equation 1 estimated from wet-sieving data by ski slope age and for ski runs compared to controls.

Ski run	Study area	<i>a</i> (%)	Ski run × control	<i>b</i> (%)	Ski run × control	<i>c</i> (min ⁻¹)	Ski run × control
1	Ski run	25.53 ^a	**	0.68 ^a	n.s.	5.11 ^a	**
	Control	4.59		0.18		40.13	
2	Ski run	54.90 ^b	**	0.39 ^a	n.s.	3.50 ^a	**
	Control	33.96		0.59		19.10	
3	Ski run	45.66 ^c	**	0.94 ^{ab}	*	6.60 ^a	**
	Control	11.20		0.22		19.13	
4	Ski run	47.47 ^c	**	1.70 ^b	*	10.60 ^b	**
	Control	33.80		0.85		19.17	

Different letters in the same column indicate significant differences ($P < 0.05$) among ski runs. ** $P < 0.01$; * $P < 0.05$; n.s. = not significant.

TABLE 5

Results of ordinations by canonical correspondence analysis (CCA) with nine environmental variables related to soil and topography: eigenvalues for the CCA with all environmental variables, cumulative percentage variance of species data and of species-environment correlation, and interset correlation coefficients for each canonical axis. The Trace is the sum of all canonical eigenvalues. CEC = cation exchange capacity, Org C = organic carbon.

	Trace	Axis 1	Axis 2	Axis 3	Axis 4	Total Inertia
Eigenvalues	2.358**	0.799	0.558	0.409	0.168	4.597
Cumulative percentage variance of species data		17.4	29.5	38.4	42.1	
Cumulative percentage variance of species-environment correlation		33.9	57.6	74.9	82.0	
Inter-set correlation coefficients of environmental variables with axes						
1	altitude	-0.1203	0.5927	-0.0972	-0.1183	
2	slope	-0.8024	0.0234	-0.0403	-0.1266	
3	loss of aggr.	-0.5974	0.0137	-0.4652	-0.4059	
4	pH	-0.7542	-0.0485	0.0054	-0.1713	
5	clay	0.8893	0.2108	0.2547	0.0835	
6	silt	-0.8494	-0.2429	-0.0022	-0.1473	
7	sand	0.8099	0.2558	-0.0674	0.1477	
8	CEC	0.4206	0.2194	0.7139	-0.1526	
9	Org C	0.3858	0.5198	0.6340	0.1595	

** $P = 0.005$.

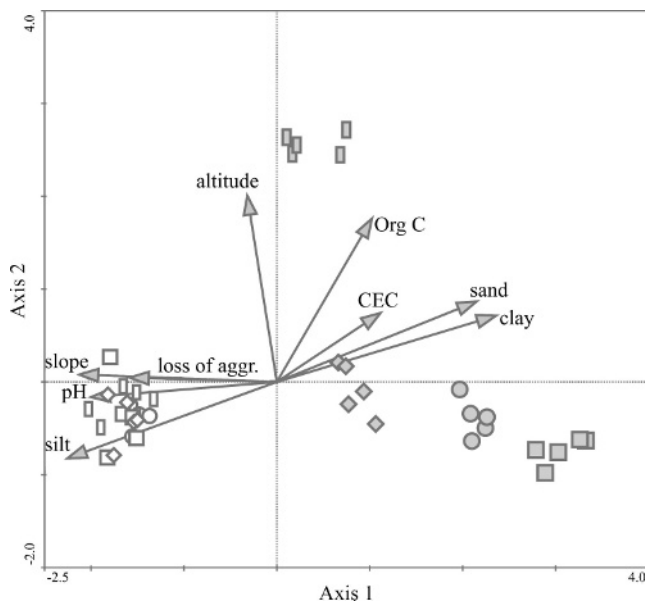


FIGURE 5. Canonical Correspondence Analysis (CCA) ordination diagram (axes 1 and 2) showing the relationship between vegetation and the environmental variables. The vegetation plots are represented by symbols: ○ = Ski run 1; □ = Ski run 2; ◇ = Ski run 3; □ = Ski run 4. The same symbols filled with gray represent the control plots relative to each ski run plot.

particularly at higher altitude; they are characterized by very low growth rates, low competitiveness, and a low ability to form dense populations. The dominant species of continuously vegetated alpine pastures were completely absent as already noted by Delarze (1994) and Argenti et al. (2000). Only in ski run 2, where soil had been brought up from lower altitudes when the substrate was prepared for seeding, were species typical of lower altitude meadows present. The observed native plants contribute to species richness but give little indication of progression toward a more mature and natural plant community.

Establishment of native species is limited by their stress-tolerant strategies, but also in great measure due to persistence of the soil alteration caused by ski-run construction. Substantial alteration of the ski run soils was apparent in the form of a higher pH, OM impoverishment, and loss of both fine particles (clay) and aggregates. The amount of clay was low both in the control and in the ski runs, where greater erosion could be responsible for the significant clay reduction. In spite of manuring and pasturing, organic C was lower in ski runs, and this may be the cause of significantly higher soil pH and higher aggregate breakdown.

Changes in soil texture between ski runs and control plots are due both to machine-grading and to different environmental conditions on the run areas during the ski season. Accumulation of silt and reduction in sand in the ski runs is consistent with chemical and physical weathering that progressively transforms larger soil particles into smaller ones. The frequent periods of freezing in the ski slopes, caused by decreased insulation due to the compressed snow cover (Rixen et al., 2004), could be a major factor responsible for the weathering of soil particles. Sand, in fact, was inversely correlated with silt content for the runs and for the entire set of samples. None of the physico-chemical soil properties considered were correlated with ski run age showing how pedogenesis in these environments is extremely slow and site-specific.

Clay content, OM, and other factors such as forms and relative concentrations of inorganic ions, microorganism species

and functions, climatic variables, type and amount of soil (Martin et al., 1955; Harris et al., 1966) affect the formation of aggregates and their stability. In particular, soil OM plays an important role in maintaining the stability of soil aggregates (Chaney and Swift, 1984). Moreover, development of roots and hyphae, especially those of associated fungal endosymbionts, form the network mainly responsible for assembly of microaggregates into macroaggregates by chemical and physical action. Soil aggregation level, greatly affected by soil disturbances (Six et al., 1999), was always lower on the ski runs; root lengths were shorter except on ski run 1, where it was the same as in the natural vegetation, and aggregate stability was highest among the runs. Nevertheless, no significant correlation was found between aggregate stability and root density for either the ski runs or the entire set of samples ($r = -0.68$, $P = 0.065$), whereas a significant inverse correlation between organic C and the total loss of aggregates was found for the runs and the entire set of samples. The organic carbon content was significantly greater in the youngest run, maybe due to its more recent manuring. Parameter “c” showed how the oldest run was characterized by an extremely slow loss of aggregates, revealing a certain degree of stability, even if root density was the lowest. Here the high exchangeable calcium and a sufficient OM content may explain the improvement in soil aggregation (Baver et al., 1972; Gu and Doner, 1993). The presence of polyvalent cations is important for the adsorption of humic substances on the negatively charged soil colloid surfaces (Gu and Doner, 1993), forming a bridge between anionic groups in OM and the negatively charged surfaces of clay particles. In ski run 2 the relatively high Ca concentration did not compensate the very low OM content.

Aggregate stability thus seems more closely related with the chemical and physical features of pre- and post-disturbance soil rather than with root density: for the altered ski run substrates a developed root system did not seem to be sufficient to restore the soil structure in the first years after seeding, whereas there was a clear relation in all the runs between the stability of their substrates and the relative pre-disturbance soil stability.

When arable soils are taken out of cultivation and restored or allowed to revegetate naturally, 30–50 years or more may be required before the size distribution of water-stable aggregates approaches the original pattern (Tisdall and Oades, 1980; Dormaar and Smoliak, 1985; Jastrow, 1987); even longer periods are thought to be required for soils above timberline. Contrasting results were obtained by Gros et al. (2004), who observed a rapid recovery of soil structure as judged by the increase in clay content and the expansion of root systems. However, also in their work, ski run construction caused a significant decrease of soil organic C and clay content in the first years, with a corresponding pH increase. Recovery of the soil organic C and partial recovery in clay content was reached after 13 years, and was probably favored by the quite advanced stage of evolution of the natural soil (Lithic Dystrochrept), the ski run preparation (mechanical crushing of stones), and the relatively gentle slope (10–15°). On the contrary, at our sites, the steeper slopes (18–25°) and the less favorable pre-disturbance soil properties, such as the low clay content, may slow down the recovery processes.

Above timberline, machine grading destroys vegetation and severely damages soil properties; intensive agronomic techniques can rapidly provide a vegetation cover but no evidence of evolution of the soil-vegetation system was observed even 12 years after seeding. In fact, all the ski run plots clustered together for the species-environment relationship in spite of different ages and altitude, whereas natural vegetation plots were clearly separated mainly for their species composition and for altitude, highlighting

the differences in soil-vegetation systems. Among the environmental variables analyzed, altered soil texture and structure, pH, and slope were the most decisive factors in limiting recolonization by native species and the shift of plant-soil dynamics toward a more natural state.

More has to be done to conserve or restore physical, chemical, and biological soil properties since these are decisive in establishing self-sustaining native plant communities; over a span of 10 years, the success of a restoration program should already be recognizable (Urbanska and Chambers, 2002).

Shallow incorporation of manure or other amendments during ski run preparation may effectively improve the soil by helping to restore structure and stabilizing pH. If the substrate were closer to that of undisturbed soils, using seeded or transplanted native species (Urbanska et al., 1987; Ebersole et al., 2002), instead of commercial seed mixtures, could also be more effective.

In view of the extreme difficulties in restoring high-altitude ecosystems, particular care should be given to allowing machine grading where plant communities present high conservation value, and to adjusting construction practices to minimize physical alteration of the native ecosystem.

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