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An International Union for the Conservation of Nature Red List ecosystems risk assessment for alpine snow patch herbfields, South-Eastern Australia

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Abstract Alpine ecosystems are globally at risk from climate change. We use the International Union for the Conservation of Nature (IUCN) Red List Criteria for ecosystems to assess the risk of ecosystem collapse in Australian alpine snow patch herbfields. These ecosystems occur on both mainland Australia and Tasmania. They are restricted to steep, south-easterly slopes where snow pack persists well into the summer growing season. Consequently, they are rare, and have high conservation significance. We evaluated the risk of snow patch herbfield 'ecosystem collapse' against criteria that accounted for the ecosystem's restricted distribution, projected decline in the snowpack and increased rates of invasion by taller growing native species of shrub and grass. Our analyses revealed considerable uncertainty in estimates of risk based on some criteria, particularly those related to thresholds of ecosystem collapse caused by biotic change. On the basis of the IUCN Red List criteria, we conclude that the ecosystem is 'endangered'. This is because of the restricted geographical distribution of the ecosystem, a substantial and highly likely decline in the abundance of snow (the principal abiotic driver of the ecosystem), and the prospect of invasion of much of the ecosystem by taller growing native shrubs and grasses. Our case study demonstrates the utility of the Red List methodology for assessing risks to biodiversity in rare ecosystems where changes to both abiotic factors and the relative dominance of native species constitute major threats. Our findings indicate the importance of snow patch herbfields as refugia for dwarf alpine plant species in the face of climate change, the need for continued monitoring, the removal of feral animals from the Australian Alps and scenario planning.

Key words: alpine, climate change, risk assessment, snow, vegetation change.

INTRODUCTION

Alpine ecosystems are globally at risk from climate change (Huber *et al.* 2005). Australian alpine ecosystems are particularly at risk, because they are rare, occur over a relatively narrow altitudinal range and have no nival zone at higher altitudes to which alpine biota may migrate (Hughes 2003; Laurance *et al.* 2011; Williams *et al.* 2014). Australian alpine and sub-alpine ecosystems occupy less than 1% of the area of the continent, and snow patch herbfields occupy less than 1% of that area (Costin *et al.* 2000; Williams *et al.* 2006; McDougall & Walsh 2007). Consequently, snow patch herbfields are one of the rarest ecosystems in Australia.

Snow patch herbfields occur on steep, leeward slopes in the Australian Alps, where snow persists well

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(a)

(b)

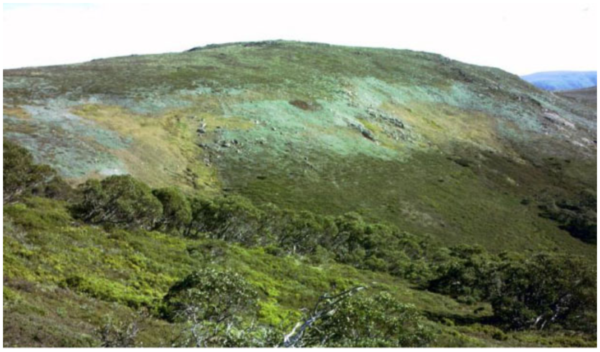

Fig. 1. Alpine snow patch herbfield ecosystem. (a) Patches of late-lying snow on the Main Range, Kosciuszko National Park, NSW, at elevation of *ca*. 2000 m, in December 2009; view from Carruthers Peak. (b) The snow patch herbfield on Mt Nelse (*ca*. 1880 m) on the Bogong High Plains, Alpine National Park, Victoria. Photos: (a) Susanna Venn; (b) Henrik Wahren.

into the spring or summer growing season (Williams *et al*. 2006; Venn & Morgan 2007; Green & Pickering 2009a,b; Fig. 1). They occur in both the alpine zone (*sensu stricto*; above the climatic tree line Costin *et al*. 2000; Körner 2003) and in treeless situations of the high subalpine zone, below the climatic tree line (McDougall 1982; Williams *et al*. 2006, 2014). For the purposes of this paper, we use the term 'alpine' to encompass those snow patch herbfields that occur in the alpine zone (*seusu stricto*), and those that occur in treeless regions of the high subalpine zone. This follows a convention used in Australia that refers to high subalpine treeless vegetation communities with similar structure and composition to those above the tree line as 'alpine' (McDougall 1982; Kirkpatrick 1997; Kirkpatrick & Bridle 1999; Williams *et al*. 2006, 2014).

Plant communities associated with late-lying snow occur in alpine ecosystems worldwide, and have been variously described as 'snow drift meadows', 'snowbanks' and 'snowbeds' (Billings & Bliss 1959; Galen & Stanton 1993; Björk & Molau 2007; Kivinen *et al*. 2012). The vegetation is typically dominated by low-growing forbs, sedges and grasses; the cover of shrubs and taller growing grasses ('snow grasses') is generally low (<10%) (Carr & Turner 1959; Wahren *et al*. 2001; Venn & Morgan 2007; Green & Pickering 2009a,b). Australian snow patch vegetation includes a number of structural and floristic types including 'tall-alpine herbfield', 'short alpine herbfield', 'short turf' and 'feldmark' (Gibson & Kirkpatrick 1985; Costin *et al*. 2000; Wahren *et al*. 2001; McDougall & Walsh 2007; Venn & Morgan 2007; Green & Pickering 2009a,b; Venn *et al*. 2011). Most Australian vegetation has not yet been classified in an international system, and the closest class for Australian snow patch herbfield under the IUCN Habitat classification system is Class 4.1 (Tundra Grassland; http://www.iucnredlist.org/technical-documents/classification-schemes/habitats-classification-scheme-ver3; accessed 7 December 2014). The vegetation conforms to the 'herbfield' class of Specht (1981), and for the purposes of this paper we term them 'snow patch herbfields'.

Australian snow patch herbfields are rare and consequently are of high conservation significance. Although not explicitly listed under national legislation (The Environment Protection and Biodiversity Conservation Act, 1999; EPBC), they are within National Heritage areas and therefore considered as 'matters of National Environmental Significance' under the EPBC Act. In Victoria, they are explicitly listed under the Flora and Fauna Guarantee Act 1988 (Government Gazette G 27, published on 5 July 2012).

Assessment of the risks to biodiversity within snow patch herbfields is timely given their highly restricted distribution, rarity and diversity of threats, which include: climate change, land use (ski resort development; summer tourism) and invasions by exotic plant and animal species (McDougall *et al*. 2005; McDougall & Walsh 2007; Williams *et al*. 2014). Evidence is mounting that climate change is inducing changes in Australian snow patch vegetation (Edmonds *et al*. 2006; Green & Pickering 2009a,b). Changing climate may also substantially alter vegetation state by increasing rates of encroachment of shrubs (Wahren *et al*. 2013; Williams *et al*. 2014; Camac *et al*. 2015) and tall grasses (Green & Pickering 2009b; Pickering *et al*. 2014) into snow patches that are otherwise dominated by short herbs and graminoids. Such expansion of taller growing native species, both woody and herbaceous, at the expense of shorter life forms, is a global phenomenon in temperature-limited systems at both high altitude and high latitude (Schöb *et al*. 2009; Myers-Smith *et al*. 2011; Elmendorf *et al*. 2012).

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Here, we assess the conservation status of Australian alpine snow patch herbfields using the IUCN Red List Criteria for ecosystems (Keith *et al.* 2013). We base our assessment on distributional data (Criteria A, B; see below), changes in the principal abiotic driver of the composition and structure of the ecosystem – the duration of snow (Hennessy *et al.* 2008; Sánchez-Bayo & Green 2013; Criterion C) and changes in the abundance of native species (in this case, shrubs) within snow patch herbfields, detected via long-term vegetation monitoring (Wahren *et al.* 2001; Williams *et al.* 2014; Criterion D). For the purposes of this paper, we restrict our application of the IUCN Red List criteria for risk assessment to the snow patch herbfields of the Australian mainland. Data for each criterion are best-developed for the mainland, and some estimates of risk are potentially biased by the large disjunction between the mainland Australian Alps and Tasmania. We recognize that there are differences in the structure and floristics of, and potential threats to, snow patch herbfields across the Australian Alps (Kirkpatrick 1989; Wahren *et al.* 2001; Green & Pickering 2009a,b). Nevertheless, the logic and protocol of the assessment developed here are likely to hold for the snow patch herbfields across the Australian Alps.

Characteristic native biota

Snow patch herbfields are one of 10 major structural assemblages of Australian alpine vegetation (Kirkpatrick & Bridle 1999; Costin *et al.* 2000; Williams *et al.* 2006; McDougall & Walsh 2007). The vast majority of native plant species that characterize the snow patch herbfields occur in the surrounding matrix of heathland and grassland. Nevertheless, because of the preponderance of particular life forms, and their characteristic topographic setting (see below), they are highly distinctive and easily recognized. Snow patch herbfields have traditionally been described and mapped as 'plant communities' in Australia, rather than 'ecosystems'; but for the purposes of this paper, we will utilize the IUCN terminology of 'ecosystem' (Keith *et al.* 2013).

Snow patch vegetation may be dominated by short graminoids (*Carex* spp., Cyperaceae; *Luzula* spp., Juncaceae; *Rytidosperma* spp., *Agrostis* spp.; Poaceae); short forbs such as *Neopaxia* (Portulacaceae), *Brachyscome* spp., *Cotula*, *Ewartia* (Asteracea) and in some situations by taller forbs such as *Celmisia* spp. (Asteraceae) and tussock grasses (e.g. *Poa spp*). Shrubs are typically rare or absent, especially at high altitudes in the Kosciuszko region (Green & Pickering 2009a,b); species include dwarf shrubs such as *Melicytus* sp. (Violaceae) and *Coprosma niphophila* (Rubiaceae). By contrast, on the Bogong High Plains, tall shrubs that dominate heathlands on slopes adjacent to snow patch herbfields may also be present within snow patch herbfields, but typically with less than 10% cover. These shrub species include *Grevillea australis* (Proteaceae), *Phebalium squamulosum* (Rutaceae), *Prostanthera cuneata* (Lamiaceae) and *Bossiaea foliosa* (Fabaceae; Wahren *et al.* 2001; Williams *et al.* 2006; Venn & Morgan 2007). Vegetation cover can vary substantially, both within and between individual herbfields, from near-complete to <10%; bare ground and rock cover is similarly variable (Green & Pickering 2009a). Snow patch herbfields are also floristically variable both between and within patches. McDougall (1982) differentiates between short turf (at relatively low altitudes) and diuturnal snow patch herbfields (at higher altitudes) on the Bogong High Plains. Floristic variation within snow patch herbfields (upper, mid and lower zones; central and outer zones) has been documented for snow patch herbfields (Atkin & Collier 1992; Wahren *et al.* 2001; Green & Pickering 2009a,b; Venn *et al.* 2011).

Data on snow patch fauna are sparse. Collections in 2011–2012 from pitfall traps revealed 118 species/morpho-species, from six classes, 17 orders and 61 families; only 45 have been positively identified to genus/species (M. Nash, unpublished data, 2014). An undescribed spider from the genus *Micropholcomma* is thought to be an obligate snow patch species. Functionally important arthropod groups are millipedes, mites, spiders, springtails, beetles and ants (Green & Osborne 2012). This represents a wide range of trophic levels, from consumers to predators, and the suite of invertebrates undoubtedly plays a significant role in the maintenance of soil health (Jouquet *et al.* 2006; Paoletti *et al.* 2007).

Despite the distinctive structural appearance and highly restricted distribution, the overwhelming majority of plants and invertebrates recorded in snow patch herbfields on the Bogong High Plains occur in other alpine vegetation communities such as grasslands, heathlands or wetlands (Wahren *et al.* 2001; Venn & Morgan 2007; M. Nash, unpublished data, 2014). The situation is similar in the Kosciuszko region, where no vascular plant species appear to be totally restricted to snow patch habitats (Edmonds *et al.* 2006; Venn & Morgan 2007; Green & Pickering 2009a,b). Despite the apparent absence of a suite of specialist snow patch species, the community is distinctive (Williams *et al.* 2006), and has been defined numerically (McDougall & Walsh 2007). There are compositional differences between snow patch herbfields as a function of altitude, both with respect to plants (McDougall 1982; Wahren *et al.* 2001) and invertebrates (M. Nash, unpublished data, 2014). There also appear to be gradients in floristic composition between upper slope, mid-slope and lower slope regions of snow patch herbfields (Atkin & Collier 1992; Wahren *et al.* 2001; Venn & Morgan 2007; Green & Pickering 2009a).

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Key abiotic features

Australian alpine and subalpine landscapes are characterized by relatively low annual temperatures and high annual precipitation (Williams *et al.* 2006, 2014). The fundamental environmental determinant of the distribution of snow patch herbfields is the persistence of snow (Wahren *et al.* 2001; Green & Pickering 2009a). The snow patches of south-east Australia occur on south to south-east aspects, which are in the lee of the predominantly north-westerly snow-bearing winds. These leeward aspects are also pole facing, hence incident radiation during the spring and summer is less than on N and W slopes (Williams 1987; Costin *et al.* 2000; Wahren *et al.* 2001; Edmonds *et al.* 2006; Green & Pickering 2009b). As a consequence, snow can persist well into the growing season (November to February, depending on altitude) resulting in a shorter growing season than in surrounding vegetation (Wahren *et al.* 2001; Green & Pickering 2009a,b; Venn *et al.* 2011). For example, in the Kosciuszko region, between 2003–2004 and 2006–2006, the snow free period between in the centre of large snow patch herbfields was between 53 and 76 days, compared with a snow-free period of 147–159 days in adjacent tall alpine herbfield (Green & Pickering 2009b). Snow patch herbfields often occur in conjunction with cold-climate landforms that are a result of the glacial and peri-glacial conditions of the recent past, such as terraces, solifluction lobes, glacial cirques and stony pavements (Williams *et al.* 2006). Snow patch herbfields are likely to be highly sensitive to climate change, both through the direct effects of declining snow, and through indirect effects such as changes in species/life-form dominance.

Distribution

The ecosystem occurs in the high mountain environments in south-eastern Australia (New South Wales (NSW), Victoria and Tasmania) across a latitudinal range of *ca.* 6° and from approximately 1000 m to 2200 m in altitude. Snow patch herbfields occur in both the alpine and the treeless, high subalpine zones of the Australian Alps (Williams *et al.* 2006, 2014; McDougall & Walsh 2007). This includes the Snowy Mountains/Kosciuszko National Park in NSW (Green & Pickering 2009a,b), the Bogong High Plains and surrounding peaks in Victoria (Wahren *et al.* 2001) and the Central and Western and highlands of Tasmania (Gibson & Kirkpatrick 1985).

Key processes and determinants

The principal determinant of the distribution of snow patch herbfields is variation in the persistence of snow (Costin *et al.* 2000; Williams *et al.* 2006, 2014; Kivinen *et al.* 2012). Snow persistence in snow patch habitats may be highly variable between years. In the Kosciuszko region, 21 hectare of land was predicted to have supported persistent summer snowdrifts in 80% of the past 50 years, while 440 hectare supported persistent summer snow in 10% of years (Edmonds *et al.* 2006). Snowdrifts persisting into late spring and summer may also accumulate windblown sediments, which add to the soil matrix of snow patch herbfields (Costin *et al.* 2000). The moisture regime of snow patches varies with position, with downslope sites receiving more spring run-off than upslope sites. This moisture gradient has been correlated with vegetation composition (Atkin & Collier 1992; Green & Pickering 2009a). Deep snow on steep slopes can also generate substantial sheer force (Costin *et al.* 1973) which can cause local disturbance – removal of vegetation, soil movement and the creation of bare round.

METHODS

Ecosystem collapse

'Ecosystem collapse' is the endpoint for ecosystem change proposed by Keith *et al.* (2013) to be the equivalent of species' extinction. They define ecosystem collapse as 'transition beyond a bounded threshold in one or more variables that define the identity of the ecosystem. Collapse is thus a transformation of identity (i.e. loss of defining features), and replacement by a novel ecosystem. It occurs when all occurrences lose defining biotic or abiotic features, and characteristic native biota are no longer sustained'. The risk of collapse is assessed by using long-term monitoring data to assess five IUCN criteria: (i) rates of decline in the abundance of the ecosystem; (ii) the degree to which the distribution of the ecosystem is restricted, with continuing declines or threats; (iii) rates of environmental (abiotic) degradation; (iv) rates of disruption to biotic processes; and (v) quantitative estimates of the risk of ecosystem collapse. There are various sub-criteria within each major criterion. For Criteria A, C and D, these quantify (i) the degree of change in the past 50 years; (ii) the predicted degree of change in the next 50 years; and (iii) the degree of change since 1750. For Criterion B, these quantify current patterns of occurrence. Based on the relative severity of change under each of these criteria, the categories of risk are: least concern; near threatened, vulnerable; endangered and critically endangered. Further details on the protocol and criteria are given in Keith *et al.* (2013) and Keith (2015).

As defined, ecosystem collapse is locally possible in Australian alpine environments. Examples include livestock grazing, especially if combined with fire, which can transform *Sphagnum* bogs to heathland or grassland (Costin 1954), and both grassland and herbfield to heathland (Wimbush & Costin 1979). Climate change poses serious threats to snow patch herbfields in Australia (Williams *et al.* 2014). Snow cover in the Australian Alps is projected to decline substan-

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tially by the mid 21st century as a consequence of global warming (Hennessy *et al.* 2008). Furthermore, warming has the potential to cause expansion of heathland at the expense of grasslands and herbfields (Williams *et al.* 2014; Camac *et al.* 2015), including snow patches (Wahren *et al.* 2001; Williams *et al.* 2014). Lastly, most of the snow patches on mainland Australia have been mapped or can be identified from remotely sensed imagery. Hence, we have sufficient data for four of the criteria (A–D) to determine rates of decline that may lead to ecosystem collapse. We have insufficient data for a quantitative, modelled assessment of risk (Criterion E).

For snow patch herbfields, we regard ecosystem collapse as having occurred when:

1. The mapped distribution of the snow patch herbfields declines to zero (Criteria A and B)
2. The 10-year running mean depth of the snowpack is zero (Criterion C), and/or
3. The native, short herbaceous vegetation becomes dominated by taller growing native species. In our example, we use invasion by native shrubs, to the extent that shrubs attain a cover of 25%, 50% or 75% (Criterion D). Shrub cover has recently increased in parts of the Australian Alps, and under climate change is projected to increase further (Wahren *et al.* 2013; Camac *et al.* 2015). The threshold of collapse due to shrub invasion has wide bounds due to uncertainty in the amount of shrub cover that will result in the loss of defining compositional and structural features of the herbfield.

Assessment of risk against criteria A–D

Data for Criterion A – rates of decline in ecosystem distribution – were derived from various sources. On the Bogong High Plains *ca.* 240 snow patch herbfields were mapped by McDougall (1982), of which 45 have been monitored at least once since 1996 (Wahren *et al.* 2001). We also have unpublished data on destruction of snow patches as a function of ski resort development in the Victorian Alps (W. Papst, unpublished data, 2014). The Kosciuszko region is data deficient with respect to Criterion A; consequently, we make an explicit assumption that the rates of decline are similar to those on the Bogong High Plains.

Under Criterion B – restricted geographic distribution – extent of occurrence (EOO; B1) and area of occupancy (AOO; B2) were determined from maps, land management agency records and aerial photographic interpretation undertaken in the late 20th century (Department of Environment and Primary Industries 2014; Office of Environment and Heritage, New South Wales 2014; see also McDougall 1982; Thomas *et al.* 2000). Extent of occurrence of snow patch herbfields was determined using mapped polygons that either supported, or were indicative of, snow patch herbfields in Victoria and NSW. Area of occupancy was determined as the number of 10 km × 10 km grid cells across the EOO wherein the ecosystem occurred, and, for these cells, the number in which the ecosystem occupied more than 1% of the area (i.e. 1 km^2).

Under Criterion C we assessed the potential rate of decline of the snowpack. Climate change is likely to lead to substantial reductions in the cover and persistence of snow in the mountains of south-eastern Australia in the coming decades; by the end of the 21st century, the snowpack may be near zero for much of the Australian Alps (Sánchez-Bayo & Green 2013). Such a decline in snow pack would constitute ecosystem collapse under criterion C. Although Australia does not have a formalized snow data network (Bormann *et al.* 2012), there are several data sources that allow estimation of when the snowpack may disappear. Whetton (1998) estimated that the total area with snow cover for at least 30 d per year in south-east Australia could decline by 39% to 96% by 2070. Hennessy *et al.* (2008) indicated that by 2050, the length of the ski season may decrease by 15% to 99%. Green and Pickering (2009b) indicated there was a significant positive correlation between the date of thaw of late-lying snow patches in the Snowy Mountains and the abundance of snow at a long-term snow monitoring site at Spencers Creek (1841 m ASL (above sea level)). Sánchez-Bayo and Green (2013) reported that the average depth of the snowpack at Spencers Creek declined from 113 cm in 1954 to 85.7 cm in 2012, a linear rate of decline of 0.48 cm per year. We used the data of Sánchez-Bayo and Green (2013) to calculate upper and lower bounds of the year in which the snowpack may decline to an average of zero across the geographical range of snow patch herbfields. We assumed that the projected changes in snow pack in NSW are broadly representative of potential changes in Victoria.

Under Criterion D our measure of ecosystem collapse was the degree to which taller growing native species invade the herbfields, thereby altering their characteristic structure and composition. We quantify one facet of this process by using data on temporal changes in native shrub cover in snow patch herbfields of the Bogong High Plains between 1992 and 2014. Shrub invasion is apparent in herbfields between 1650 m and 1850 m ASL on the Bogong High Plains (Wahren *et al.* 2001). We recognize that shrubs are generally absent from snow patch herbfields at altitudes greater than *ca.* 1800 m in the Kosciuszko region (Green & Pickering 2009a,b) and that invasion of such snow patch herbfields by taller growing snow grasses (Pickering *et al.* 2014) is a potentially greater threat to their persistence than is shrub invasion. However, longitudinal data spanning multiple decades on snowgrass abundance in the snow patch herbfields of Kosciuszko are not available. Hence, we cannot apply the risk analysis under Criterion D for this ecological process.

We determined the degree of shrub invasion using a subset of the reference snow patch monitoring sites on the Bogong High Plains. These were established initially as part of a long-term ecological monitoring programme in the 1990s (Wahren *et al.* 2001), and are currently part of the Long Term Ecological Research Network (LTERN) set of reference monitoring sites in the mainland Australian Alps (Williams *et al.* 2014). Of these sites, 23 were surveyed in both 1996 and 2012. These samples were distributed across the altitudinal range of the ecosystem in Victoria (*ca.* 1620–1900 m). Shrub cover was estimated from 500 point quadrats per site, sampled along multiple random 10 m transects; methods are described in Wahren *et al.* (2001).

The point at which ecosystem collapse occurs as a consequence of shrub invasion is uncertain, but we assumed that transition from snow patch herbfield to heathland occurs when shrub cover reached 50% ± 25% (i.e. with bounded estimates of 25% and 75% shrub cover). The change in shrub

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cover was calculated for each of the 23 sites for which we had shrub cover data in 1996 and 2012. To estimate the change in shrub cover over the past 50 years (1962–2012; criterion D1), we assumed (conservatively) that the average shrub cover in 1962 was half that recorded in 1996; that is, a minor modest change between 1962 and 1996. To forecast future changes (next 50 years; 1996–2046; criterion D2), we assumed that the rate of invasion observed between 1996 and 2012 would remain constant. To calculate the relative severity over a historic time frame (criterion D3), we assumed that all shrub invasion observed in 2011 had occurred since 1750. We further assumed that 1750 shrub cover was bounded between *ca*. 1% and the lowest of bounded estimate observed in 1996 (*ca*. 3%). In each case, we used the mean and 90% confidence intervals across the 23 samples to calculate a best estimate, and upper and lower bounded estimates, of change in percent native shrub cover. Finally, we estimated the relative severity of biotic processes for each of the three time frames by range standardizing the best estimate, upper and lower bounds, respectively, by best estimate, least conservative and most conservative thresholds of collapse as specified above.

RESULTS

Criterion A – rates of decline in ecosystem distribution

Of the 240 snow patch herbfields on the Bogong High Plains mapped by McDougall (1982), we are aware of two that have been destroyed as a consequence of ski resort development in Victoria in the past 50 years (W. Papst, unpublished data, 2014). Assuming the number lost is proportional to the area lost, then under Criterion A1, this represents a decline of less than 5% and thus the risk status is least concern (Table 1). Although the Kosciuszko region is data deficient in this regard, we assumed a similar rate of decline. With respect to Criterion A2, we assumed that because snow patches are within Australia's National Reserve System, none will be destroyed by human land use, resulting in a least concern status (Table 1). With respect to Criterion A3, past livestock grazing between *ca*. 1850 and 1950 is likely to have damaged snow patch herbfields. Livestock grazing is known to have caused substantial damage in Australian alpine environments, including snow patch herbfields (Costin 1954; Williams *et al*. 2014). However, in the absence of quantitative data on loss of number or area of snow patch herbfields since grazing commenced, we conclude the risk rating is data deficient (Table 1).

Criterion B – restricted geographic distribution

We identified *ca*. 650 individual snow patches across the Victorian and NSW Alps, most of which were less than 4 ha in area. The mean altitude across all sites was 1876 m ASL (SD = 160 m). The area of the minimum convex polygon enclosing the known, mapped EOO was 2971 km^2 (Appendix S1), meeting the requirement for endangered (Table 1), and very close to the threshold for critically endangered (2000 km^2). Snow patch herbfields have a limited AOO. Across the EOO, the ecosystem occurs in only 19 10 km × 10 km grid cells. The ecosystem comprises more than 1% (or 1 km^2) of the total area of just six of these 19 grid cells, also meeting the requirement for endangered. Thus, given the restricted distribution, in combination with evidence of continuing decline due to documented decreases in the snow pack, and shrub incursion, (see criteria C and D below), the status is endangered under both B1 and B2. Under criterion B3, there are plausibly six broad regions (high alpine, low alpine and high subalpine altitudinal belts in both Victoria and NSW) none of which are likely to disappear en masse in the next 20 years, giving a risk rating of least concern (Table 1).

Criterion C – rates of environmental (abiotic) degradation

The average depth of the snow pack at Spencers Creek declined by 27% between 1954 and 2011

Table 1. Summary of the Red List Risk Assessment of the Australian alpine snow patch ecosystem

Criterion	A	B	C	D	E	Overall
Sub-criterion 1 (past 50 years)	**LC**	**EN** (EN-EN)	**NT**	**LC** (LC-EN)	**DD**	**EN**
Sub-criterion 2 (next 50 years)	**LC**	**EN** (EN-EN)	**NT** (LC-EN)	**DD** (LC-CR)	**DD**	
Sub-criterion 3 (since 1750)	**DD**	**LC**	**LC** (LC-VU)	**LC** (LC-EN)	**DD**	

Criteria: A = distribution; B = spatial extent; C = change in primary abiotic driver(s), in this case depth of snowpack; D = change in primary biotic driver(s), in this case change in shrub cover. Sub-criteria for A, C and D: 1 = present to past 50 years; 2 = next 50 years; 3 = since 1750. Risk categories: CR, critically endangered; DD, data deficient; EN, endangered; LC, least concern; NT, near threatened; VU, Vulnerable. Assessment against Criterion E was not possible; hence, the risk category is DD against all sub-criteria. Bold = best estimate; parentheses indicate plausible bounds. Overall represents the highest risk rating returned from all non-data deficient criteria and sub-criteria.

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(Sánchez-Bayo & Green 2013), making the assessment under Criterion C1 (past 50 years) near threatened (Table 1). Under Criterion C2 (next 50 years), we estimated plausible bounds of the year when the snowpack is projected to reach zero. The best estimate was based on the average snow depth in 2011 with a rate of decline of 0.48 cm per year. For the upper (pessimistic) estimate, we combined the average snow depth determined for 2011 (85.7 cm) with double the rate of decline recorded for 1954–2011 (i.e. 0.96 cm per year; plausible under a high anthropogenic greenhouse gas emissions scenario). For the lower (optimistic) estimate, we combined the maximum snow depth determined for 2011 (175.7 cm) with the current rate of decline of 0.48 cm per year (plausible for the largest snow patches at the highest elevations). This gave the best estimate of the projected severity of decline (i.e. one based on an intermediate rate of decline of the snowpack) between 2012 and 2062 as 28% (near threatened), within the plausible bounds of 14% (least concern) and 56% (endangered; Table 1, Fig. 2).

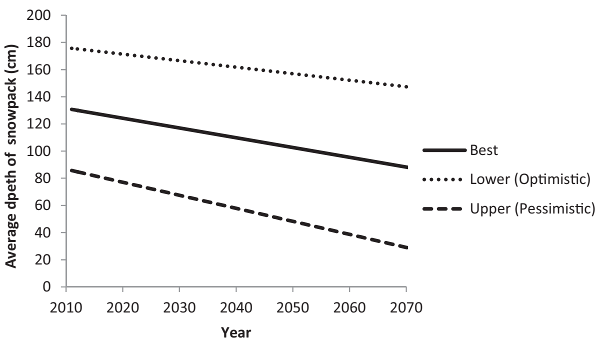

Fig. 2. Bounded estimates of the future rate of decline of the depth of the snowpack at Spencers Creek monitoring station (1841 m), Kosciuszko National Park, NSW. Best = intermediate estimate. Lower bound = optimistic, based on lowest rate of decline of snowpack (0.48 cm per year); Upper = pessimistic, based on highest rate of decline of snowpack (0.96 cm per year). Data source: Table 1, in Sánchez-Bayo and Green (2013).

Under Criterion C3 (change from 1750), the risk rating is least concern (plausible range least concern–vulnerable) if we assume the rate of decline in snow cover to be negligible prior to 1954 (hence 14–56% since 1750).

Criterion D – rates of disruption to biotic processes

There was a net increase in shrub cover of 7.7 ± 3.7% between 1996 and 2012 on the Bogong High Plains snow patch herbfields. For assessment under Criterion D1 (past 50 years), shrubs were estimated to have increased by 23% over that period (plausible range 9–77%; Table 2). Range-standardizing these estimates against the respective threshold values for collapse (Table 2), the status of the ecosystem under criterion D1 is therefore least concern (plausible range least concern to endangered; Tables 1,2). Assuming that the trends observed during 1996–2012 continue at least until 2046, the mean shrub cover was projected to increase to 62.9% (plausible range 4–100%) over a 50-year period. After range standardization (Table 2), the risk status of the ecosystem under criterion D2 (next 50 years) was therefore estimated to be data deficient because the outcomes of our calculations spanned the full range of risk categories (least concern–critically endangered). Assuming that all shrub invasion observed in 2012 had occurred since European settlement, and after range standardization (Table 2) the estimated status under criterion D3 (change since 1750) was least concern (plausible range: least concern–endangered; Tables 1,2).

DISCUSSION

Overall, our analysis classified Australian alpine snow patch herbfields as endangered. This is largely a result of the assessments made under criterion B. However,

Table 2. Bounded estimates of the relative severity of increase (%) in native shrub cover on snow patch herbfields (Criterion D) over three time frames, range standardized by thresholds of collapse (see text)

Time frame (criterion)	Best estimate; collapse = 50% shrub cover	Lower bound; collapse = 75% shrub cover	Upper bound; collapse = 25% shrub cover	Risk status	Assumptions
D1; Current 1962–2012	23	9	77	**LC** (LC-EN)	Minor shrub invasion between 1962 and 2012
D2; Future 1996–2046	100	1	100	**DD** (LC-CR)	Shrubs invade at same rate 2012–2046 as observed in 1996–2012
D3; Historic since 1750	23	4	81	**LC** (LC-EN)	All shrubs have invaded since 1750

Status is the best estimate (bolded) with plausible bounds (in parentheses). Assumptions for each criterion noted. Criteria, sub-criteria and risk categories as per Table 1.

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our analyses also revealed that assessments based on declining snow depth and shrub invasion (Criteria C and D) were less certain than those based on distribution, as the outcomes of the former spanned a broader plausible range of risk categories.

Future prognosis for the ecosystem

The prognosis for the snow patch herbfield ecosystem is potentially grim. Under all criteria, the ecosystem is evaluated as at least endangered; under Criterion B1, the status is very close to the threshold for critically endangered (EOO 2000 km^2). A plausible, albeit worst case, scenario for the ecosystem in the next 100 years is ecosystem collapse. This prognosis is based on restricted geographical distribution of the herbfields, a substantial and highly probable decline in the abundance of snow (the principal abiotic driver of the ecosystem) and the prospect of invasion of the ecosystem by taller growing native shrubs and grasses. Thus, the risk of collapse of the ecosystem over the next 50–100 years will depend on the direct effects of climate change in combination with changing biotic interactions between the major alpine life forms (shrubs, grasses and forbs).

For the snow patch herbfields of the Bogong High Plains, we quantified the risk posed to herbfields from invasion by native shrubs. Shrub invasion of herb-grass dominated vegetation in alpine and arctic biomes is a global phenomenon (Myers-Smith *et al.* 2011; Elmendorf *et al.* 2012). However, snow patch herbfield vegetation may also be at risk from invasion by taller growing grasses (Schöb *et al.* 2009). At Kosciuszko, Green and Pickering (2009a) and Pickering *et al.* (2014) highlighted the potential loss of snow patch vegetation due to invasion by tall 'snow grass' species such as *Poa costiniana*; shrub invasion was not identified as a potential threat to snow patch herbfield vegetation. This spatial variation in the degree of risk to snow patch herbfields posed by shrubs invasion is consistent with our data and analyses. Specifically, our bounded estimates for the relative severity of increase in native shrub cover on snow patch herbfields on the Bogong High Plains ranged from 1% to 100% (Table 2). This implies that in some situations, the risk of invasion by shrubs is high, in others low. Shrub invasion may become a problem, particularly under changing climate and fire regimes (Camac *et al.* 2015), in the high altitude snow patch herbfields of the Kosciuszko region, even if it is not currently recognized as one.

Policy and management implications

There are four principal management/policy implications of our data. These are:

1. Snow patch herbfields as refugia. Under global change, refugia will be important to ecosystem function and biodiversity conservation (Mackey *et al.* 2008). With declining snow, snow patch herbfields will be the last alpine ecosystem to hold any snow. Moreover, there is the potential for ecosystem transformation as a consequence of invasion of snow patch herbfields by taller growing shrubs and grasses. Thus, snow patch environments, particularly those at the highest altitudes, are highly likely to become refugia for some alpine species, particularly dwarf herbs, grasses and shrubs within the Australian alpine flora. Under these scenarios of change, snow patch herbfields have great conservation significance.
2. The need for continued monitoring. There is a clear case for targeted monitoring of snow patch herbfields across the Australian Alps. Despite substantial multi-site data on ecosystem state over the past two decades, the use of these data to derive bounded estimates of risk in some cases resulted in high uncertainties that span the full range of risk possibilities (e.g. least concern–critically endangered under Criterion D2). Given the national conservation significance of snow patch herbfields, continued and indeed expanded, monitoring of the state of snow patch herbfields is essential.

   There does not appear to be a specialist snow patch flora or fauna (at least based on present data), which would require detailed and specialist monitoring, and snow patch herbfields have topographic fidelity and easily identified vegetation structure. This means that effective monitoring for biodiversity conservation can be based on simple attributes such as location, shrub cover, grass cover, species dominance and the amount of bare ground. With respect to individual species, *Coprosma niphophila* and *Colobanthus nivicola* were both described as characteristic of the snow patch feldmark community by Costin *et al.* (1979), but were noted as uncommon by Green and Pickering (2009a). Both species may be in decline, and are worthy of detailed monitoring.

   The monitoring protocol developed for the Bogong High Plains (following Wahren *et al.* 2001) could be adapted and applied elsewhere. The techniques for monitoring changes in the abundance of different life forms across the Australian Alps are well developed (Williams *et al.* 2014). Moreover, the techniques outlined in this paper regarding the risk posed by shrub invasion on the Bogong High Plains can be adapted easily in order to quantify risk to snow patch herbfields posed by invasion by snow grasses, whether on the Bogong High Plains, Kosciuszko or elsewhere in the world.

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3. Manage the ecosystem such that disturbance is minimized. Shrub establishment in forb–grass systems in Australian alpine vegetation inexorably depends on the creation of bare ground (Carr 1962; Williams & Ashton 1987; Williams *et al.* 2006, 2014). While shrubs are absent from snow patch herbfields at the highest elevations in NSW (Green & Pickering 2009a,b), they have established on most of the reference snow patches on Victoria's Bogong High Plains. Shrub expansion is likely to be enhanced by warming associated with global climate change (Camac *et al.* 2015). Shrub establishment will also be enhanced by fire, and continued grazing of exotic ungulates such as deer and horses, because ungulate grazing increases the amount of bare ground (e.g. Fig. 3) and, through selective browsing, reduces the cover of the herbaceous vegetation (Williams *et al.* 2014). Horse and deer numbers have increased substantially in the Australian Alps over the past decade (Nimmo & Miller 2007; Dawson & Miller 2008; Williams *et al.* 2014), and removal of these feral animals from alpine environments, particularly at high altitudes, needs to be made a high priority for national biodiversity conservation. In addition to native shrubs, introduced plants, especially species such as *Hypochoeris radicata*, appear to be increasing in abundance in snow patch herbfields (C.-H. Wahren *et al.*, unpublished data, 2014). Control of such species within snow patch herbfields should also be a high priority.
4. Commence scenario planning now. We have provided plausible future trajectories for a rare ecosystem that is at risk of extinction. To manage threats, and their outcomes, it will be necessary to begin scenario planning now, such that the environmental, social and monetary costs and benefits of various management options can be evaluated. These include deriving thresholds of concern for changes in ecosystem state (*sensu* Bond & Archibald 2003), ways of eliminating feral animals from the Australian Alps and sound criteria for any potential, explicit interventions to reduce the cover of taller growing native shrubs and snowgrasses, and introduced plants.

Fig. 3. Footprints of samba deer, *Rusa unicolour*, near the summit of Mount Bogong (1984 m), Alpine National Park, Victoria. (Photo: Henrik Wahren).

The utility and challenges of the IUCN Red List risk analysis system

We found that the IUCN system was easily applied to Australian alpine snow patch herbfields. We were able to derive plausible, bounded estimates of risk under four of the five assessment criteria. We conclude that snow patch herbfields are an ideal system on which to apply the IUCN framework because they are a part of a globally threatened biome (alpine ecosystems), there are analogue systems across the world, the principal driver of their biogeography (snow) is highly sensitive to climate change, they are locally restricted, and monitoring data needed to derive estimates of risk under the IUCN framework are available. Furthermore, clear and practical management options flow from these analyses. There is much potential to assess change in ecosystem state over time of snow patch herbfields across Australia, and continued assessment of the conservation status of this globally rare ecosystem using the IUCN Red List Criteria would assist global conservation planning.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Extent of occurrence of the alpine snow patch herbfield ecosystem.

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