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

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

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

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

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

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

21

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

23

24

25 **Introduction**

26 High mountain environments are among those most likely to be altered by climate
27 change (Grabherr et al. 1994; Pauli et al. 2007). Reductions in snow cover and rising
28 temperatures have been documented for many high mountain areas (Beniston 2003),
29 with associated vegetation responses including the colonisation of nival areas by
30 alpine plant species (Grabherr et al. 1994; Pauli et al. 2007). Within the alpine zone,
31 there are specialised plant communities limited to snowbeds, defined here as sites
32 where snow cover remains weeks or months after the general thaw (Gough et al.
33 2000). These snowbeds and their constituent species could be particularly at risk
34 because they are limited spatially, being dependent upon the specific microclimatic
35 and topographical conditions that result in the accumulation of deeper and longer
36 lasting snow than at adjacent sites.

37 The Snowy Mountains (36°27'S 148°16'E) have the longest lasting snowpatches
38 in Australia, while further south the last snowpatches of the lower altitude Victorian
39 Alps and alpine Tasmania generally melt by late January (Wahren et al. 2001;
40 Kirkpatrick pers. comm. 2007). Snowpatches occur in areas of the Snowy Mountains
41 generally above 2000 m a.s.l., in locations receiving least sun (south to south-east
42 aspects) that are also in the lee of slopes with snow-bearing winds being
43 predominantly north-westerly (Davis 1998; Green and Pickering in press). Hence, the
44 process of snow-drift and lowered insolation reinforce each other to create large
45 snowpatches that have in the past reached depths of 30 m (Costin et al. 1973), and
46 remained continuously for several years (McLuckie and Petrie 1927). The associated
47 vegetation was characterised by snowpatch feldmark above the snowbed, the centre of
48 the snowbed supporting few or no vascular plants on skeletal soils, and short alpine
49 herbfield occurring down slope (Costin 1954). The alpine regions of south-eastern

50 Australia have warmed over the past 35 years at a rate of about 0.2°C per decade,
51 with projections for 2050 of possible reductions by 96% in the area sustaining snow
52 cover for more than 60 days year⁻¹ (Whetton 1998; Hennessy et al. 2003). The date of
53 thaw for snowpatches is generally related to the duration of the snowpack as
54 measured at Spencers Creek, where the duration of the snowpack has declined
55 significantly over the past 54 years (Green 2008; Green and Pickering in press). As a
56 result, these two vegetation communities, supporting several locally endemic species
57 (i.e. to just this alpine region, Costin et al. 1979), are at risk and may be among the
58 most threatened alpine ecosystems in the world (Edmonds et al. 2006; Green and
59 Pickering in press).

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

65 Beneath the earlier melting snowpatches in the lower altitude Victorian Alps,
66 Wahren et al. (2001) examined variation in floristics in relation to physical factors
67 and date of snow melt and Venn and Morgan (2007) examined growth and phenology
68 across a snow-melt gradient. However, the snowbeds they studied had nearly complete
69 vegetation cover and did not include short alpine herbfield or snowpatch feldmark. .
70 The most recent study of the snowpatches of the Snowy Mountains was by Edmonds
71 et al. (2006) who compared vegetation on 88 sites that had snow lying in mid January
72 at different frequencies (snow in 1, 3 and 8 years out of 10). They studied the upper,
73 often rocky section of snowbeds, However, little is known about the current status of
74 vegetation in the middle and lower sections beneath the late lying snowpatches.

75 The aims of the present study were, therefore, to determine whether discernible
76 zones beneath the late lying snowpatches of the Snowy Mountains conformed to
77 previous descriptions or if the zones today have a different species composition. We
78 examined variation in microclimate, soil characteristics and vegetation beneath
79 snowpatches. From this information we compared the latest-lying Australian
80 snowpatches with those of shorter duration in other alpine regions of Australia, and
81 with late-lying snowpatches in other alpine regions of the world. We discuss how
82 these, the latest lying snowpatches in Australia and their associated plant communities
83 may have changed and are likely to change with a warmer, drier climate.

84

85 **Materials and methods**

86 *Study area*

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

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

99

100 *Selection of sites*

101
 102 For detailed sampling of snowpatches, soils, subsurface temperature, and vegetation,
 103 seven study sites were chosen from among the 31 snowpatches extant in mid February
 104 (late summer) 2004 (see Fig. 1 for numbered snowpatches). The seven snowpatches
 105 were chosen to give a wide geographic spread and to cover the two main rock types in
 106 the alpine zone of the Snowy Mountains with three on granite and four on
 107 sedimentary rock. They were: Twynam Cirque (1), Blue Lake Cirque north (6) and
 108 south (7), Club Lake Cirque (11), Mawson Cirque (12), the north-east ridge of Mt.
 109 Kosciuszko (19) and the Cootapatamba Cornice (22). Aspect was generally east to
 110 south-east on average slopes of 13.5° to 24.5° (Table 1).

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

121

122 *Vegetation beneath snowpatches*

123 Plant species and life form composition were recorded in each of the seven snowbeds
 124 in March 2007 (Table 1). In each zone present, all plant species, bare ground, rock
 125 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

151 only those species that occurred in more than 5% of quadrats based on the five
 152 contiguous 1 m² quadrats. To determine if there were significant differences in
 153 vegetation among snowbeds and among zones within snowbeds a Two-way Nested
 154 Analysis of Similarity (ANOSIM) was performed for the dissimilarity matrixes.
 155 ANOSIM is a non-parametric permutation procedure applied to the rank dissimilarity
 156 matrix that is analogous to Analysis of Variance but is distribution-free (Clarke 1993).
 157 The SIMPER function was used on the nMDS dissimilarity matrixes for plant
 158 composition to identify which plant species, rock, bare ground or litter contributed to
 159 the separation of the zones.
 160 It was not possible to match different combinations of physical variables to the nMDS
 161 dissimilarity matrix for plant composition using Mantel's test because some physical
 162 variables could not be measured in all zones (Table 1).
 163 In addition to assessing plant assemblages using ordinations, differences in percentage
 164 cover of rock, total vegetation cover, cover of herbs, cover of graminoids, cover of
 165 cryptogams and species richness (per 1 m² quadrat) among zones were tested using
 166 One-way ANOVAs with snowbeds treated as a block in the statistical package SPSS
 167 (Version 14.0). To normalize the percentage cover data before analysis, values were
 168 transformed using the arcsine of the square root of the fraction.

169

170 **Insert Table 1 here**

171

172 *Physical characteristics beneath snowpatches*

173 A Tinytag Plus temperature logger (Gemini Data Loggers, Chichester, England)
 174 recording at 90-minute intervals was buried beneath approximately 75 mm of soil in
 175 each of the five zones in the snowbeds (Table 1). Because of the presence of rock, this

176 was the deepest that loggers could be inserted into zones A and B and therefore the
177 same depth was used in the remaining zones. A range of microclimatic parameters
178 (snow-free season length, average daily temperature, growing-period-day-equivalents
179 and growing-degree days) was obtained from soil temperature data for each zone in
180 each snowbed. These soil temperature derived variables have been used to
181 characterise the thermal regimes of alpine areas in Europe (Körner et al. 2003), in
182 examining phenological response of plants to snow melt (Huelber *et al.* 2006, Molau
183 et al. 2005) and in the analysis of species richness patterns in this (Pickering et al.
184 2008) and other alpine areas (Kazakis et al. 2006, Staniski et al. 2005).

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

200 fashion to the commencement and was the point at which the noon temperature ± 2
 201 hours fell below 3.2 °C and remained below that level.

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

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

216 Soil depth, soil moisture and height of water table were measured, and soil
 217 nutrients were sampled in zones C, D and E within snowbeds. Zones A and B were
 218 not sampled because they consisted mainly of rock (Table 2) with virtually no soil in
 219 between. Soil depth was measured by inserting a steel peg until it hit impassable rock
 220 at three points spread across the slope in each zone. Soil moisture (% saturation) was
 221 measured in March 2006 using a ThetaProbe soil moisture sensor type ML2x (Delta-
 222 T Devices, Cambridge, England). Soil moisture measurements and water table height
 223 were made within the top 150 mm, where most alpine assessments are made because
 224 most biological activity including nutrient cycling occurs there (Körner 2003). 150

225 mm lengths of PVC storm water pipe were located in the soil, where possible, in
226 zones C, D and E of each snowbed and were capped with steel plates. The full 150
227 mm of the pipe was used unless soils were too shallow when the pipe had to be cut to
228 size. The pipes were checked at each visit to each site to determine the height of the
229 water table.

230 Three soil samples were taken from zone E of all seven snowbed sites, from the
231 five snowbeds where zone D occurred and the six snowbeds where zone C occurred
232 (Table 1). A minimum 500 g was collected at each zone in a single sample of soil
233 taking the top 10 cm of soil in a 75 mm core, and samples were air dried and sieved
234 through a 2 mm mesh. Soil was analyzed by the CSIRO Division of Soil and Water.
235 Total carbon and nitrogen were determined by high temperature combustion in an
236 atmosphere of oxygen using a Leco CNS-2000. Carbon was converted to CO₂ and
237 determined by infrared detection. Nitrogen was determined as N₂ by thermal
238 conductivity detection (Matejovic 1997). Inorganic nitrogen was determined by
239 segmented flow colorimetry following extraction using 2M KCl. Nitrate was dialysed
240 then reduced to nitrite by Cd reduction and the resultant nitrite reacted with N-1-
241 naphthylethylenediamine dihydrochloride (NEDD) with sulphanilamide (Rayment
242 and Higginson 1992a). NH₄⁺ was separated from interferences by gas diffusion and
243 determined after reaction with sodium salicylate and dichloro-isocyanurate (DCIC).
244 This procedure is modified from Rayment and Higginson (1992a) according to the
245 International Standard ISO 11732 (1997). Extractable phosphorus was determined by
246 segmented flow colorimetry following Colwell extraction using 1M NaHCO₃ at pH
247 8.5 (Rayment and Higginson 1992b). Total metals were determined by US EPA
248 method 3051A (1998). The finely ground sample was digested in a microwave oven
249 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

276 differences in plant species richness and plant composition among and within
 277 snowbeds (ANOVA and ANOSIM, Tables 3 and 4, Fig. 2). The composition of the
 278 vegetation under the snowpatches differed from the original descriptions (Costin et al.
 279 1979) particularly that for short alpine herbfield.

280

281 **Insert Table 2 here**

282 **Insert Table 3 here**

283 **Insert Table 4 here**

284 **Insert Fig. 2 hereabouts.**

285

286 The quadrats in the central section of the snowbed in Zone A had little vegetation
 287 (10% cover) with most of the zone consisting of rocks (88%). This zone was the most
 288 consistent in plant composition among snowbeds with 84% similarity (Fig. 2a, Table
 289 2). Instead of having species that were considered characteristic of snowpatch
 290 fieldmark (*Coprosma niphophila*, *Colobanthus nivicola*, *Ranunculus anemoneus* and
 291 *Epilobium tasmanicum*), the vegetation in this zone consisted nearly entirely of the
 292 low growing stoloniferous *Neopaxia australasica* (6.7%, Table 2, Appendix 1), which
 293 is considered characteristic of short alpine herbfields (Costin et al. 1979). Six
 294 graminoids including the characteristic tall alpine herbfield grasses *Poa costiniana*
 295 and *P. fawcettiae* were found in this zone, although at low cover values. Out of the
 296 total of 51 vascular species recorded, 13 were found in this zone, with an average of
 297 four species per m². The snow-free season was shortest in this zone, averaging 62
 298 days (Table 5).

299 In the transition (Zone B) between the rock-dominated zone under the late-lying
 300 snowpatches and the short herbfield in Zone C, the snow-free season was longer

301 (average 82 days, Table 5). Rocks still covered most of the ground (67%), but
 302 vegetation cover, nearly half of which was cryptogams (Appendix 1), was higher at
 303 34% (Table 2). *Neopaxia australasica* was again important with 13% cover. The
 304 cover of graminoids increased, with snowgrasses (*Poa costiniana* and *P. hiemata*)
 305 accounting for just under 4% of the ground cover.

306 In the locations that have been considered characteristic of short alpine herbfield
 307 vegetation (Zone C), the snow-free season averaged 99 days (Table 5). There was
 308 considerable variation in composition and cover of surface types in this zone, with an
 309 average similarity of only 36% among quadrats (Fig. 2). Rocks covered an average of
 310 21% of the ground, with vegetation cover at 76%, consisting of equal amounts of
 311 graminoids (33%) and herbs (33%) (Table 2). Vegetation was characterised by
 312 *Neopaxia australasica* (28%), cryptogam (15%), and the two graminoids, *Luzula*
 313 *acutifolia* (a species of short alpine herbfield, 9%) and *Rytidosperma nudiflorum* (a
 314 species of tall alpine herbfield, 7%) (Appendix 1). Species richness was high, with 6.6
 315 species per m², and a total of 35 species recorded in the zone (Appendix 1). Ten of
 316 these species were considered characteristic of short alpine herbfield, three of which
 317 were also found in snowpatch feldmark (Costin et al. 1979). A high diversity,
 318 particularly of herb species that each occurred at low cover and frequency is likely to
 319 have contributed to variation in this zone.

320 The intermediate zone (D) between short alpine herbfield (C) and tall alpine
 321 herbfield (E) had higher cover values for graminoids, principally the snowgrasses *Poa*
 322 *costiniana* (51%) and *P. fawcettiae* (13%), and another grass, *Rytidosperma*
 323 *nudiflorum* accounting for another 7% of cover. As a result, the cover of graminoids
 324 was 82%. There were many species of herbs, but at low frequency and cover values,

325 with total herb cover averaging only 3.9%. There was limited rock cover (6.6%), and
 326 some bare ground (~4%). The snow-free season averaged 118 days (Table 5).

327 The final zone, tall alpine herbfield (E) was characterised by near complete
 328 vegetation cover (95%), predominantly graminoids (87%), with *Poa costiniana* alone
 329 having 56% cover. The other important grasses were *Rytidosperma nudiflorum* (21%)
 330 and *Poa fawcettiae* (8%). Herb cover was higher than in the transition zone (D) with
 331 12% herbs, the most common of which was *Celmisia costiniana* (9%). Species
 332 richness per quadrat was low (3.9), although 27 species were recorded in this zone, all
 333 of which are species of tall alpine herbfield (Costin et al. 1979). The snow-free season
 334 averaged 152 days (Table 5).

335

336 *Physical characteristics beneath snowpatches*

337 There were significant differences in average daily soil temperature among the five
 338 zones ($F=17.868$, $P<0.001$) among the snowbeds ($F=6.373$, $P=0.005$) and among
 339 years (Fig. 3). Most snowpatches remained longer into 2005 than 2004, which helps
 340 to explain the generally lower average soil temperature in 2004/05 than 2003/04. For
 341 average daily temperature, growing-period-day-equivalents and growing degree days,
 342 2005/06 was much warmer than other years.

343

344 **Insert Fig. 3 hereabouts.**

345 **Insert Table 5 here**

346 **Insert Table 6 here**

347

348 The soil temperature differed among zones in snowbeds (Fig. 3). Zone A at the
 349 core of the snowbed with little or no vegetation cover differed from the heavily

350 vegetated zone E in that it had: a lower average daily temperature (1.6 °C cf. 4.7°C), a
 351 shorter snow-free season (62 cf. 152 days) and fewer growing-period-day-equivalents
 352 (48 cf. 123) (Table 5 and 6). There was a consistent gradient of longer snow free
 353 periods and higher average temperatures from zones A to E except that there was no
 354 significant difference for growing-period-day-equivalents and temperature sum
 355 between zones A and B. Because the bare soil surface was exposed most to insolation
 356 in zone A, the highest temperatures and greatest variation occurred there. By contrast,
 357 the warmest zone (E) had a lower maximum temperature and less variation because of
 358 the shading effect of tall grass in the covering herbfield.

359 There were clear differences in soils within snowbeds from zone C to E (Table 4,
 360 Appendix 2). There were significant differences among zones in the snowbeds in C,
 361 N, $-_4\text{N}$, nitrate/nitrite, extractable and total P, Al, K, Na, and soil depth. Most nutrients
 362 increased in soils with progression down slope from zone C to zone E; percentage C
 363 and N, together with NH_4N , total P, Al, K, and Na were all significantly higher in
 364 zone E than in zone C. Extractable P decreased significantly down slope. Soil depth
 365 increased from an average of 58 mm in zone C to 225 mm in zone E in snowbeds
 366 (Table 7). Over the same distance, soil moisture content fell from 23% to 10% (but
 367 this was not statistically significant) and the temporal frequency at which the water
 368 table occurred in the top 150 mm of the soil declined from about 44% to 4% down
 369 slope but could not be tested using parametric statistics, because there were so many
 370 zero values (Table 7).

371

372 **Insert Table 7 here**

373

374 **Discussion**

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

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

390 Snowpatches accumulate nitrogen, which is released during the growing season
391 into vegetation communities below (Bowman 1992). However, with roots in cold,
392 saturated shallow soil, particularly in zone C, the capacity of plants to sequester this
393 nitrogen is limited (Bowman 1992) and in the present study both total N and $\text{NH}_4\text{-N}$
394 increased significantly down-slope from zones C to E. Ammonium was the dominant
395 form of nitrogen as found in tundra soils (McKown 1978), with levels twice that of
396 nitrates as would be expected from soils with a pH of around 4.6 (Costin et al. 1969).
397 Levels of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the C zone were of the same order of magnitude as in
398 nival zone soils the Tyrolean Alps (Haselwandter et al. 1983). By contrast, in the
399 Scandes in northern Sweden there was more nitrogen in snowbeds than the adjacent

400 plant communities but this may be due to topography, and it appears that there was
401 little uptake of this nitrogen by snowbed plants (Björk et al. 2007).

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

409 Species richness, cover of vegetation and plant composition all varied under
410 snowpatches as has been found elsewhere (Billings and Bliss 1959; Stanton et al.
411 1994). The zone under the deepest part of the snowpatch (zone A), with the shortest
412 snow-free season, had low species richness and limited vegetation cover. Zones down
413 slope of this had more species and greater vegetation cover. The range of cover values
414 across zones was similar to the 17 to 85% in snowbeds in the Giant Mountains of the
415 Czech Republic (Hejcman et al. 2006). However, this situation differs from the
416 shorter lasting, lower altitude snowpatches elsewhere in Australia, where there is no
417 obvious altitudinal stratification of vegetation within snowbeds and no snowbed -
418 specific plant communities (Costin et al. 2000; Wahren et al. 2001; Harvey 2003). In
419 the Snowy Mountain, forbs dominated vegetation beneath the longest lasting snow
420 with graminoids dominating where snow melted first, with about equal distribution in
421 the mid zones - the short alpine herbfield. By contrast, in northern Sweden graminoids
422 dominated snowbeds with a mid-range of timing of snowmelt with cover decreasing
423 as snowmelt was both earlier and later (Björk and Molau 2007).

424 Low species richness in snowbeds has been recorded elsewhere, with usually 5-10
425 species m⁻² but up to 18 reported in northern Sweden (Björk and Molau 2007). The
426 figures for the Snowy Mountains were even lower with a range of 1-11 vascular
427 species for the 83 1 m² plots. Average diversity rose from the centre of the snowbed
428 down slope to the short alpine herbfield and the transition to tall alpine herbfield but
429 was lower again in the tall alpine herbfield where one or two species of *Poa*
430 dominated. In contrast, in the upper section of the Snowy Mountains snowbeds, mean
431 species richness increased with the earlier melt of snow with greatest richness the
432 shorter the snow period (Edmonds et al. 2006).

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

449 distinct communities, but rather individual species responding to differences in snow
 450 cover and moisture (Venn 2001).

451 In the period of transhumance up until the 1940s, heavy grazing pressure on short
 452 alpine herbfield resulted in severe structural degradation below many snowpatches,
 453 but because of the specialised environment, exotic species were excluded (Costin
 454 1954) and instead recolonisation was by short alpine herbfield species (Wimbush and
 455 Costin 1973). In the present study, it is apparent that there have been significant
 456 changes beneath snowpatches since the work by Wimbush and Costin (1973). It
 457 appears now that the characteristic vegetation sequence beneath snowpatches is
 458 breaking down under intrusion of plants species from communities that in the past
 459 were found in areas with shorter snow duration. This suggests strongly that the
 460 present changes are the result of changes in the specialised environment once
 461 occupied by these communities potentially due to the loss of snow from snowpatches
 462 (Green and Pickering in press). A similar situation has occurred in alpine Norway and
 463 Finland where there has been an increase of grassland species at the expense of
 464 snowbed vegetation concurrent with a reduction in the period of snow cover (Virtanen
 465 et al. (2003).

466 The results of these changes are obvious particularly with regard to the two
 467 ‘characteristic’ plants of short alpine herbfield, *Neopaxia australasica* and *Plantago*
 468 *glacialis* (Costin et al. 1979). *Neopaxia australasica* achieved greatest cover in Zone
 469 C (short alpine herbfield - preferentially on wet sites) but was more likely to be found
 470 uphill in Zones A and B rather than downhill in D and E (Appendix 1) suggesting that
 471 as a colonising species (Irwin and Rogers 1986; Good 1998) it has taken advantage of
 472 bare ground made available for plant growth by the loss of snow cover. By contrast,
 473 *Plantago glacialis* only occurred in 39% of plots in Zone C and 47% in Zone D where

474 it also had a higher cover value. Rather than suggesting that *P. glacialis* is colonising
 475 downslope, the finding of this species more commonly in the transition zone between
 476 E (tall alpine herbfield) and C (short alpine herbfield) associated with *Poa* suggests
 477 that these transition zones were, in the past, short alpine herbfield and that *Poa* is
 478 invading upslope. It is possible that *N. australasica* is now more common than it was
 479 because of its colonising ability but *P. glacialis* appears to be less common. It was
 480 also seldom recorded in the study by Campbell (2004) who had transects running
 481 through some of the snowbeds reported here or by Edmonds et al. (2006) who
 482 investigated vegetation in the upper sections of snowbeds. Another change noted in
 483 recent studies is the rarity of *Coprosma niphophila* and *Colobanthos nivicola*.
 484 Described as characteristic of the snowpatch feldmark community (Costin et al.
 485 1979), neither species was found to be common beneath the latest lying snowpatches
 486 in Australia more recently (e.g. Campbell 2004; Edmonds et al. 2006). By contrast,
 487 *Senecio pinnatifolius*, a species of tall alpine herbfield (Costin et al. 1979), was
 488 recorded most commonly in the present study in zones A and B that are least like tall
 489 alpine herbfield. The invasive species from down slope tall alpine herbfield appear to
 490 be *Poa costiniana* and *P. fawcettii*.

491 In predicting what effect decreasing snow cover might have on the current
 492 vegetation, it is important to take into consideration the relative importance of
 493 microclimatic versus soil conditions in determining which plant species grow beneath
 494 snowpatches (Venn and Morgan 2007). Currently the short snow-free season might
 495 still be favouring shorter growing mat species of herbs in zone C, but this situation
 496 may be changing as growing seasons become longer. Currently, in areas where there
 497 is reasonable soil depth, both short and tall alpine herbfield species are able to grow,
 498 with any separation being associated with growing season rather than soils per se.

499 Because *Poa* species are relatively competitive, and dominate much of the alpine area,
500 it may be that as growing seasons lengthen, most of the area that was previously
501 considered short alpine herbfield dominated by herbs, becomes dominated by taller
502 growing grasses.

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

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

524

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528

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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).

Snowpatch	Twynam Cirque	Blue Lake Cirque north	Blue Lake Cirque south	Club Lake Cirque	Mawson Cirque	Mt. Kosciuszko north east ridge	Cootapatamba Cornice
Number (see Fig. 1)	1	6	7	11	12	19	22
Altitude (m)	2140	2065	2060	2065	2041	2110	2150
Aspect (True°)	107	115	107	123	167	72	107
Slope (°)	13.5	16.5	19	24.5	22.5	20.5	21.5
Rock type	Granite	Slates etc.	Slates etc.	Slates etc.	Slates etc.	Granite	Granite
Samples and zones in which they were measured:							
Soil temp.	A, C, E	A, B, C, D, E	B, C, D, E	B	A, B, C, D, E	B, C, D, E	A, B, C, D, E
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
Vegetation	A, C, E	A, B, C, D, E	B, C, D, E	B, D, E	A, B, C, D, E	B, C, D, E	A, B, C, D, E

Slates etc. = Slates, phyllites, quartzites & schists.

Table 2. Mean ($\pm$ 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).

Zone	A	B	C	D	E
Number of samples	12	18	18	15	20
Percent cover					
Litter	0.1 ± 0.1	0.6 ± 0.6	0	1.2 ± 0.7	2.8 ± 1.1
Rock	88.6 ± 3.7	64.9 ± 4.8	21.0 ± 4.2	6.6 ± 3.7	1.2 ± 0.7
Bare ground	1.2 ± 0.8	0	1.5 ± 0.6	4.4 ± 1.2	1.4 ± 0.5
Total vegetation	10.2 ± 3.0	34.4 ± 4.8	77.5 ± 4.3	87.8 ± 4.3	94.6 ± 1.7
Graminoid	2.0 ± 0.6	7.4 ± 1.5	33.4 ± 4.9	82.1 ± 3.8	86.9 ± 7.2
Herb	7.2 ± 3.1	13.1 ± 2.5	32.9 ± 7.1	3.9 ± 1.3	11.9 ± 6.2
Cryptogams	1.4 ± 0.9	15.1 ± 4.5	16.1 ± 3.0	7.8 ± 2.5	3.2 ± 1.9
Species richness					
Per 1 m ² quadrat (mean of three per zone)	4.0 ± 0.5	4.8 ± 0.2	6.6 ± 0.5	6.3 ± 0.7	3.9 ± 0.5
Total in 3 x 1 m ² quadrats	15	15	25	27	20
Total in 3 x 5 m ² quadrats	-	-	37	31	29

Table 3. Results from Nested Two-Way Analysis of Similarity (ANOSIM) for zone nested in snowbed. P/A = presence/absence.

ANOSIM performed on dissimilarity matrix of	Zone		Snowbed	
	Rho	P	Rho	P
Ground cover values for 1 m ² quadrats	0.846	0.001	0.09	0.856
% Total vegetation cover for 1 m ² quadrats	0.722	0.001	0.043	0.271
P/A of plant species for 5 x 1 m ² quadrats*	0.687	0.001	0.402	0.002
Soil and duration of growing season	0.586	0.001	0.068	0.001

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.

	Snowbed		Zone	
	F	P	F	P
Species richness in 1 m ² quadrats	4.338	0.001	8.474	<0.001
Cover of rock	3.627	<0.003	111.120	<0.001
Total vegetation cover	4.746	<0.001	86.499	<0.001
Graminoid cover	5.267	<0.001	64.55	<0.001
Herb cover	11.516	<0.001	10.776	<0.001
Cryptogam cover	1.375	0.236	7.179	<0.001
% Carbon	8.488	<0.001	22.126	<0.001
% Nitrogen	8.647	<0.001	28.631	<0.001
NH ₄ -N ammonium	2.348	0.048	10.647	<0.001
NO _x -N nitrate/nitrite (sqrt)	2.242	0.056	8.572	0.001
Ext. P	16.161	<0.001	18.875	<0.001
P (ln)	20.234	<0.001	12.137	<0.001
Al	10.076	<0.001	14.060	<0.001
Ca (sqrt)	18.567	<0.001	1.151	0.326
Cu	12.513	<0.001	0.779	0.465
Fe (sqrt)	72.257	<0.001	0.093	0.912
K	39.146	<0.001	7.541	0.001
Mg (sqrt)	4337.488	<0.001	0.266	0.767
Mn	26.321	<0.001	2.644	0.081
Na	16.527	<0.001	10.030	<0.001
Pb	29.321	<0.001	4.623	0.015
Sr	11.723	<0.001	4.697	0.015
Zn	35.872	<0.001	0.434	0.651
Soil depth	1.337	0.261	6.262	0.004
Soil moisture	4.795	0.001	23.036	0.058

Table 5. Mean ($\pm$ 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).

Year	A	B	C	D	E
03/04	76 $\pm$ 38	81 $\pm$ 40	99 $\pm$ 32	121 $\pm$ 30	147 $\pm$ 25
04/05	53 $\pm$ 34	80 $\pm$ 17	94 $\pm$ 13	111 $\pm$ 28	159 $\pm$ 21
05/06	58 $\pm$ 16	84 $\pm$ 17	105 $\pm$ 11	123 $\pm$ 31	150 $\pm$ 25
Annual average	62	82	99	118	152

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.

	Year		Year x snowbed		Year x zone		Zone	
	F	P	F	P	F	P	F	P
Av. daily temp.	32.359	<0.001	9.980	<0.001	0.998	0.463	24.283	<0.001
Season days	0.380	0.688	8.903	<0.001	0.818	0.594	37.136	<0.001
Growing period	13.323	<0.001	10.946	<0.001	1.380	0.255	33.332	<0.001
day equivalents								
Hourly temp. sum	107.671	<0.001	25.454	<0.001	1.385	0.297	7.001	0.004

Table 7. Mean ($\pm$ 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).

Zone	Depth (mm)	Moisture%	Water table%	n
C	58.4 $\pm$ 14.0	23.4 $\pm$ 24.8	44.0 $\pm$ 32.7	6
D	162.4 $\pm$ 100.1	13.0 $\pm$ 10.9	21.1 $\pm$ 36.2	5
E	225.0 $\pm$ 129.0	10.4 $\pm$ 2.2	3.6 $\pm$ 5.0	7

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.