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Recovery of Alpine Herbfield on a Closed Walking Track in the Kosciuszko Alpine Zone, Australia

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Abstract

Human use of arctic and alpine environments can result in damage to the natural vegetation and soils. Restoration of the damage can have limited success due to the severity of the environment, which restricts plant germination and growth and increases the potential for soil erosion. In this study, we evaluated the success of restoration of a closed track in the alpine area around continental Australia's highest mountain, Mount Kosciuszko. Vegetation and soils along a 4 km walking track (that was closed and rehabilitated more than 15 yr ago) were compared with the adjacent undisturbed vegetation and soils. There was limited success in restoration with clear differences in soil nutrients, extent of vegetation cover, plant species composition, and height of vegetation between the track and adjacent natural vegetation sampled using 1 m^2 quadrats. The study highlights the need for limiting disturbance in such environments, and for ongoing rehabilitation in areas that have been disturbed. It also indicates that when non-native species are used in rehabilitation, they may not necessarily be succeeded by natives, particularly if soil conditions do not return to a state similar to undisturbed areas.

Introduction

The process and time frame of vegetation recovery in disturbed natural systems are important issues for natural area management, particularly in severe environments such as alpine zones, where a short growing season and harsh climatic conditions may limit plant establishment and growth (Urbanska, 1997; Körner, 1999; Urbanska and Chambers, 2002; Sarmiento et al., 2003; Whinam and Chilcott, 2003). Human use of such systems, for instance by tourism activities, can rapidly degrade them by damaging the native flora and soils (Urbanska, 1997; Sarmiento et al., 2003; Whinam and Chilcott, 2003). Evaluating the recovery of disturbed sites in these severe environments is the focus of a growing body of research (e.g., Densmore et al., 1990; Urbanska, 1997; Bakker and Berendse, 1999; Forbes and Jefferies, 1999; Stampfli and Zeiter, 1999; Zabinski and Cole, 1999; McDougall, 2001; Prach et al., 2001; Sarmiento et al., 2003; Whinam and Chilcott, 2003). This research has highlighted that: (1) natural revegetation can take a long time to recover (order of decades to centuries; Roxburgh et al., 1988; Urbanska, 1997; Hartley, 2000; McDougall, 2001; Sarmiento et al., 2003); (2) continued degradation can occur even when the activity that originally caused the damage ceases (Johnston et al., 2003); and (3) active revegetation can speed up the process of recovery (Roxburgh et al., 1988; Densmore et al., 1990; Urbanska, 1997; Bakker and Berendse, 1999; McDougall, 2001).

Increasingly, native species are used in revegetation work, but sometimes non-native species were/are still used because of availability, low cost, and/or faster growth rates (Cameron, 1962; Keane, 1977; Cargill and Chapin II, 1987; McDougall, 2001; Gray, 2002). When non-natives were used, particularly in protected areas, it was often with the assumption that native species would eventually replace alien species as site conditions returned to a more natural state, although that often does not occur (Cargill and Chapin II, 1987; McDougall, 2001; Gray, 2002).

While extensive revegetation and restoration work has been done in the Kosciuszko alpine area and other alpine areas in Australia, particularly in response to damage from grazing and tourism, few studies have examined the longer term success of such efforts. Those studies have found that exotic taxa can still be prominent components of the vegetation decades after use in rehabilitation, and that it can take decades for areas of bare ground to be colonized by vegetation (McDougall, 2001; Johnston et al., 2003; Scherrer, 2003; Scherrer and Pickering, 2005).

This study examines the restoration of a 4-km-long walking track that was a primary access route to Australia's highest mountain, Mount Kosciuszko (2228 m), from the ski village of Thredbo (Fig. 1). The objective was to determine the state of vegetation and soils at undisturbed and revegetated sites in order to establish if, in the 15 yr since track closure and revegetation, the damaged areas had returned to a state comparable to adjacent natural vegetation. Specifically, the questions addressed were: (1) How different is the vegetation on the former track compared to adjacent natural vegetation? (2) How different are the soils on the former track compared to the soils in adjacent natural vegetation? (3) Are there any trends in the measured environmental, plant, or soil characteristics that could explain the variation in recovery between sites along the former track, and thus contribute to our understanding of why some sites recover more quickly than others?

Methods

STUDY AREA

The study was located in the alpine zone of Kosciuszko National Park, southeastern Australia. The average annual precipitation is 1606 mm, most of which falls as snow in winter and early spring (Costin et al., 2000). The soils are predominantly acidic organo-mineral soils classed as alpine humus (Costin, 1954). The vegetation is characterized by low-growing shrub, herb, and grass species, forming a variety of structurally and floristically distinct vegetation communities. Since the cessation of livestock grazing (cattle and sheep) in 1944, the area has experienced little grazing or trampling by large herbivores (Costin et al., 2004).

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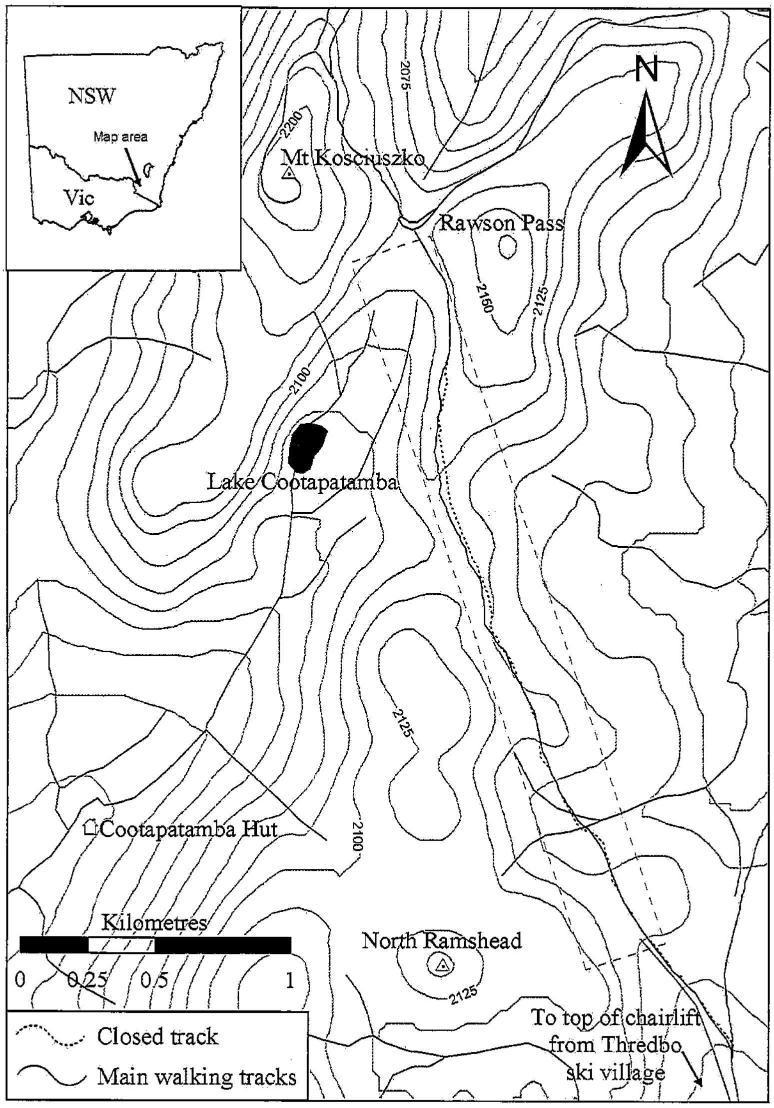

FIGURE 1. Location of the closed walking track within the Kosciuszko alpine zone in south-eastern Australia. The closed track was replaced by a raised steel-mesh walkway that followed a similar route and overlapped the closed track in parts.

STUDY SITE

The study track was largely in tall alpine herbfield vegetation of the *Celmisia–Poa* alliance (*sensu* Costin et al., 2000), which is the most widespread alpine community. The closed walking track initially developed as an informal foot trail that connected the top of a chairlift from the Thredbo ski village to Rawson Pass, below Mount Kosciuszko (Fig. 1). After about 20 yr, the track was replaced by a raised steel-mesh walkway (started in 1982, completed in 1989) to alleviate severe erosion problems and prevent further damage to the vegetation.

Once closed, the track was seeded and mulched to rapidly attain a protective vegetation cover minimizing soil erosion, but with the ultimate goal to facilitate the return of the bare track to the natural vegetation cover (Worboys et al., 1995; Good, 1992). The seed mixture applied consisted of cultivars of **Agrostis capillaris*, **Festuca rubra*, and **Lolium perenne* (R. Good, personal communication, 2003) (* denotes alien species). Mulching involved the spread of hay and straw at unknown rates which was sprayed with liquid tar to hold it in place. Unlike many other rehabilitated areas in Kosciuszko National Park, no fertilizer was applied to the closed track and no further restoration work has been carried out since track closure (D. Woods, personal communication, 2001; G. Johnston, personal communication, 2003). The portion of the track studied is about 4 km northwest of the Thredbo ski village and ranges in altitude from about 2030 to 2130 m. There was a range of aspects among sites; slopes ranged from flat to 13°.

SAMPLING METHODS

Site Selection

The raised steel-mesh walkway crisscrosses and/or overlaps the study track, which it replaces, several times, thus cutting the old track into sections. Areas of overlap were not sampled to eliminate potential effects of the raised walkway on vegetation recovery (K. Green, personal communication, 2001; G. Worboys, personal communication, 2003). In each section of the study track, the first site was randomly located at a minimum distance of 5 m from the nearest overlap with the raised walkway. Subsequent sites were placed every 50 m to ensure independence between the sites and adequate representation of the entire track, giving a total of 22 sites in tall alpine herbfield vegetation.

Vegetation Sampling

In February 2001, vegetation cover, height, composition, and species abundance were measured using 1 m^2 quadrats. At each site, two quadrats were placed 4 m apart: one on the closed track and the other in the natural vegetation adjacent to the track, on the side furthest away from the raised steel-mesh walkway. The quadrats were divided into a grid of twenty-five 20×20 cm sub-quadrats, which were used to estimate percent cover of rock, litter, and percent overlapping cover of species. Species were rated in terms of + (present but < ¼ of sub-quadrat cover); 1 (1% of total cover, which equals ¼ of sub-quadrat cover), 2, 3, or 4% of total cover. The abundance of each species was estimated using shoot frequency (number of sub-quadrats containing a portion of the aerial part of the plant) (Morrison et al., 1995). Vegetation height was measured at six randomly chosen points in each quadrat. Diversity indices (Richness, Shannon-Weaver, Simpson's) were calculated and compared between track and natural vegetation.

Soil Sampling

To determine the nutrient status and compaction of natural and track sites, soil samples were collected from the surface horizons (top 10 cm) at a randomly selected subset of 10 sites (due to the high cost of soil analysis, sub-sampling was used). Most of the root uptake of nutrients in herbfield and grassland vegetation occurs in the top 10 cm (Allen et al., 1974). Each sample was made up of six bulked subsamples collected within 1 m of the northern and southern edge of the quadrats (in line with the direction of the track). Electrical conductivity and pH were determined in a 1:5 distilled water dilution (Rayment and Higginson, 1992). Soil pH and conductivity provide an indication of the availability of plant nutrients, as most plant-essential elements are linked to the pH of the soil (Binkley and Vitousek, 1989; Cresser et al., 1993). Organic carbon levels were determined using the Walkley and Black method (Rayment and Higginson, 1992). Extractable P was determined using a modification of the Olsen et al. (1954) procedure, extractable N using method 7C1c, and exchangeable cations (K, Ca, Mg, Mn, As, and Zn) using an ammonium acetate extraction (Rayment and Higginson, 1992).

Bulk density samples of the surface horizon were collected from 15 sites using a steel cylinder (height, 53 mm; diameter, 48 mm). The samples were weighed, dried at 105°C for 24 h, and reweighed to determine the water content and bulk density of the soils.

Statistical Analysis and Ordinations

The non-parametric Wilcoxon signed-rank test was used to compare the mean of cover values for the paired track and natural quadrats where the data were not normally distributed. This test is the non-parametric alternative to the parametric paired *t*-test, which assumes normality of the data and the population difference scores. Where the parametric assumptions were met, paired *t*-tests were applied. Vegetation height, overlapping cover, species richness, shoot frequency, heterogeneity (Shannon-Weaver Index), and evenness (Simpson's Index) as well as soil bulk density, nutrient content, and soil water content were compared between track and natural quadrats. Where multiple comparisons were made on the same data set, a Bonferroni correction was applied to reduce the risk of a type I error (Quinn and Keough, 2002). All calculations were performed in SPSS for Windows 10.0 (SPSS Inc., 1999).

The Bray-Curtis index of similarity, which was used to quantify the similarity of species cover and composition among quadrats, was chosen as it does not attribute similarity to joint absences of species and is generally preferred over other metric measures for ecological studies (Minchin, 1987; Clarke, 1993; Hero et al., 1998; Anderson, 2001). Ordinations were done using Semi-Strong Hybrid Multidimensional Scaling (SSH MDS) in the pattern analysis software package PATN (Belbin, 1991, 1994).

Results

VEGETATION

The vegetation cover on the closed track was significantly different ($p = 0.01$) from adjacent natural vegetation. The most obvious difference, even to the casual observer, was an intact vegetation cover

TABLE 1

Percent cover of litter, bare, rock, and vegetation from twenty-two 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. Values are means ± standard error. Bonferroni adjusted significance values determined by paired *t*-tests are displayed ($n = 22$). n.s. = not significant.

% cover	Track	Natural	*p*
Vegetation	63.5 ± 8.3	89.3 ± 3.9	0.01
Bare	25.6 ± 4.5	1.07 ± 0.6	0.00
Litter	8.2 ± 2.5	8.9 ± 2.8	n.s.
Rock	3.2 ± 1.3	0.71 ± 0.5	n.s.

in areas adjacent to the closed track compared to considerable bare areas on the track. Only around 64% of the 1 m^2 quadrats on the closed track were covered by vegetation, with around 26% bare ground (Table 1). This contrasted with the adjacent natural vegetation, where quadrats averaged 89% vegetation cover and only 1% bare area (Table 1). The remaining area on both the closed track and in the adjacent quadrats consisted of around 8–9% litter with 3–1% exposed granite rocks.

Species Composition

A total of 60 plant species (including the taxon bryophytes, which includes *Sphagnum cristatum* and unidentified moss species) representing 20 plant families were recorded at the 22 sites. The most diverse families were Asteraceae with 15 species, followed by Poaceae (13 species), Cyperaceae (7 species), and Juncacae (3 species). Three species are endemic to the Kosciuszko alpine area (*Chionogentias muelleriana* ssp. *alpestris*, *Craspedia costiniana*, and *Euphrasia collina* ssp. *glacialis*), while three are environmental weeds (**Acetosella vulgaris*, **Agrostis capillaris* and **Festuca rubra*).

There were clear differences in species composition between the track and adjacent native vegetation with 11 species recorded exclusively along the closed track and a further 6 taxa predominantly found on the track (*Euchiton argentifolius*, **Agrostis capillaris*, **Festuca rubra*, Bryophytes, *Erigeron nitidus*, *Euchiton nitidilus*) (Fig. 2). Correspondingly, there was a suite of species that were recorded either only (seven species) or predominately in natural vegetation (*Viola betonicifolia* ssp. *betonicifolia*, *Pentachondra pumila*, *Poa saxicola*, *Microseris lanceolata*, *Lycopodium fastigiatum*) (Fig. 2).

Differences in species richness were entirely attributable to exotic species on the track. This is supported by the significantly higher shoot frequencies of alien species on the closed track compared to adjacent natural vegetation (Table 3). However, differences due to alien species were not large enough to influence estimates of heterogeneity (Shannon-Weaver Index) and evenness (Simpson's Index), as these did not significantly differ between the track and adjacent natural vegetation, when alien species were included and excluded from the analysis (Table 2).

The two most diverse life form groups were graminoids (24 species) and herbs (31 species), while only 3 shrub species were recorded. When examined at the life form level, richness, heterogeneity, and evenness of graminoids were significantly higher on the closed track than in natural vegetation, but again this was due to the presence of weed grasses on the track. There was no difference in these measures for herbs (Table 4).

Cover, Shooting Frequency, and Height

In addition to differences in species composition, there were clear differences in the cover of individual species between the closed track and adjacent vegetation. These differences resulted in a clear separation

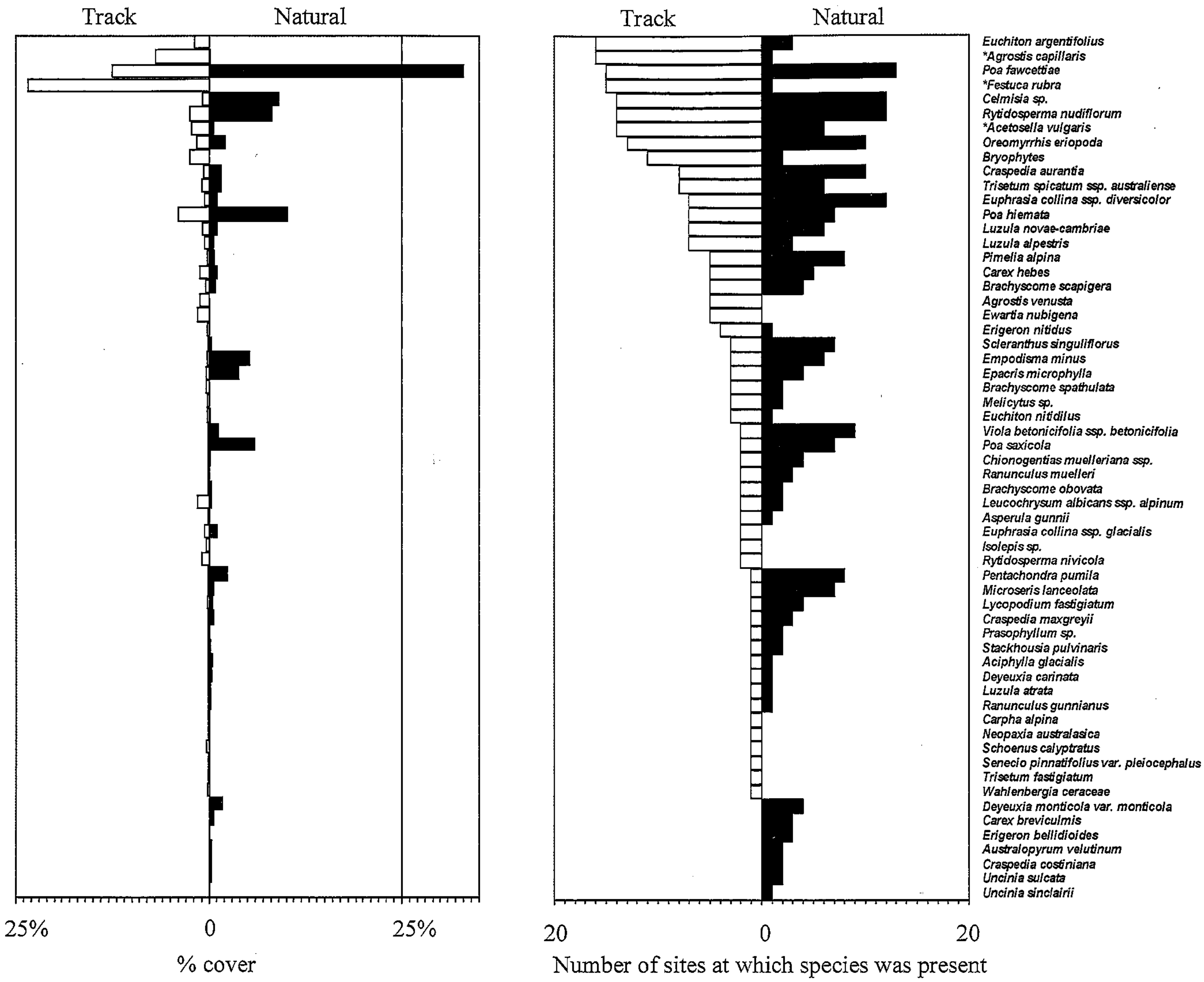

FIGURE 2. Mean percentage overlapping cover of individual species and the number of sites (out of 22) where the species were recorded on the closed track (empty bars) and in natural vegetation (filled bars). Data from twenty-two 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. * denotes alien species.

of the track and adjacent natural vegetation sites in the ordination, based on percent cover (stress = 0.17; Fig. 3). The key species driving the difference were *Euchiton argentifolius*, *Poa* spp., *Celmisia* sp., and the alien species **Festuca rubra* and **Agrostis capillaris* (Fig. 3). The track was dominated by the cover of alien grasses, with 23% of quadrats covered by **Festuca rubra*. In contrast, the cover of the native snow grasses dominated the natural vegetation, with *Poa fawcettiae* covering 33% of quadrats and *P. hiemata* accounting for another 10% (Table 3). Other species that had higher cover on the track were **Acetosella vulgaris*, **Agrostis capillaris*, and *Euchiton argentifolius* (Table 3). The data for percentage shoot frequency showed a similar pattern, with over half of the sub-quadrats containing **Festuca rubra* on the closed track, while over 75% of the sub-quadrats in the adjacent natural vegetation had one or several *Poa* species. Shoot frequency of bryophytes was significantly higher for track quadrats (Table 3).

Herbs was the most diverse life form in terms of overall species richness, but graminoids dominated in terms of percentage overlapping cover. On the closed track, 56.0 ± 4.4% of overlapping cover was by graminoids, 10.9 ± 1.4% by herbs, and 2.2 ± 0.9% by shrubs. This compares to 70.4 ± 6.2% graminoids, 20.5 ± 3.5% herbs, and 7.3 ± 3.4% shrubs in adjacent natural vegetation. Overlapping cover of herbs was significantly higher in the natural vegetation quadrats compared to track quadrats ($p = 0.001$), while the comparison was not significant for graminoids ($p > 0.05$) or shrubs ($p > 0.05$). There was no significant difference in percent cover of litter or rock between the track and the natural vegetation (Table 1). The extent of bare soil, however, was significantly higher ($p = 0.00$) on the track than in the natural vegetation.

At 61 mm, the average vegetation height was significantly lower ($p = 0.00$) in quadrats on the closed track compared to adjacent natural vegetation (109 mm) (Fig. 4).

SOILS

There was a clear separation of track and natural quadrats along the gradients of soil nutrient levels and acidity (Fig. 5). Electrical conductivity was significantly lower and pH was significantly higher on the former track compared to the natural areas (Fig. 6). Soils from the track quadrats had significantly lower levels of organic C and the elements N, P, K, and Ca than adjacent quadrats (Fig. 6). Sodium levels at both natural and track quadrats were similar. Although there appears to be a difference in extractable Mg and Mn between the track and adjacent areas, it was not significant (Fig. 6). The effects of soil compaction from former trampling were still evident, with bulk density

TABLE 2

Diversity indices from 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. Values are means ± standard error (n = 22). Significance was determined by paired t-test for richness values, and by Wilcoxon signed ranks test for heterogeneity and evenness. n.s. = not significant.

	Track	Natural	p
Richness			
Native species (# species/quadrat)	9.5 ± 0.6	9.6 ± 0.9	n.s.
Alien species (# species/quadrat)	2.0 ± 0.2	0.4 ± 0.1	0.000
All species (# species/quadrat)	11.6 ± 0.7	10.0 ± 0.9	0.036
Heterogeneity			
Native species (Shannon-Weaver Index)	1.8 ± 0.1	1.9 ± 0.1	n.s.
All species (Shannon-Weaver Index)	2.0 ± 0.1	1.9 ± 0.1	n.s.
Evenness			
Native species (Simpson's Index)	0.8 ± 0	0.8 ± 0	n.s.
All species (Simpson's Index)	0.8 ± 0	0.8 ± 0	n.s.

being significantly higher and moisture content being significantly lower on the track compared to natural vegetation (Fig. 6).

Discussion

Restoration of natural areas affected by recreation activities poses many challenges for managers and researchers. Restoration must be done rapidly to prevent exposed soils from eroding and to limit reuse of closed sites (Zabinski et al., 2000). However, the rapid establishment of plants in alpine environments is a challenge, particularly with limited information of suitable growing conditions for native plants and limited availability of propagules (Zabinski and Cole, 1999). Thus, in the past, alien species which were commercially available were often used for seeding, sometimes in combination with fertilizers (McDougall, 2001). Once a vegetation cover was achieved and microclimate and soil conditions improved, native species were generally expected to replace the alien sward (McDougall, 2001).

This study shows that about 15 yr after the closure and initial revegetation efforts (seeding and then mulching) of a popular walking track in the Kosciuszko alpine zone, around 26% of the track was still bare ground, and alien species were the dominant component of the vegetation on the track (32% overlapping cover aliens compared to <1% in adjacent natural vegetation). Further, plant species composition, vegetation height, and nutrient status of the soils on the closed track were still different from those of adjacent natural areas. Therefore, the longer term goal of restoration to a comparable natural state has not yet been achieved and even the initial goal of revegetation has only been partly reached, with a quarter of the closed track remaining bare ground. Given the climatic conditions of the area, these results were not unexpected. The type and extent of the differences between the closed track and natural areas, however, could be the key to the future progress of restoration.

Many studies have documented a lower species richness and plant cover at disturbed sites compared to surrounding undisturbed vegetation (Bishop and Chapin III, 1989; Harper and Kershaw, 1996; Ebersole, 2002). Two main factors, however, may contribute to a higher species richness such as that observed during this study: (1) increased presence of opportunistic or introduced alien species at disturbed sites; and/or (2) the wider range of successional states at disturbed sites, with some areas still at the colonizing stage and other sections at a more mature stage, thus providing a greater variety of species overall (Cole and Hall, 1992; Whinam and Chilcott, 1999). The

TABLE 3

Overlapping cover and shoot frequency of the dominant plant species sampled in twenty-two 1 m^2 paired quadrats along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. Values are means ± standard error. Significance values are Bonferroni adjusted results of Wilcoxon square ranks tests (n = 22). n.s. = not significant.

	Overlapping cover (%)			Shoot frequency (%)		
Species	Track	Natural	p	Track	Natural	p
Poa fawcettiae	12.5 ± 4.3	33.0 ± 7.9	n.s.	26.0 ± 6.4	51.6 ± 10.1	n.s.
Poa hiemata	4.0 ± 2.2	10.2 ± 3.9	n.s.	8.0 ± 3.7	24.7 ± 8.5	n.s.
Celmisia sp.	0.7 ± 0.2	9.0 ± 3.3	n.s.	6.9 ± 1.7	29.9 ± 7.7	n.s.
Rytidosperma nudiflorum	2.4 ± 0.8	8.1 ± 4.3	n.s.	13.3 ± 3.0	20.6 ± 6.5	n.s.
Empodisma minus	0.2 ± 0.1	5.3 ± 2.5	n.s.	1.8 ± 1.1	21.1 ± 7.9	n.s.
Oreomyrrhis eriopoda	1.5 ± 0.5	2.1 ± 0.8	n.s.	17.1 ± 5.3	21.6 ± 6.9	n.s.
**Acetosella vulgaris*	2.2 ± 0.7	0.5 ± 0.3	0.03	24.7 ± 7.4	6.2 ± 3.7	0.03
**Agrostis capillaris*	7.0 ± 1.7	0.14 ± 0.1	0.01	43.8 ± 8.2	1.6 ± 1.6	0.01
Bryophytes	2.4 ± 1.1	0.1 ± 0.05	n.s.	16.7 ± 0.4	0.6 ± 0.4	0.03
Euchiton argentifolius	1.9 ± 0.5	0.09 ± 0.05	0.01	22.0 ± 6.0	1.1 ± 0.7	0.01
**Festuca rubra*	23.3 ± 5.2	0.03 ± 0.0	0.01	52.0 ± 8.8	0.4 ± 0.4	0.01

* denotes alien species.

presence of alien plants was the driving factor behind the greater species richness on the closed track compared to adjacent natural vegetation. Thus, the species diversity of native species alone, as measured in richness, heterogeneity and evenness, was not significantly different. Nevertheless, considerable differences in species composition remained, as shown by the high proportion of species (18 out of a total of 60 species) that were recorded either only in track quadrats or only in natural vegetation quadrats. While an increase in the number of samples may have resulted in statistically significant differences in the diversity of native species between the closed track and in natural vegetation, there was a trend toward species from earlier successional stages in the track quadrats and species from more mature stages in the natural vegetation. At least 5 of the 11 species found only in the track quadrats (*Euphrasia collina* ssp. *glacialis*, *Ewartia nubigena*, *Neopaxia australasica*, *Senecio pinnatifolius* var. *pleiocephalus*, and *Trisetum fastigiatum*) have been described in the literature as colonizers (Keane, 1977; Wimbush and Costin, 1979). The comparatively high richness of colonizing species is consistent with the cover results, which indicated that there are still significantly more bare areas in track quadrats compared to natural vegetation quadrats, thus providing opportunities for colonizers. These colonizing species are able to revegetate bare areas but tend to be out-competed once other species

TABLE 4

Diversity of the life forms herbs and graminoids on twenty-two 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. Values are means ± standard errors (n = 22). Significance was determined by paired t-tests. n.s. = not significant.

	Track	Natural	p
Herbs			
Richness (# species/quadrat)	5.1 ± 0.4	4.9 ± 0.5	n.s.
Heterogeneity (Shannon-Weaver Index)	1.2 ± 0.1	1.2 ± 0.1	n.s.
Evenness (Simpson's Index)	0.7 ± 0	0.7 ± 0.1	n.s.
Graminoids			
Richness (# species/quadrat)	5.1 ± 0.2	3.7 ± 0.5	0.004
Heterogeneity (Shannon-Weaver Index)	1.3 ± 0	1.0 ± 0.1	0.009
Evenness (Simpson's Index)	0.7 ± 0	0.6 ± 0	0.011

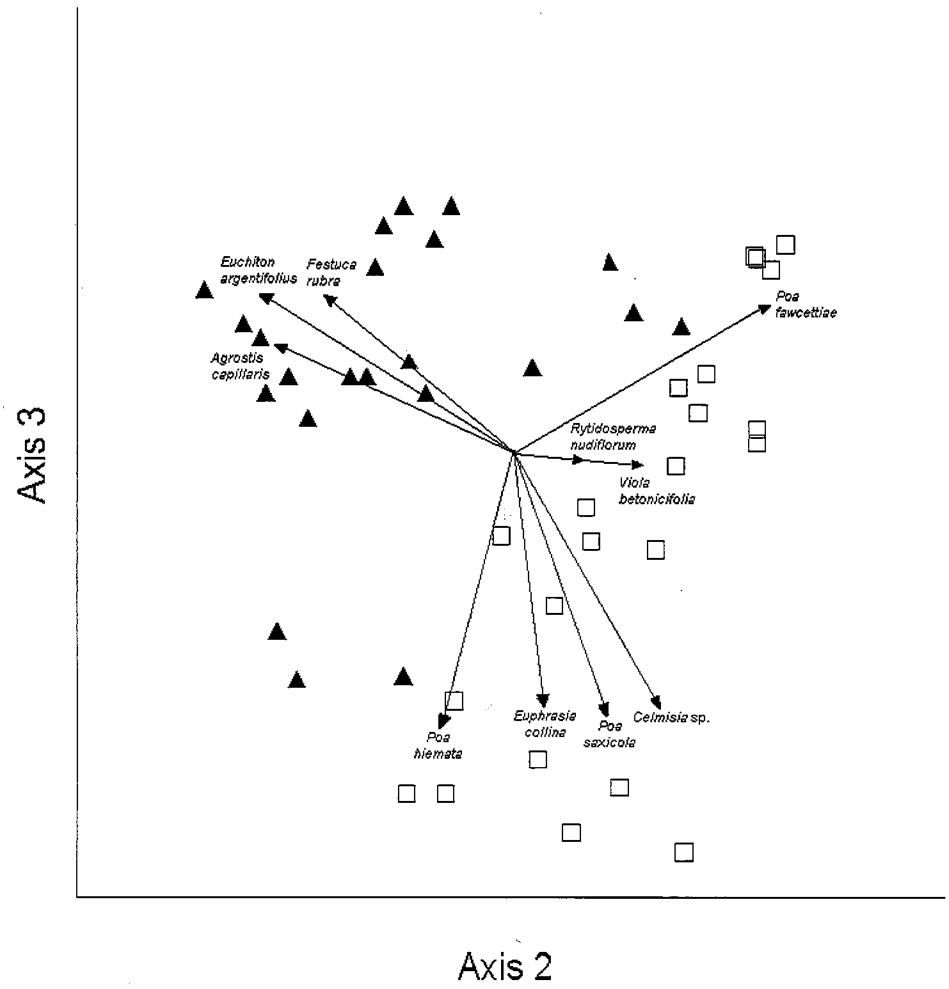

FIGURE 3. Two-dimensional view of the three-dimensional MDS-ordination of percent overlapping cover data from twenty-two 1 m^2 paired quadrats along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone (stress = 0.171). Filled triangles represent quadrats on the closed track, and hollow squares represent quadrats in adjacent natural vegetation. Vectors represent the dominant species.

establish (Keane, 1977; Mallen-Cooper, 1990). Thus they could potentially fulfill an important role in future restoration programs.

The comparatively high abundance of bryophytes on closed track quadrats is consistent with findings indicating that these species benefit from the destruction of vascular plants and are among the first species to establish on bare areas (Harper and Kershaw, 1996; Whinam and Chilcott, 1999).

Alien species were expected to be more prevalent on the closed track than in the adjacent natural vegetation, as disturbance is the key to the establishment of many alien species and the seed mix commonly used

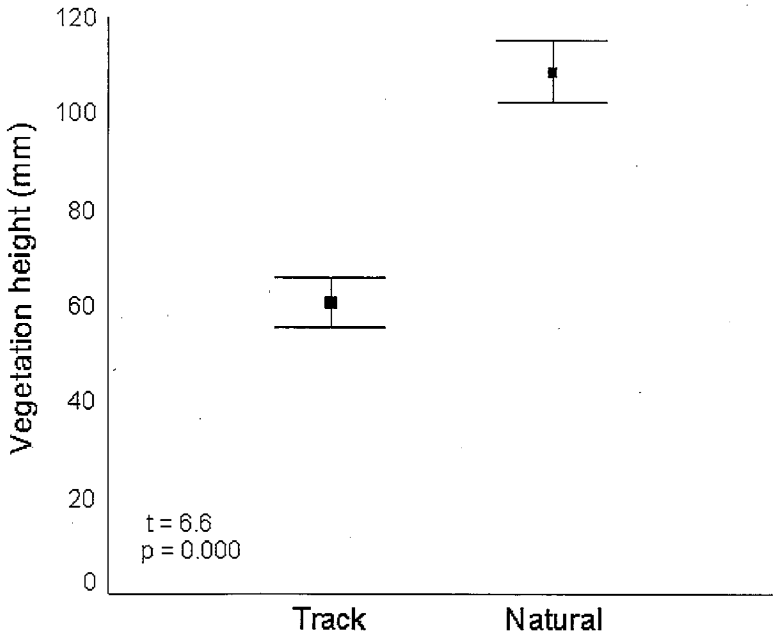

FIGURE 4. Height of vegetation in twenty-two 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone. Values are means ± standard errors. Significance values are results of a paired-samples *t*-test ($n = 22$).

in revegetation work consisted of alien species (Mallen-Cooper, 1990; Hobbs, 1991). Only three alien species were found at the study sites and all were significantly more abundant in closed track quadrats compared to adjacent natural vegetation. Two of these species, the introduced grasses **Agrostis capillaris* and **Festuca rubra*, were included in the seed mix commonly used at the time for restoration work to achieve a quick vegetation cover and prevent further erosion. These species have persisted on this closed track and now form the bulk (44% of overlapping cover) of vegetative cover on the track, even spreading to natural areas in some cases. **Acetosella vulgaris*, the third recorded alien species, is a widespread and naturalized herb introduced during the grazing era (Costin et al., 2000). It thrives as a colonizer in disturbed areas but generally does not persist when native vegetation recovers (Mallen-Cooper, 1990). Despite their prevalence on the track, none of the alien species were frequent components of adjoining native vegetation. Also, **Lolium perenne*, which was part of the seed mix applied in the 1980s, did not persist and was not recorded during this study.

Despite considerable vegetation cover from alien species, there were still extensive areas of bare ground on the closed track. This outcome, combined with the persistence and dominance of alien species, indicates that alien species should not be used in restoration programs or at least their use should be minimized to where no suitable alternatives exist. Partially, this has already occurred in practice with all but one species, **Festuca rubra*, now removed from the former "alpine mix" used for revegetation in the Australian Alps (W. Papst, personal communication, 2003). With increasing calls for the consideration of ecological and management costs associated with the introduction of alien species in revegetation programs and walking track construction, there is a growing need for information on suitable native rehabilitation species (McDougall, 2001; Pickering et al., 2002).

In terms of restoration success, perhaps the result of greatest significance in this study was the differential nutrient status of the soils on the track and in the natural vegetation. Australian alpine soils generally have low levels of nutrients (Costin, 1954; Bryant, 1971; Mallen-Cooper, 1990; Johnston, 1998). Surface soils of the Kosciuszko alpine zone have a low nutrient status with deficiencies in nitrogen, phosphorus, and possibly marginal deficiencies in potassium, magnesium, calcium, and some micro-nutrients (Costin, 1954; Bryant, 1972). The native plant species are adapted to these low nutrient conditions (Mallen-Cooper, 1990).

The removal of vegetation cover on tracks through trampling and subsequent erosion may have depleted nutrients further by facilitating the reduction or even removal of the organic surface horizon. This is reflected in percent organic carbon levels being almost four times lower on the closed track quadrats compared to adjacent areas. Nutrient levels measured in this study support findings by Johnston (1998), who found soils with low nutrient levels at undisturbed sites and decreasing levels of micronutrients with increasing levels of disturbance.

Nutrient levels may be important in determining the organization of native and alien plant assemblages (Mallen-Cooper, 1990). Nitrogen, phosphorus, potassium, calcium, and magnesium have been shown to influence plant growth in other high altitude environments (Bryant, 1972; Mallen-Cooper, 1990). Therefore, the reduced levels of nutrients in the already nutrient poor alpine soils, as found in the closed track quadrats, are likely to hinder the establishment and growth of native and alien vegetation, delaying the process of restoration and promoting exposed ground. The comparatively low nutrient status of soils in track quadrats is also likely to have contributed to the reduction in vegetation height found in this study. Bare soil is prone to further erosion, and excessive soil losses may prevent, delay, or permanently change the composition of future vegetative cover (Keane et al., 1979; Grabherr, 1985).

Seedling germination, growth, and survival along the closed track is likely to be limited due to the combination of bare areas, exposed

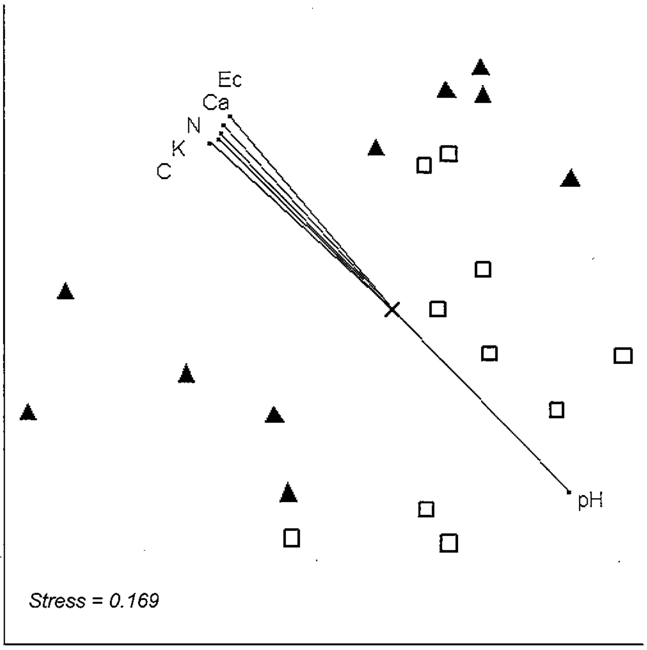

FIGURE 5. Three dimensional MDS-ordination of presence/absence data for ten 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine zone (Stress = 0.169). Hollow squares represent quadrats on the closed track and filled triangles represent quadrats in adjacent natural vegetation. Vectors represent significant soil variables.

rocks, reduced nutrients, decreased soil water content, and higher soil bulk density, as measured in the track quadrats. Other studies have found low seedling establishment in highly disturbed alpine sites (Urbanska, 1997). Thus, without further intervention, recovery of the closed walking track through natural revegetation could be expected to occur primarily by gradual encroachment from the edges as has occurred post-grazing (Scherrer, 2003).

Walking tracks create narrow, long scars in the landscape and thus generally have a high ratio of edge length to disturbance area. As much of the recovery occurs by colonization from the edges, the lower the edge to disturbance area ratio and the larger the diameter of a bare patch, the longer recovery can be expected to take. For example, bare strips of alpine tundra wider than 1 m in the Canadian Eastern Arctic remained unvegetated, except for occasional clumps of mosses and small tufts of invading grasses, even after decades without disturbance (Forbes, 1992). The shape and size of disturbance will also strongly influence the stabilization of soil and the effects of erosion. With increasing patch size and decreasing edge-to-area ratio of bare areas, the soil's exposure increases and the availability of so called "safe sites" decreases (Urbanska and Chambers, 2002). Thus, damage prevention and minimization is of great importance.

Despite the differences between adjacent natural vegetation and the closed track, the progress of restoration and the current state of the track, 15 yr after closure, provides some grounds for optimism. Examples from the literature estimating the time for recovery from recreation impacts of areas with similar vegetation, range from 20–50 yr at low altitude sites (Cole, 1987) to several hundred years in arctic tundra (Willard and Marr, 1971; Harper and Kershaw, 1996), or recovery may not happen at all (Grabherr, 1985). Thus, the current cover by vegetation, rock, and litter of 75% and a high surface area-to-edge ratio of the remaining bare patches (i.e., small or narrow patches; personal observation by author) indicate that a comparatively quick recovery of cover by vegetation may still be possible, although such a cover is likely to consist largely of exotic species. Further, the progress of

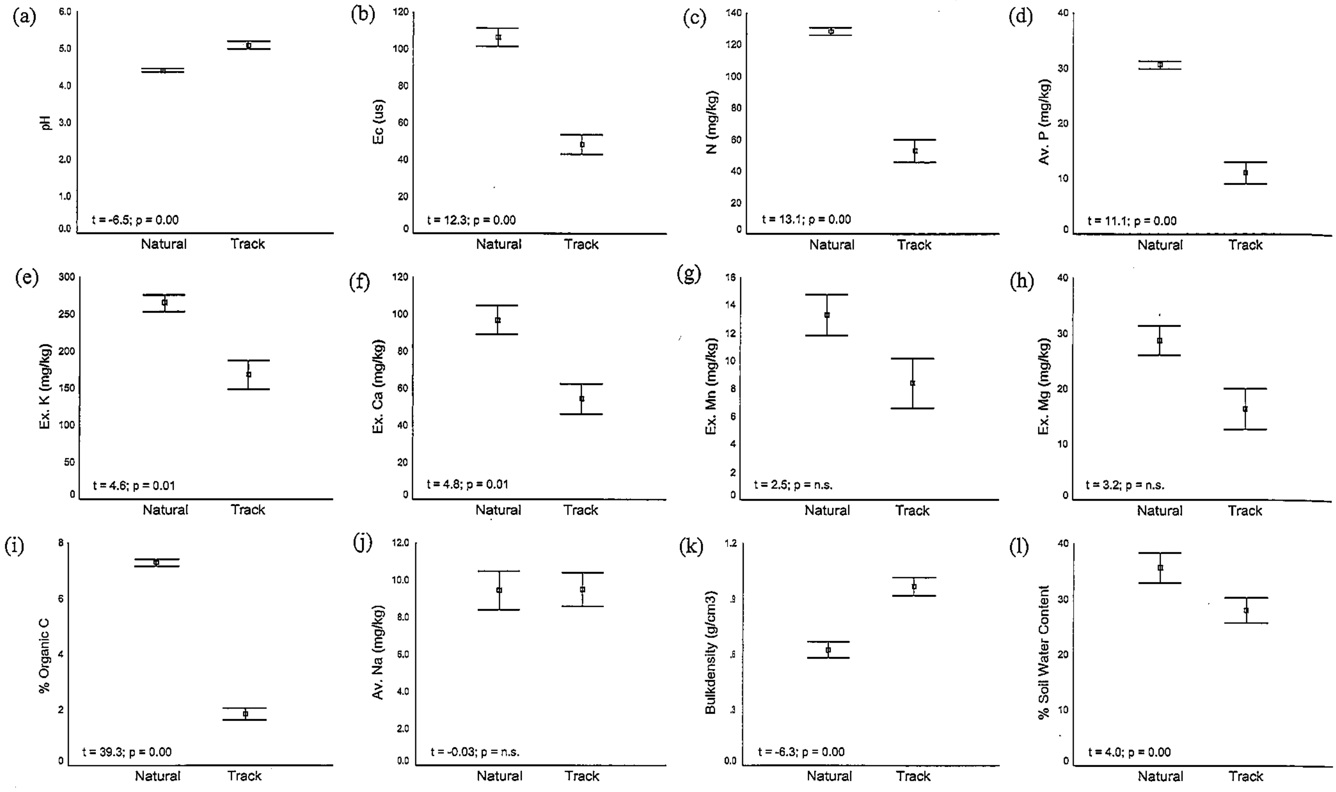

FIGURE 6. Soil nutrients and physical characteristics for ten 1 m^2 paired quadrats sampled along a closed track and in adjacent natural vegetation in the Kosciuszko alpine area: (a) pH, (b) conductivity, (c) nitrogen, (d) phosphorus, (e) potassium, (f) calcium, (g) manganese, (h) magnesium, (i) organic carbon, (j) sodium, (k) bulk density, and (l) soil water content. Significance values are Bonferroni adjusted paired *t*-test results.

recovery may not be linear. For example, McDougall (2001) reports a rapid acceleration in vegetation cover and species richness over a period of 6 yr, after 30 yr of relatively little increase, on a stabilized road verge on the Bogong High Plains, Victoria. This change is likely to stem from the increasing supply of native plant propagules within the verge (McDougall, 2001).

Currently, the main concerns with the studied track in terms of vegetation are the high proportion of alien species and the remaining high percentage of bare areas. Also, given the large variation in cover among the track quadrats, some areas with very low vegetation cover may require much longer to recover or may change to a different type of vegetation (e.g., disturbance feldmark community; Johnston et al., 2003). Thus, to achieve restoration, the priorities are: (1) the re-establishment of plants on the remaining bare areas, and (2) the replacement of alien species with natives.

This study has also shown that the removal of walking pressures from an alpine area may not in itself be sufficient to achieve full restoration even in the longer term. Continuing active restoration efforts may be needed after initial treatment of damaged areas to ensure full recovery. The underlying factors are: (1) the condition of soils, which provide the basis for a complete vegetation cover; and (2) a dense vegetation cover, which helps prevent soil erosion and nutrient depletion. The results of this study highlight the importance of impact prevention and/or minimization through proactive management and strategic planning to deal with visitor activities. Once damage to vegetation and soils has occurred, the recovery period is extensive, even for narrow, actively revegetated areas, and may never occur at all if soils have been depleted. Shorter restoration times may be achieved by (1) focusing on soil protection, (2) continued maintenance of revegetation areas after the initial efforts, and (3) using native rather than alien species.

The results from this study show the state of the track 15 yr after closure and highlight the recovery time required for restoration of alpine systems following prolonged tourism use. Such information can benefit future restoration efforts in this and other mountain regions.

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