Vegetation, microclimate and soils associated with the latest lying snowpatches in Australia

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Background: The Snowy Mountains contain Australia’s longest-lasting snowpatches. Because of climate change, their longevity has declined, with the loss of some specialist vegetation in the underlying snowbeds.

Aims: To characterise the current status of the vegetation associated with the longest-lasting snowpatches in Australia and its association with abiotic factors.

Methods: We assessed plant composition, soil depth, moisture and nutrients and subsurface temperatures in five zones of increasing vegetation height and cover in snowbeds.

Results: The zone beneath the middle of snowpatches was characterised by little vegetation cover and lower species richness, later emergence from snow, skeletal soils, and lower mean soil temperatures than zones further downslope where soils increased in depth and nutrient levels. Vegetation beneath these snowpatches no longer occurs in distinct communities. Plants have not simply migrated upslope. Instead, areas that have deep soil that used to have snowpatch specialist species are being colonised upslope by grasses and downslope by tall alpine herbfield species that prefer bare ground.

Conclusions: Reduced longevity of Australia’s longest-lasting snowpatches has led to the loss of distinct snowpatch vegetation communities. With limited soils beneath the centre of current snowpatches, and a lack of other suitable sites there is no location for these plant communities to migrate to.

Keywords: Alpine, Climate Change, Mountain, Snow, Snowy Mountains, Feldmark.
**Introduction**

High mountain environments are among those most likely to be altered by climate change (Grabherr et al. 1994; Pauli et al. 2007). Reductions in snow cover and rising temperatures have been documented for many high mountain areas (Beniston 2003), with associated vegetation responses including the colonisation of nival areas by alpine plant species (Grabherr et al. 1994; Pauli et al. 2007). Within the alpine zone, there are specialised plant communities limited to snowbeds, defined here as sites where snow cover remains weeks or months after the general thaw (Gough et al. 2000). These snowbeds and their constituent species could be particularly at risk because they are limited spatially, being dependent upon the specific microclimatic and topographical conditions that result in the accumulation of deeper and longer lasting snow than at adjacent sites.

The Snowy Mountains (36°27'S 148°16'E) have the longest lasting snowpatches in Australia, while further south the last snowpatches of the lower altitude Victorian Alps and alpine Tasmania generally melt by late January (Wahren et al. 2001; Kirkpatrick pers. comm. 2007). Snowpatches occur in areas of the Snowy Mountains generally above 2000 m a.s.l., in locations receiving least sun (south to south-east aspects) that are also in the lee of slopes with snow-bearing winds being predominantly north-westerly (Davis 1998; Green and Pickering in press). Hence, the process of snow-drift and lowered insolation reinforce each other to create large snowpatches that have in the past reached depths of 30 m (Costin et al. 1973), and remained continuously for several years (McLuckie and Petrie 1927). The associated vegetation was characterised by snowpatch feldmark above the snowbed, the centre of the snowbed supporting few or no vascular plants on skeletal soils, and short alpine herbfield occurring down slope (Costin 1954). The alpine regions of south-eastern
Australia have warmed over the past 35 years at a rate of about 0.2°C per decade, with projections for 2050 of possible reductions by 96% in the area sustaining snow cover for more than 60 days year\(^{-1}\) (Whetton 1998; Hennessy et al. 2003). The date of thaw for snowpatches is generally related to the duration of the snowpack as measured at Spencers Creek, where the duration of the snowpack has declined significantly over the past 54 years (Green 2008; Green and Pickering in press). As a result, these two vegetation communities, supporting several locally endemic species (i.e. to just this alpine region, Costin et al. 1979), are at risk and may be among the most threatened alpine ecosystems in the world (Edmonds et al. 2006; Green and Pickering in press).

Despite the increasing recognition of the importance of conserving geographically limited and specialised plant communities such as the two communities above (Edmonds et al. 2006), there have been few recent studies that have examined the physical characteristics and vegetation of snowbeds and how these vary among and within snowbeds.

Beneath the earlier melting snowpatches in the lower altitude Victorian Alps, Wahren et al. (2001) examined variation in floristics in relation to physical factors and date of snow melt and Venn and Morgan (2007) examined growth and phenology across a snow-melt gradient. However, the snowbeds they studied had nearly complete vegetation cover and did not include short alpine herbfield or snowpatch fieldmark.

The most recent study of the snowpatches of the Snowy Mountains was by Edmonds et al. (2006) who compared vegetation on 88 sites that had snow lying in mid January at different frequencies (snow in 1, 3 and 8 years out of 10). They studied the upper, often rocky section of snowbeds. However, little is known about the current status of vegetation in the middle and lower sections beneath the late lying snowpatches.
The aims of the present study were, therefore, to determine whether discernible zones beneath the late lying snowpatches of the Snowy Mountains conformed to previous descriptions or if the zones today have a different species composition. We examined variation in microclimate, soil characteristics and vegetation beneath snowpatches. From this information we compared the latest-lying Australian snowpatches with those of shorter duration in other alpine regions of Australia, and with late-lying snowpatches in other alpine regions of the world. We discuss how these, the latest lying snowpatches in Australia and their associated plant communities may have changed and are likely to change with a warmer, drier climate.

Materials and methods

Study area

The alpine area in the Snowy Mountains around continental Australia’s Mt Kosciuszko (2228 m), is characterised by continuous snow cover for at least four months per year with six to eight months having minimum temperatures below freezing. Precipitation is in the range of 1800-3100 mm per year with about 60% of this falling as snow (Costin et al. 1979). The absence of a nival zone in Australia places limits on potential future increases in suitable alpine habitats with increasing temperature and decreasing snow cover.

Cattle and sheep grazing in the summer in the alpine area from the late 1850s till the 1940s resulted in massive soil erosion. As a result of which some areas were actively rehabilitated (Green et al. 2005). Currently there are few grazing mammals, principally the vole-like broad-toothed rat (*Mastacomys fuscus*) and introduced hares (*Lepus europaeus*) (Green and Osborne 1994).
Selection of sites

For detailed sampling of snowpatches, soils, subsurface temperature, and vegetation, seven study sites were chosen from among the 31 snowpatches extant in mid February (late summer) 2004 (see Fig. 1 for numbered snowpatches). The seven snowpatches were chosen to give a wide geographic spread and to cover the two main rock types in the alpine zone of the Snowy Mountains with three on granite and four on sedimentary rock. They were: Twynam Cirque (1), Blue Lake Cirque north (6) and south (7), Club Lake Cirque (11), Mawson Cirque (12), the north-east ridge of Mt. Kosciuszko (19) and the Cootapatamba Cornice (22). Aspect was generally east to south-east on average slopes of 13.5° to 24.5° (Table 1).

To examine patterns in vegetation and associated physical characteristics within the seven snowbeds, the area of each snowbed was divided into five visually identifiable zones: (A) the bare zone beneath the core of the snowpatch, (B) transitional zone between bare zone and continuous short alpine herbfield, (C) continuous short alpine herbfield, (D) transitional zone between short alpine herbfield and tall alpine herbfield, and (E) tall alpine herbfield. These were chosen to examine the vegetation along an expected temporal sequence of snow duration. Not all snowbeds had all vegetation zones. Also, it was not possible to measure all physical variables in all zones in all snowbeds due to practical constraints (e.g. lack of some of the zones, depth of soil) (Table 1).

Vegetation beneath snowpatches

Plant species and life form composition were recorded in each of the seven snowbeds in March 2007 (Table 1). In each zone present, all plant species, bare ground, rock and litter cover were assessed visually for three 1 m² quadrats. The use of visual
assessments of vegetation cover in multiple quadrats of this size is consistent with methods used in other studies of alpine vegetation such as the Global Observation Research Initiative in Alpine Environments (see www.gloria.ac.at). Cover values for individual species were summed to obtain overlapping cover for herb, graminoid and cryptogam life forms for each quadrat (i.e. their sum could exceed 100%). Total vegetation top cover per quadrat was estimated as 100 minus the sum of the cover values of rock, litter and bare ground. To ensure adequate sampling of species richness, all species (but not cover values) were recorded in an additional two 1 m² quadrats on either side of each of the original three quadrats, making a total of 15 m² per zone per snowbed. The taxonomy is according to the Kosciuszko Alpine Flora (Costin et al. 2000).

Plant assemblage composition was analysed using dissimilarity matrix and ordinations performed in the multivariate statistical package PRIMER (version 5.2.2). First, cover data for all vascular plant species and other surface categories (bare ground, rock and litter cover) were used to calculate dissimilarity matrices using the Bray-Curtis dissimilarity measures. Then, non-metric multidimensional scaling (nMDS), with 50 repetitions, was used to describe the maximum variation among zones/ snowbeds graphically in two dimensions (nMDS axes 1 and 2) with the closeness of fit of the nMDS axes to the dissimilarity matrix expressed in terms of stress. This type of ordination has produced reliable, simple and statistically significant analyses of a wide range of ecological community data and is commonly used to analyse vegetation composition data including for indirect gradient analysis (Minchin 1987; Clarke 1993; Clarke et al. 2006). Ordinations were performed on (1) cover values for the central 1 m² quadrat, (2) presence/absence data for all plant species based on the five contiguous 1 m² quadrats, and (3) presence/absence data for
only those species that occurred in more than 5% of quadrats based on the five contiguous 1 m² quadrats. To determine if there were significant differences in vegetation among snowbeds and among zones within snowbeds a Two-way Nested Analysis of Similarity (ANOSIM) was performed for the dissimilarity matrixes. ANOSIM is a non-parametric permutation procedure applied to the rank dissimilarity matrix that is analogous to Analysis of Variance but is distribution-free (Clarke 1993). The SIMPER function was used on the nMDS dissimilarity matrixes for plant composition to identify which plant species, rock, bare ground or litter contributed to the separation of the zones. It was not possible to match different combinations of physical variables to the nMDS dissimilarity matrix for plant composition using Mantel’s test because some physical variables could not be measured in all zones (Table 1). In addition to assessing plant assemblages using ordinations, differences in percentage cover of rock, total vegetation cover, cover of herbs, cover of graminoids, cover of cryptogams and species richness (per 1 m² quadrat) among zones were tested using One-way ANOVAs with snowbeds treated as a block in the statistical package SPSS (Version 14.0). To normalize the percentage cover data before analysis, values were transformed using the arcsine of the square root of the fraction.

Insert Table 1 here

Physical characteristics beneath snowpatches

A Tinytag Plus temperature logger (Gemini Data Loggers, Chichester, England) recording at 90-minute intervals was buried beneath approximately 75 mm of soil in each of the five zones in the snowbeds (Table 1). Because of the presence of rock, this
was the deepest that loggers could be inserted into zones A and B and therefore the same depth was used in the remaining zones. A range of microclimatic parameters (snow-free season length, average daily temperature, growing-period-day-equivalents and growing-degree days) was obtained from soil temperature data for each zone in each snowbed. These soil temperature derived variables have been used to characterise the thermal regimes of alpine areas in Europe (Körner et al. 2003), in examining phenological response of plants to snow melt (Huelber et al. 2006, Molau et al. 2005) and in the analysis of species richness patterns in this (Pickering et al. 2008) and other alpine areas (Kazakis et al. 2006, Staniski et al. 2005).

The commencement of the snow-free season was a relatively easy point to find in the temperature trace because snow thaws in a warming environment, which causes fluctuation in the trace. Within this period of fluctuation, the actual day of thaw was determined as when the temperature first rose above 3.2 °C at noon or within two hours either side of noon. This figure was chosen as a surrogate for air temperature on the assumption that there was no thermal heat flux driven by direct solar radiation. Temperature close to 0 °C and diurnal oscillation in the trace by <1 °C generally meant that the soil was snow covered; oscillation of >3 °C generally meant that the snow had melted. This temperature threshold excluded early season snowfalls that subsequently thawed before the onset of the continuous winter snowpack and also served to remove periods of cold weather (<0 °C air temperature) lacking snow cover from the calculation of growing period (Körner and Paulsen 2004; Körner pers. comm. 2007). The commencement of the snow season was harder to determine from the temperature trace (except in 2003/04) because snow fell in a cooling rather than a warming period. However, the end of the snow-free season was calculated in a similar
fashion to the commencement and was the point at which the noon temperature ±2 hours fell below 3.2 °C and remained below that level.

Other parameters were calculated from the temperature data set. The average daily temperature was calculated from 1 July to 30 June in 2003/04, 2004/05, and 2005/06. The growing-period-day-equivalents in each year were calculated as the sum of all hours in which the soil temperature was >5 °C divided by 24 (Huelber et al. 2006). The >5 °C threshold was used, because it has been assumed that photosynthesis and growth will be occurring above that soil temperature threshold (Huelber et al. 2006). Finally, the hourly temperature sum >5 °C (growing-degree days or GDD) was calculated by adding all soil temperature values per hour that were >5 °C for a year (Huelber et al. 2006).

The snow-free season length, average daily temperature, growing-period-day-equivalents and GDD were compared in SPSS using a Repeated Measures Split Plot ANOVA with year as the repeated measure, snowbed as the plot, and zones nested within plots. In addition, a Two-Way ANOVA with no interaction was used to compare average daily temperature for the three years among snowbeds and zones.

Soil depth, soil moisture and height of water table were measured, and soil nutrients were sampled in zones C, D and E within snowbeds. Zones A and B were not sampled because they consisted mainly of rock (Table 2) with virtually no soil in between. Soil depth was measured by inserting a steel peg until it hit impassable rock at three points spread across the slope in each zone. Soil moisture (% saturation) was measured in March 2006 using a ThetaProbe soil moisture sensor type ML2x (Delta-T Devices, Cambridge, England). Soil moisture measurements and water table height were made within the top 150 mm, where most alpine assessments are made because most biological activity including nutrient cycling occurs there (Körner 2003).
mm lengths of PVC storm water pipe were located in the soil, where possible, in zones C, D and E of each snowbed and were capped with steel plates. The full 150 mm of the pipe was used unless soils were too shallow when the pipe had to be cut to size. The pipes were checked at each visit to each site to determine the height of the water table.

Three soil samples were taken from zone E of all seven snowbed sites, from the five snowbeds where zone D occurred and the six snowbeds where zone C occurred (Table 1). A minimum 500 g was collected at each zone in a single sample of soil taking the top 10 cm of soil in a 75 mm core, and samples were air dried and sieved through a 2 mm mesh. Soil was analyzed by the CSIRO Division of Soil and Water.

Total carbon and nitrogen were determined by high temperature combustion in an atmosphere of oxygen using a Leco CNS-2000. Carbon was converted to CO₂ and determined by infrared detection. Nitrogen was determined as N₂ by thermal conductivity detection (Matejovic 1997). Inorganic nitrogen was determined by segmented flow colorimetry following extraction using 2M KCl. Nitrate was dialysed then reduced to nitrite by Cd reduction and the resultant nitrite reacted with N-1-naphthylethlenediamine dihydrochloride (NEDD) with sulphanilamide (Rayment and Higginson 1992a). NH₄⁺ was separated from interferences by gas diffusion and determined after reaction with sodium salicylate and dichloro-isocyanurate (DCIC). This procedure is modified from Rayment and Higginson (1992a) according to the International Standard ISO 11732 (1997). Extractable phosphorus was determined by segmented flow colorimetry following Colwell extraction using 1M NaHCO₃ at pH 8.5 (Rayment and Higginson 1992b). Total metals were determined by US EPA method 3051A (1998). The finely ground sample was digested in a microwave oven using a mixture of nitric acid and hydrochloric acid. The solution was then analyzed
for a wide range of elements by inductively coupled plasma optical emission spectrometry (ICPOES).

Differences in soil nutrients among zones within snowbeds were compared using one-way ANOVAs with snowbeds treated as a block in the statistical package SPSS (Version 14.0). When required to satisfy the assumptions of the ANOVA, some of the soils data were transformed either using square root or natural log transformations as required.

Insert Fig. 1 hereabouts.

Results

Vegetation beneath snowpatches

A total of 51 vascular plants species was recorded under the latest-lying snowpatches, consisting of 32 species of herbs, 16 graminoids, and three shrubs (Appendix 1).

Thirty-eight of these species have previously been described as occurring in tall alpine herbfield, 11 in short alpine herbfield and three in snowpatch feldmark (Costin et al. 1979). The most common family was Asteraceae, with 14 species. Only one non-native species was recorded, the naturalised herb *Acetosella vulgaris* (syn. *Rumex acetosella*). Eight of the species were endemic to just the alpine region around Mt. Kosciuszko, including four buttercups (*Ranunculus acrophilus*, *R. dissectifolius*, *R. anemoneus* and *R. niphophilus*).

There were strong differences in species richness, total vegetation cover, the cover of graminoids, herbs and the cover of rock among zones within snowbeds and among the seven snowbeds (ANOVA, Tables 2-4, Appendix 1, Fig. 2). There were also
differences in plant species richness and plant composition among and within snowbeds (ANOVA and ANOSIM, Tables 3 and 4, Fig. 2). The composition of the vegetation under the snowpatches differed from the original descriptions (Costin et al. 1979) particularly that for short alpine herbfield.

The quadrats in the central section of the snowbed in Zone A had little vegetation (10% cover) with most of the zone consisting of rocks (88%). This zone was the most consistent in plant composition among snowbeds with 84% similarity (Fig. 2a, Table 2). Instead of having species that were considered characteristic of snowpatch feldmark (*Coprosma niphophila*, *Colobanthus nivicola*, *Ranunculus anemoneus* and *Epilobium tasmanicum*), the vegetation in this zone consisted nearly entirely of the low growing stoloniferous *Neopaxia australasica* (6.7%, Table 2, Appendix 1), which is considered characteristic of short alpine herbfields (Costin et al. 1979). Six graminoids including the characteristic tall alpine herbfield grasses *Poa costiniana* and *P. fawcettiae* were found in this zone, although at low cover values. Out of the total of 51 vascular species recorded, 13 were found in this zone, with an average of four species per m². The snow-free season was shortest in this zone, averaging 62 days (Table 5).

In the transition (Zone B) between the rock-dominated zone under the late-lying snowpatches and the short herbfield in Zone C, the snow-free season was longer
Rocks still covered most of the ground (67%), but vegetation cover, nearly half of which was cryptogams (Appendix 1), was higher at 34% (Table 2). *Neopaxia australasica* was again important with 13% cover. The cover of graminoids increased, with snowgrasses (*Poa costiniana* and *P. hiemata*) accounting for just under 4% of the ground cover.

In the locations that have been considered characteristic of short alpine herbfield vegetation (Zone C), the snow-free season averaged 99 days (Table 5). There was considerable variation in composition and cover of surface types in this zone, with an average similarity of only 36% among quadrats (Fig. 2). Rocks covered an average of 21% of the ground, with vegetation cover at 76%, consisting of equal amounts of graminoids (33%) and herbs (33%) (Table 2). Vegetation was characterised by *Neopaxia australasica* (28%), cryptogam (15%), and the two graminoids, *Luzula acutifolia* (a species of short alpine herbfield, 9%) and *Rytidosperma nudiflorum* (a species of tall alpine herbfield, 7%) (Appendix 1). Species richness was high, with 6.6 species per m², and a total of 35 species recorded in the zone (Appendix 1). Ten of these species were considered characteristic of short alpine herbfield, three of which were also found in snowpatch feldmark (Costin et al. 1979). A high diversity, particularly of herb species that each occurred at low cover and frequency is likely to have contributed to variation in this zone.

The intermediate zone (D) between short alpine herbfield (C) and tall alpine herbfield (E) had higher cover values for graminoids, principally the snowgrasses *Poa costiniana* (51%) and *P. fawcettiae* (13%), and another grass, *Rytidosperma nudiflorum* accounting for another 7% of cover. As a result, the cover of graminoids was 82%. There were many species of herbs, but at low frequency and cover values,
with total herb cover averaging only 3.9%. There was limited rock cover (6.6%), and some bare ground (~4%). The snow-free season averaged 118 days (Table 5).

The final zone, tall alpine herbfield (E) was characterised by near complete vegetation cover (95%), predominantly graminoids (87%), with Poa costiniana alone having 56% cover. The other important grasses were Rytidosperma nudiflorum (21%) and Poa fawcettiae (8%). Herb cover was higher than in the transition zone (D) with 12% herbs, the most common of which was Celmisia costiniana (9%). Species richness per quadrat was low (3.9), although 27 species were recorded in this zone, all of which are species of tall alpine herbfield (Costin et al. 1979). The snow-free season averaged 152 days (Table 5).

Physical characteristics beneath snowpatches

There were significant differences in average daily soil temperature among the five zones (F = 17.868, P < 0.001) among the snowbeds (F = 6.373, P = 0.005) and among years (Fig. 3). Most snowpatches remained longer into 2005 than 2004, which helps to explain the generally lower average soil temperature in 2004/05 than 2003/04. For average daily temperature, growing-period-day-equivalents and growing degree days, 2005/06 was much warmer than other years.

Insert Fig. 3 hereabouts.

Insert Table 5 here

Insert Table 6 here

The soil temperature differed among zones in snowbeds (Fig. 3). Zone A at the core of the snowbed with little or no vegetation cover differed from the heavily
vegetated zone E in that it had: a lower average daily temperature (1.6°C cf. 4.7°C), a shorter snow-free season (62 cf. 152 days) and fewer growing-period-day-equivalents (48 cf. 123) (Table 5 and 6). There was a consistent gradient of longer snow free periods and higher average temperatures from zones A to E except that there was no significant difference for growing-period-day-equivalents and temperature sum between zones A and B. Because the bare soil surface was exposed most to insolation in zone A, the highest temperatures and greatest variation occurred there. By contrast, the warmest zone (E) had a lower maximum temperature and less variation because of the shading effect of tall grass in the covering herbfield.

There were clear differences in soils within snowbeds from zone C to E (Table 4, Appendix 2). There were significant differences among zones in the snowbeds in C, N, -4N, nitrate/nitrite, extractable and total P, Al, K, Na, and soil depth. Most nutrients increased in soils with progression down slope from zone C to zone E; percentage C and N, together with NH₄-N, total P, Al, K, and Na were all significantly higher in zone E than in zone C. Extractable P decreased significantly down slope. Soil depth increased from an average of 58 mm in zone C to 225 mm in zone E in snowbeds (Table 7). Over the same distance, soil moisture content fell from 23% to 10% (but this was not statistically significant) and the temporal frequency at which the water table occurred in the top 150 mm of the soil declined from about 44% to 4% down slope but could not be tested using parametric statistics, because there were so many zero values (Table 7).

Discussion

Insert Table 7 here
Beneath the latest-lying snowpatches in Australia, soils generally increased in depth with distance down slope, from late melting sites to early melting sites as found for snowpatches elsewhere (Ostler et al. 1982; Venn and Morgan 2007). As a consequence of these shallower soils in short alpine herbfield, the water table was at a higher level throughout the growing season, however, soil moisture in the top 60 mm (the length of the probe used) did not yield significantly higher moisture levels.

There were significant differences in soil chemistry among snowbeds that were generally not related to the differences in geology, with only magnesium, manganese and zinc associated with rock type being lower on granites than on sedimentary rock (Appendix 2). This reflects the fact that soils in the Snowy Mountains are generally independent of rock type and largely influenced by high levels of aeolian inputs from the interior of Australia (Walker and Costin 1971; Johnston 2001). This dust is preferentially captured in snowpatch sites with accession rates of 1.8-113 kg ha\(^{-1}\) (Johnston 2001), similar to figures for mountains in Nevada and California (Reheis and Kihl 1995).

Snowpatches accumulate nitrogen, which is released during the growing season into vegetation communities below (Bowman 1992). However, with roots in cold, saturated shallow soil, particularly in zone C, the capacity of plants to sequester this nitrogen is limited (Bowman 1992) and in the present study both total N and NH\(_4\)-N increased significantly down-slope from zones C to E. Ammonium was the dominant form of nitrogen as found in tundra soils (McKown 1978), with levels twice that of nitrates as would be expected from soils with a pH of around 4.6 (Costin et al. 1969). Levels of NH\(_4\)-N and NO\(_3\)-N in the C zone were of the same order of magnitude as in nival zone soils the Tyrolean Alps (Haselwandter et al. 1983). By contrast, in the Scandes in northern Sweden there was more nitrogen in snowbeds than the adjacent
plant communities but this may be due to topography, and it appears that there was
little uptake of this nitrogen by snowbed plants (Björk et al. 2007).

In the present study, levels of nitrogen, organic matter and phosphorus were
significantly higher in the deeper soils of zone E than zone C, a similar situation to
that occurring in Colorado (Stanton et al. 1994). This provides opportunities for
nutrient uptake, partially offsetting the advantage further upslope of greater moisture
availability through the growing season (see Venn and Morgan 2007). The greater
length of the growing season on these deeper soils would also give plants an
advantage in productivity (Venn and Morgan 2007).

Species richness, cover of vegetation and plant composition all varied under
snowpatches as has been found elsewhere (Billings and Bliss 1959; Stanton et al.
1994). The zone under the deepest part of the snowpatch (zone A), with the shortest
snow-free season, had low species richness and limited vegetation cover. Zones down
slope of this had more species and greater vegetation cover. The range of cover values
across zones was similar to the 17 to 85% in snowbeds in the Giant Mountains of the
Czech Republic (Hejcman et al. 2006). However, this situation differs from the
shorter lasting, lower altitude snowpatches elsewhere in Australia, where there is no
obvious altitudinal stratification of vegetation within snowbeds and no snowbed -
specific plant communities (Costin et al. 2000; Wahren et al. 2001; Harvey 2003). In
the Snowy Mountain, forbs dominated vegetation beneath the longest lasting snow
with graminoids dominating where snow melted first, with about equal distribution in
the mid zones - the short alpine herbfield. By contrast, in northern Sweden graminoids
dominated snowbeds with a mid-range of timing of snowmelt with cover decreasing
as snowmelt was both earlier and later (Björk and Molau 2007).
Low species richness in snowbeds has been recorded elsewhere, with usually 5-10 species m$^{-2}$ but up to 18 reported in northern Sweden (Björk and Molau 2007). The figures for the Snowy Mountains were even lower with a range of 1-11 vascular species for the 83 1 m$^2$ plots. Average diversity rose from the centre of the snowbed down slope to the short alpine herbfield and the transition to tall alpine herbfield but was lower again in the tall alpine herbfield where one or two species of Poa dominated. In contrast, in the upper section of the Snowy Mountains snowbeds, mean species richness increased with the earlier melt of snow with greatest richness the shorter the snow period (Edmonds et al. 2006).

The demarcations among plant communities in alpine regions are often sharp and occur over a short distance. Körner (2003 p. 35) has stated generally that, ‘boundaries between units of low stature alpine vegetation are mostly sharp rather than gradual and can be defined with an accuracy better than half a meter’. Clear demarcation below late lasting snowpatches in the Snowy Mountains has been described (Costin et al. 1979; Atkin and Collier 1992). We, however, had difficulty in finding this pattern even though our study included snowpatches such as the complex above Blue Lake examined in both previous studies. Rather than distinct communities of species, there was a gradation of vegetation downhill from the centre of snowbeds with plant intrusions from non-snowbed communities. This suggests a real change from the first descriptions by Costin (1954) and that, where soil is present, there may no longer be a limit on the movement of plants, particularly graminoids into the centre of these snowbeds, a situation similar to that in snowbeds in alpine Norway and Finland (Virtanen et al. 2003). In this regard, there appears to be a change from distinct communities in the historically more extreme snowbeds in the Snowy Mountains towards the more moderate snowbeds found in the Victorian Alps where there are no
distinct communities, but rather individual species responding to differences in snow
cover and moisture (Venn 2001).

In the period of transhumance up until the 1940s, heavy grazing pressure on short
alpine herbfield resulted in severe structural degradation below many snowpatches,
but because of the specialised environment, exotic species were excluded (Costin
1954) and instead recolonisation was by short alpine herbfield species (Wimbush and
Costin 1973). In the present study, it is apparent that there have been significant
changes beneath snowpatches since the work by Wimbush and Costin (1973). It
appears now that the characteristic vegetation sequence beneath snowpatches is
breaking down under intrusion of plants species from communities that in the past
were found in areas with shorter snow duration. This suggests strongly that the
present changes are the result of changes in the specialised environment once
occupied by these communities potentially due to the loss of snow from snowpatches
(Green and Pickering in press). A similar situation has occurred in alpine Norway and
Finland where there has been an increase of grassland species at the expense of
snowbed vegetation concurrent with a reduction in the period of snow cover (Virtanen
et al. (2003).

The results of these changes are obvious particularly with regard to the two
‘characteristic’ plants of short alpine herbfield, Neopaxia australasica and Plantago
glacialis (Costin et al. 1979). Neopaxia australasica achieved greatest cover in Zone
C (short alpine herbfield - preferentially on wet sites) but was more likely to be found
uphill in Zones A and B rather than downhill in D and E (Appendix 1) suggesting that
as a colonising species (Irwin and Rogers 1986; Good 1998) it has taken advantage of
bare ground made available for plant growth by the loss of snow cover. By contrast,
Plantago glacialis only occurred in 39% of plots in Zone C and 47% in Zone D where
it also had a higher cover value. Rather than suggesting that \textit{P. glacialis} is colonising downslope, the finding of this species more commonly in the transition zone between E (tall alpine herbfield) and C (short alpine herbfield) associated with \textit{Poa} suggests that these transition zones were, in the past, short alpine herbfield and that \textit{Poa} is invading upslope. It is possible that \textit{N. australasica} is now more common than it was because of its colonising ability but \textit{P. glacialis} appears to be less common. It was also seldom recorded in the study by Campbell (2004) who had transects running through some of the snowbeds reported here or by Edmonds et al. (2006) who investigated vegetation in the upper sections of snowbeds. Another change noted in recent studies is the rarity of \textit{Coprosma niphophila} and \textit{Colobanthos nivicola}.

Described as characteristic of the snowpatch feldmark community (Costin et al. 1979), neither species was found to be common beneath the latest lying snowpatches in Australia more recently (e.g. Campbell 2004; Edmonds et al. 2006). By contrast, \textit{Senecio pinnatifolius}, a species of tall alpine herbfield (Costin et al. 1979), was recorded most commonly in the present study in zones A and B that are least like tall alpine herbfield. The invasive species from down slope tall alpine herbfield appear to be \textit{Poa costiniana} and \textit{P. fawcetii}.

In predicting what effect decreasing snow cover might have on the current vegetation, it is important to take into consideration the relative importance of microclimatic versus soil conditions in determining which plant species grow beneath snowpatches (Venn and Morgan 2007). Currently the short snow-free season might still be favouring shorter growing mat species of herbs in zone C, but this situation may be changing as growing seasons become longer. Currently, in areas where there is reasonable soil depth, both short and tall alpine herbfield species are able to grow, with any separation being associated with growing season rather than soils per se.
Because *Poa* species are relatively competitive, and dominate much of the alpine area, it may be that as growing seasons lengthen, most of the area that was previously considered short alpine herbfield dominated by herbs, becomes dominated by taller growing grasses.

The historic impacts of long-lasting snow beneath the centre of snowpatches has left skeletal soils with >80% rock cover. With reduction in snow cover there may be a change in which species are able to grow in these sites as growing season lengthen. However, seedling emergence, growth and survival are all reduced in areas of sparse vegetation cover and infertile soil that characterise these areas (Stanton et al. 1994). With loss of snow cover, these sites will also experience more variable climatic conditions during the snow-free period. As a result it appears unlikely that many short alpine herbfield species that tend to prefer wet deep soils will be able to colonise these sites. Instead, other species including those from the snowpatch feldmark above snowpatches or colonising species associated with tall alpine herbfields may colonise these areas. The future of short alpine herbfield as a distinct plant community associated with snowpatches is, therefore, now in doubt (Good 1998; Pickering and Armstrong 2003).

The lack of earlier repeatable quantitative studies on snowpatch vegetation in the Snowy Mountains renders some of the conclusions here speculative. However long term monitoring has been initiated with the establishment of permanently marked quadrats in each zone and a series of transects from the feldmark zone down to the tall alpine herbfield. Data from these quadrats and transects will be used to examine the survival of the vegetation communities and to examine future management considerations, if not to preserve the communities at least to preserve the constituent species.
Acknowledgements

We thank Wendy Hill, Tanya Fountain and Rachel Hill who assisted us in the field and Robert Björk and Stuart Johnston who commented on the manuscript.

References


Irwin F, Rogers J. 1986. Above the treeline. How the high country was rescued. Sydney: Soil Conservation Service of NSW.


Table 1. Physical characteristics and zones sampled beneath each of the seven late-lying snowpatches. Zones were of increasing vegetation height and cover from the centre of the snowpatch (A) to the tall alpine herbfield downslope of snowpatches (E).

<table>
<thead>
<tr>
<th>Snowpatch</th>
<th>Twynam Cirque</th>
<th>Blue Lake Cirque north</th>
<th>Blue Lake Cirque south</th>
<th>Club Lake Cirque</th>
<th>Mawson Cirque</th>
<th>Mt. Kosciuszko north east ridge</th>
<th>Cootapatamba Cornice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (see Fig. 1)</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>11</td>
<td>12</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>2140</td>
<td>2065</td>
<td>2060</td>
<td>2065</td>
<td>2041</td>
<td>2110</td>
<td>2150</td>
</tr>
<tr>
<td>Aspect (True°)</td>
<td>107</td>
<td>115</td>
<td>107</td>
<td>123</td>
<td>167</td>
<td>72</td>
<td>107</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>13.5</td>
<td>16.5</td>
<td>19</td>
<td>24.5</td>
<td>22.5</td>
<td>20.5</td>
<td>21.5</td>
</tr>
<tr>
<td>Rock type</td>
<td>Granite</td>
<td>Slates etc.</td>
<td>Slates etc.</td>
<td>Slates etc.</td>
<td>Slates etc.</td>
<td>Granite</td>
<td>Granite</td>
</tr>
</tbody>
</table>

Samples and zones in which they were measured:
- Soil nutrients C, E C, D, E C, D, E D, E C, E C, D, E C, D, E
- Soil moisture/water table C, E C, D, E C, D, E D, E C, E C, D, E C, D, E

Slates etc. = Slates, phyllites, quartzites & schists.
Table 2. Mean (± Standard error) of ground and vegetation cover values and species richness counts for the five zones below the seven studied late lying snowpatches.

Zones were of increasing vegetation height and cover from the centre of the snowpatch (A) to the tall alpine herbfield below snowpatches (E).

<table>
<thead>
<tr>
<th>Zone</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>12</td>
<td>18</td>
<td>18</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Percent cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Litter</td>
<td>0.1 ± 0.1</td>
<td>0.6 ± 0.6</td>
<td>0</td>
<td>1.2 ± 0.7</td>
<td>2.8 ± 1.1</td>
</tr>
<tr>
<td>Rock</td>
<td>88.6 ± 3.7</td>
<td>64.9 ± 4.8</td>
<td>21.0 ± 4.2</td>
<td>6.6 ± 3.7</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>Bare ground</td>
<td>1.2 ± 0.8</td>
<td>0</td>
<td>1.5 ± 0.6</td>
<td>4.4 ± 1.2</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>Total vegetation</td>
<td>10.2 ± 3.0</td>
<td>34.4 ± 4.8</td>
<td>77.5 ± 4.3</td>
<td>87.8 ± 4.3</td>
<td>94.6 ± 1.7</td>
</tr>
<tr>
<td>Graminoid</td>
<td>2.0 ± 0.6</td>
<td>7.4 ± 1.5</td>
<td>33.4 ± 4.9</td>
<td>82.1 ± 3.8</td>
<td>86.9 ± 7.2</td>
</tr>
<tr>
<td>Herb</td>
<td>7.2 ± 3.1</td>
<td>13.1 ± 2.5</td>
<td>32.9 ± 7.1</td>
<td>3.9 ± 1.3</td>
<td>11.9 ± 6.2</td>
</tr>
<tr>
<td>Cryptogams</td>
<td>1.4 ± 0.9</td>
<td>15.1 ± 4.5</td>
<td>16.1 ± 3.0</td>
<td>7.8 ± 2.5</td>
<td>3.2 ± 1.9</td>
</tr>
<tr>
<td>Species richness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Per 1 m² quadrat (mean of three per zone)</td>
<td>4.0 ± 0.5</td>
<td>4.8 ± 0.2</td>
<td>6.6 ± 0.5</td>
<td>6.3 ± 0.7</td>
<td>3.9 ± 0.5</td>
</tr>
<tr>
<td>Total in 3 x 1 m² quadrats</td>
<td>15</td>
<td>15</td>
<td>25</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>Total in 3 x 5 m² quadrats</td>
<td>-</td>
<td>-</td>
<td>37</td>
<td>31</td>
<td>29</td>
</tr>
</tbody>
</table>
Table 3. Results from Nested Two-Way Analysis of Similarity (ANOSIM) for zone nested in snowbed. P/A = presence/absence.

<table>
<thead>
<tr>
<th>ANOSIM performed on dissimilarity matrix of</th>
<th>Zone</th>
<th>Snowbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground cover values for 1 m² quadrats</td>
<td>0.846</td>
<td>0.09 0.856</td>
</tr>
<tr>
<td>% Total vegetation cover for 1 m² quadrats</td>
<td>0.722</td>
<td>0.043 0.271</td>
</tr>
<tr>
<td>P/A of plant species for 5 x 1 m² quadrats*</td>
<td>0.687</td>
<td>0.402 0.002</td>
</tr>
<tr>
<td>Soil and duration of growing season</td>
<td>0.586</td>
<td>0.068 0.001</td>
</tr>
</tbody>
</table>
Table 4. Results of One-Way ANOVA with snowbed as a block comparing soils, species richness and cover values of five zones (vegetation data) or three zones (soil nutrients) under late lying snowpatches in the Snowy Mountains. Due to the high number of tests on the same data set, a conservative P of 0.01 was used to assess significance. Percent cover values were arcsine (square-root) transformed. Some soil nutrient variables required either square root (sqrt) or natural log (ln) transformation to satisfy assumptions of the ANOVA.

<table>
<thead>
<tr>
<th></th>
<th>Snowbed F</th>
<th>P</th>
<th>Zone F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species richness in 1 m² quadrats</td>
<td>4.338</td>
<td>0.001</td>
<td>8.474</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cover of rock</td>
<td>3.627</td>
<td>&lt;0.003</td>
<td>111.120</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total vegetation cover</td>
<td>4.746</td>
<td>&lt;0.001</td>
<td>86.499</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Graminoid cover</td>
<td>5.267</td>
<td>&lt;0.001</td>
<td>64.55</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Herb cover</td>
<td>11.516</td>
<td>&lt;0.001</td>
<td>10.776</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cryptogam cover</td>
<td>1.375</td>
<td>0.236</td>
<td>7.179</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% Carbon</td>
<td>8.488</td>
<td>&lt;0.001</td>
<td>22.126</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% Nitrogen</td>
<td>8.647</td>
<td>&lt;0.001</td>
<td>28.631</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>NH₄-N ammonium</td>
<td>2.348</td>
<td>0.048</td>
<td>10.647</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>NOx-N nitrate/nitrite (sqrt)</td>
<td>2.242</td>
<td>0.056</td>
<td>8.572</td>
<td>0.001</td>
</tr>
<tr>
<td>Ext. P</td>
<td>16.161</td>
<td>&lt;0.001</td>
<td>18.875</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P (ln)</td>
<td>20.234</td>
<td>&lt;0.001</td>
<td>12.137</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Al</td>
<td>10.076</td>
<td>&lt;0.001</td>
<td>14.060</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ca (sqrt)</td>
<td>18.567</td>
<td>&lt;0.001</td>
<td>1.151</td>
<td>0.326</td>
</tr>
<tr>
<td>Cu</td>
<td>12.513</td>
<td>&lt;0.001</td>
<td>0.779</td>
<td>0.465</td>
</tr>
<tr>
<td>Fe (sqrt)</td>
<td>72.257</td>
<td>&lt;0.001</td>
<td>0.093</td>
<td>0.912</td>
</tr>
<tr>
<td>K</td>
<td>39.146</td>
<td>&lt;0.001</td>
<td>7.541</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg (sqrt)</td>
<td>4337.488</td>
<td>&lt;0.001</td>
<td>0.266</td>
<td>0.767</td>
</tr>
<tr>
<td>Mn</td>
<td>26.321</td>
<td>&lt;0.001</td>
<td>2.644</td>
<td>0.081</td>
</tr>
<tr>
<td>Na</td>
<td>16.527</td>
<td>&lt;0.001</td>
<td>10.030</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pb</td>
<td>29.321</td>
<td>&lt;0.001</td>
<td>4.623</td>
<td>0.015</td>
</tr>
<tr>
<td>Sr</td>
<td>11.723</td>
<td>&lt;0.001</td>
<td>4.697</td>
<td>0.015</td>
</tr>
<tr>
<td>Zn</td>
<td>35.872</td>
<td>&lt;0.001</td>
<td>0.434</td>
<td>0.651</td>
</tr>
<tr>
<td>Soil depth</td>
<td>1.337</td>
<td>0.261</td>
<td>6.262</td>
<td>0.004</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>4.795</td>
<td>0.001</td>
<td>23.036</td>
<td>0.058</td>
</tr>
</tbody>
</table>
Table 5. Mean (± Standard error) of snow-free season days for zones A-E for three years for the seven snowbeds. Zones were of increasing vegetation height and cover from the centre of the snowpatch (A) to the tall alpine herbfield below snowpatches (E).

<table>
<thead>
<tr>
<th>Year</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/04</td>
<td>76 ±38</td>
<td>81 ±40</td>
<td>99 ±32</td>
<td>121 ±30</td>
<td>147 ±25</td>
</tr>
<tr>
<td>04/05</td>
<td>53 ±34</td>
<td>80 ±17</td>
<td>94 ±13</td>
<td>111 ±28</td>
<td>159 ±21</td>
</tr>
<tr>
<td>05/06</td>
<td>58 ±16</td>
<td>84 ±17</td>
<td>105 ±11</td>
<td>123 ±31</td>
<td>150 ±25</td>
</tr>
<tr>
<td>Annual average</td>
<td>62</td>
<td>82</td>
<td>99</td>
<td>118</td>
<td>152</td>
</tr>
</tbody>
</table>
Table 6. Results of a repeated measures split-plot ANOVA comparing soil temperature parameters among five zones under late lying snowpatches at seven sites in the Snowy Mountains for 2003/04, 2004/05 and 2005/06. Annual data run from 1 July to 30 June the following year.

<table>
<thead>
<tr>
<th></th>
<th>Year</th>
<th>Year x snowbed</th>
<th>Year x zone</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
</tr>
<tr>
<td>Av. daily temp.</td>
<td>32.359</td>
<td>&lt;0.001</td>
<td>9.980</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Season days</td>
<td>0.380</td>
<td>0.688</td>
<td>8.903</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Growing period day equivalents</td>
<td>13.323</td>
<td>&lt;0.001</td>
<td>10.946</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Hourly temp. sum</td>
<td>107.671</td>
<td>&lt;0.001</td>
<td>25.454</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Table 7. Mean (± Standard error) of soil depths (mm), moisture (% by volume) at soil sampling sites in zones C (short alpine herbfield), D (transitional) and E (tall alpine herbfield) in March 2006, and average annual percentage of inspections when soil water table was recorded in the top 150 mm over four years 2004-2007. (Proportions are averaged over three sites in each zone of each snowbed, n is number of snowbeds sampled).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Depth (mm)</th>
<th>Moisture%</th>
<th>Water table%</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>58.4 ± 14.0</td>
<td>23.4 ± 24.8</td>
<td>44.0 ± 32.7</td>
<td>6</td>
</tr>
<tr>
<td>D</td>
<td>162.4 ± 100.1</td>
<td>13.0 ± 10.9</td>
<td>21.1 ± 36.2</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>225.0 ± 129.0</td>
<td>10.4 ± 2.2</td>
<td>3.6 ± 5.0</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure captions

Figure 1. Map of study area showing the sites of all snowpatches in February 2004 and three additional snowpatches occurring in December 2006. Major drainage lines and the 2000 and 2100 m contours are shown. The five water bodies all exist in glacial features. Cirque boundaries are based on Galloway et al. (1998) and Barrows et al. (2001).

Figure 2. Ordinations of (a) percentage cover of individual species, bare ground, litter and rock in 1 m² quadrats among five zones (A to E); (b) cover of all species in 1 m² quadrats as proportion of total vegetation cover in five zones (A to E), (c) presence/absence of plant species in 5 x 1 m² quadrats in three zones (C, D and E) within each of the seven studied late lying snowbeds.

Figure 3. Mean annual temperatures for each zone beneath six of the seven studied late lying snowpatches over three years, 2003/04, 2004/05 and 2005/06. Annual data run from 1 July to 30 June the following year. No data were obtained from Club Lake Cirque. Open circle = Twynam Cirque, closed circle = Blue Lake north, open triangle = Blue Lake south, closed triangle = Mawson Cirque, open square = Mt. Kosciuszko north-east ridge, closed square = Cootapatamba Cornice.