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POTENTIAL EFFECTS OF GLOBAL WARMING ON THE BIOTA OF THE AUSTRALIAN ALPS

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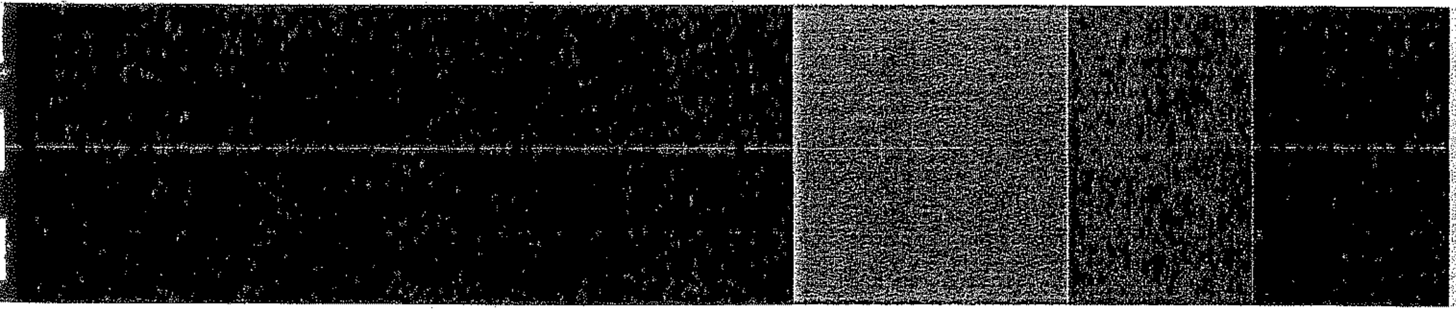
SUSTAINABLE TOURISM CRC



POTENTIAL EFFECTS OF GLOBAL WARMING ON THE BIOTA OF THE AUSTRALIAN ALPS

A report for the Australian Greenhouse Office
by Dr Catherine Pickering, Roger Good, Dr Ken Green

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Photographs courtesy of Roger Good, NSW Department of Environment and Conservation and
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EXECUTIVE SUMMARY

Photo: Roger Good, NSW Department of Environment and Conservation

This initial report summarises current knowledge of predicted climate change effects on alpine and subalpine biota, with a focus on Kosciuszko National Park in south-eastern NSW. It outlines some possible scenarios of the impacts and responses of the native flora and fauna, and feral animals and weeds to climate change, particularly responses to the scenarios of increased mean temperatures as a result of global warming.

It is predicted that there will be both negative and positive impacts on the flora, with increases in the occurrence and distribution of several dominant plant communities (tall alpine herbfield, heathland and sod-tussock grassland) and, as a consequence, decreases in the much smaller areas of the more sensitive communities, particularly short alpine herbfield and the groundwater communities (fens, bogs and peatlands) that are of particular significance for catchments.

It is predicted that the impacts of global warming on the native fauna will first be seen in the decreased distribution and abundance of the alpine endemic Mountain Pygmy Possum and the Broad-toothed Rat, both of which have narrow environmental tolerances. The diversity and abundance of birds at a specified altitude may increase with increasing warming. Little or no information is available in the literature on the possible responses of the alpine invertebrate populations and the soil fauna to climate change. These aspects require much research.

Possible interactions between climate change and tourism are likely, including potential synergistic effects on alien plant species resulting in an increased diversity and abundance of weeds, particularly those associated with tourism infrastructure. Increased use of snow manipulation techniques by resorts in response to poor snow years are likely to have negative effects on the vegetation, soils and hydrology of subalpine-alpine areas within ski resorts.

The report outlines two major research projects that have been established to gather information on global warming in the Kosciuszko National Park section of the Australian Alps: first, the quantification of regional climatic changes; and second, the formulation of sound predictions on the degree and extent of impacts on the flora and fauna of predicted or quantified climate changes. These studies are complemented by research work being carried out as part of two worldwide alpine area climate change projects in which the authors are involved: GLORIA (Global Observation Research Initiative in Alpine Environments) and the Global Mountain Biodiversity Assessment (GMBA) program.

BACKGROUND

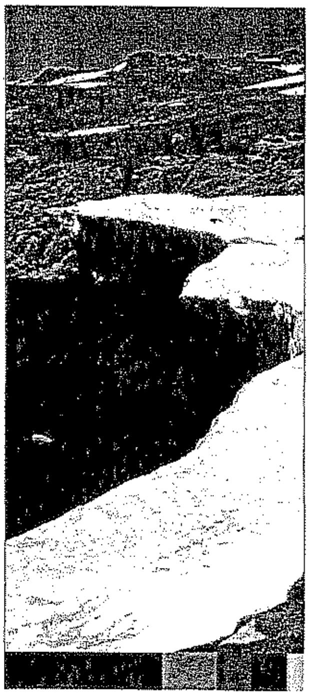


Photo: Roger Good, NSW Department of Environment and Conservation

Predictions of climate change have been made over the past decade, and there are now a number of indicators that give support to global warming and changes in precipitation distribution and form. These climatic changes are attributed predominantly to human activities and resource use (Intergovernmental Panel on Climate Change, IPCC 2001).

The global average temperature has increased by approximately 0.6 °C in the past 100 years, and is predicted to continue to rise. An average global warming of 0.7 to 2.5 °C by 2050 and 1.4 to 5.8 °C by 2100 is predicted, with greater warming at higher latitudes (IPCC 2001; Hennessy *et al.* 2002; Root *et al.* 2003).

Recent reports, including several by personnel associated with the IPCC, indicate that there is a very high level of confidence that climate change is already affecting sensitive ecosystems (Bouma *et al.* 1996; Parmesan and Yohe 2003; Root *et al.* 2003). For example, a meta-analysis of 279 native species found that there has been an average range shift of 6.1 km towards the poles per decade (or metres per decade in altitude) and significant advancement of seasonal spring events by 2.3 days per decade (Parmesan and Yohe 2003). Other studies also report advancements in springtime events of an average of 5.1 days per decade for those species showing a change (Root *et al.* 2003).

The major concerns expressed in these studies are that the species responses/changes have occurred for an average temperature change of just 0.6 °C (Root *et al.* 2003). Therefore, the much larger climatic changes predicted to occur worldwide, including those for Australia and the Australian Alps, are likely to have even more far-reaching effects on the native biota (Pearman 1988; Bouma *et al* 1996; Williams and Mitchell 1996; Root *et al.* 2003).

Based on the climate change models and existing information about distribution of high mountain animals and plants, predictions can be made about the potential effects on alpine and subalpine biota. There are four main types of changes in biota that can occur in response to climate change:

1. changes in the number and abundance of species at given locations and/or changes in the altitudinal range of individual species and/or species associations, with a shift either toward the poles or towards higher altitudes (narrower altitudinal range). Changes of this type have been found in many forms and species of biota (lichens to mammals) and a wide range of environments (e.g. marine zooplankton to treelines) (Parmesan and Yohe 2003; Root et al. 2003)
2. change in the timing and extent of seasonal events for natural history traits that are triggered by temperature. These changes/responses could include changes in migration, flowering, egg laying etc. Already, meta-analysis has indicated earlier flowering and bird migration of the order of 2.3 days per decade in response to existing climatic change (Green and Pickering 2002; Parmesan and Yohe 2003)
3. change in morphology and productivity, e.g. larger or smaller trees, changes in biomass etc and
4. changes in genetic traits, including plant species and an increase in hybridisation.

The authors of this report have to date concentrated on examining changes in the abundance and range of species, as there is some inferential evidence that this type of change is already occurring in alpine biota, including those in the Australian Alps (Green and Pickering 2002; Parmesan and Yohe 2003; Root *et al.* 2003).

MOUNTAIN ECOSYSTEMS AND CLIMATE CHANGE

The ecosystems of high mountain environments, whose dynamics and functionality are controlled by low-temperature conditions, are considered to be particularly sensitive to climate change and global warming (Green 1998; Körner 1999; IPCC 2001; Pauli *et al.* 2001; Root *et al.* 2003). For example, the thermal life zones of alpine/mountain environments are compressed and their temperature determined ecotones are narrow, compared with their horizontal/latitudinal transition zones. Therefore, these narrow mountain ecotones are the most appropriate sites for quantification of expected biotic changes from global warming. In addition, the impacts of human land use, which could mask climate-related signals at lower elevations, are relatively limited in many mountain ecosystems, including the Australian Alps (Green 1998; Körner 1999; Pauli *et al.* 2001; Hamilton 2002). Therefore, high mountain ecosystems will be important 'ecological indicators' of climate change and its effects, due to their comparatively low biotic complexity and the dominance of abiotic factors (particularly climate) over biotic factors, such as competition (Green 1998; Körner 1999; Pauli *et al.* 2001). Hence, global warming impacts on alpine precipitation (amount of rainfall and snow),and its impacts on the flora and fauna, and ecosystem functioning are expected to be among the first quantifiable indications of climate change.

Climate change is increasingly recognised as having a diverse range of potential impacts on the Australian alpine and subalpine biota, and is now identified as a major threat to some species and ecological communities (Good 1998a; Kosciuszko National Park Independent Scientific Committee, ISC 2002; Pickering and Hill 2003; Pickering and Armstrong 2003). According to ISC, this will require specific management actions, research and monitoring to be implemented in the next two to three years to ameliorate the impacts of climate change on the sensitive biota (ISC 2002).

SIGNIFICANCE OF AUSTRALIAN ALPS AS A SITE TO QUANTIFY CLIMATE CHANGE

The total amount of precipitation falling as snow, its distribution and cover are limited, both temporally and spatially in Australia (Figure 1), compared to Europe and north and south America. Only 11,500 km^2 (approximately 0.15%) of the continent receives regular winter snow falls (Costin *et al.* 2000). The most extensive snow-covered area is in the south-east of the continent, around Mt Kosciuszko in New South Wales (Snowy Mountains), and it is only around 2500 km^2. Of this, only 1200 km^2 receives 60 or more days of snow cover, and only 250 km^2 (or 0.001% of Australia) is true alpine (Green and Osborne 1994; Costin *et al.* 2000, Figure 2). Other smaller alpine regions occur as relatively isolated areas in Victoria between Mt Hotham and Mt Bogong (around 1000 km^2 with 60 or more days of snow cover), in the Brindabella ranges in the Australian Capital Territory (150 km^2) and in the Central Highlands and higher peaks in Tasmania (1270 km^2 of alpine and subalpine) (Costin 1989; Green and Osborne 1994). In addition, the maximum altitudinal range within which snow occurs is very limited – around 800 m from the snowline to the highest peak on the Australian continent, Mt Kosciuszko (2228 m) (Figure 2). Snow cover is also very variable and often patchy, particularly in the smaller alpine areas in Victoria and Tasmania. Even in the higher and more extensive alpine area around Mt Kosciuszko, snow-patches that last from year to year are a rare event. The general period of snow cover lasts about five months (Slayter *et al.* 1984; Galloway 1988; Brown and Millner 1989).

FIGURE 1. DISTRIBUTION OF THE AUSTRALIAN ALPINE AND SUBALPINE ZONES.

Adapted from Green 1998.

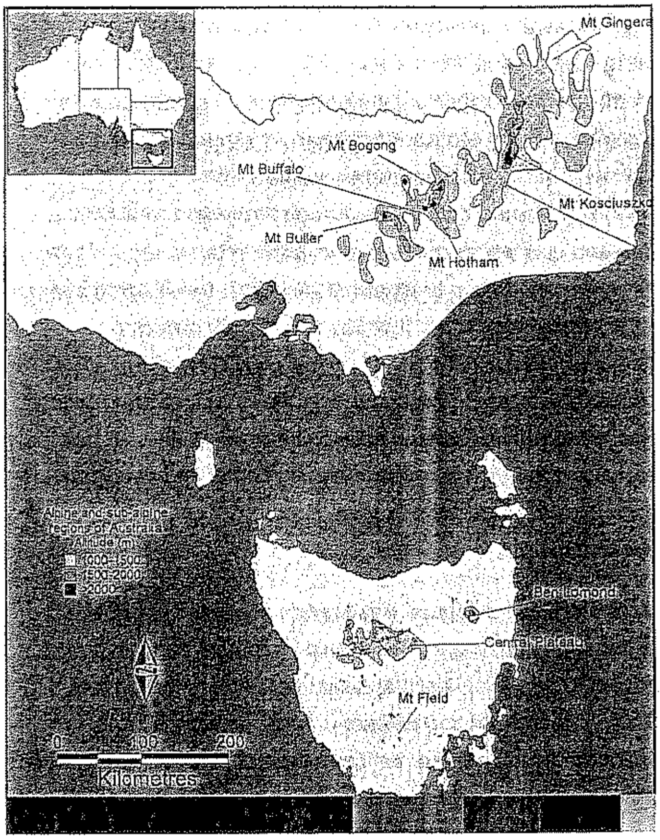
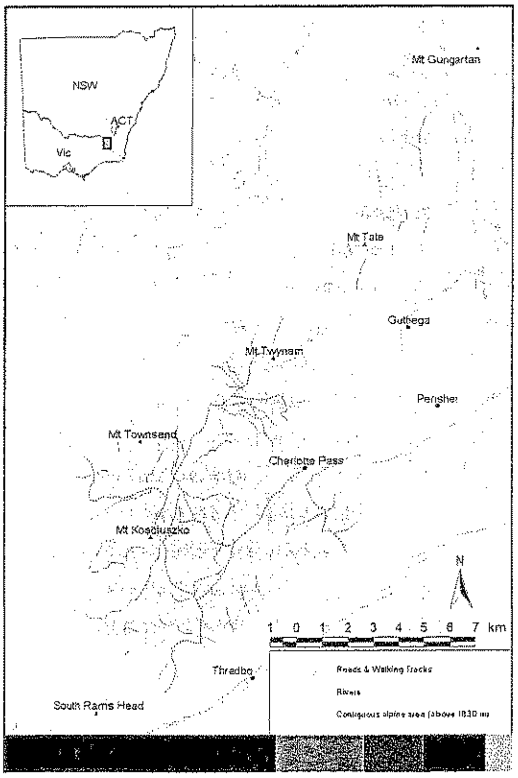


FIGURE 2. LOCATION OF THE KOSCIUSZKO ALPINE AREA.

Modified from Scherrer and Pickering 2001.



Each of the alpine regions in Australia has a distinctive and characteristic biota that individually and collectively are of considerable biological importance. A high number of endemic species occur within the main alpine regions in south-eastern Australia, including the 'living fossil' and the Mountain Pygmy Possum (*Burrymus parvu*) (Good 1992; Green and Osborne 1994). The Mt Kosciuszko alpine area flora is particularly diverse containing a unique combination of plant species, some of which are related to those of alpine areas elsewhere in the world, but many of which are indigenous, having evolved through millions of years of continental drift and changing climatic conditions (mainly increasing aridity). The indigenous species mirror the biological separateness of Australian flora (Smith 1986; Good 1992; Costin *et al.* 2000). There is a very high number of endemic and rare flora species (25%), one of the highest proportions of endemic species of any world alpine flora (21 endemic species and 33 rare species in a total of 212 native ferns and flowering plants, Smith 1986; Good 1992; Costin *et al.* 2000).

Photo: Roger Good, NSW Department of Environment and Conservation

The alpine plants and animals exhibit a range of distinctive adaptations to the extreme environmental conditions, particularly survival traits to the climatic conditions. For example, body temperature regulation by changing body colour is found in different degrees in the alpine grasshoppers, while bats, the Mountain Pygmy Possum and Echidna can lower their metabolism and body functions and enter a 'hibernation-like' state of torpor, the only mammals to do so in Australia (Green and Osborne 1994). The plants exhibit a suite of reproductive and vegetative characteristics similar to alpine plants elsewhere in the world (Pickering 1997), several specific and interesting survival mechanisms are exhibited by species such as the Alpine Marsh Marigold (*Caltha introloba*) and the Alpine Sky Lilly (*Herpilerion novae-zealandae*) (Good 1992; Good 1998a; Costin *et al.* 2000).

PREDICTIONS OF CLIMATE CHANGE FOR THE AUSTRALIAN ALPS

Early predictions of climate change and global warming and its impacts on agricultural productivity and the occurrence of bushfires relevant to the Australian environment were made in the late 1980s and 1990s by Pittock and Nix (1986), Gifford (1988 and 1991), Pearman (1988), Bouma *et al.* (1996), Whetton *et al.* (1996) and others. Gifford (1988 and 1991) reports on several models used to predict the percentage reduction or increase in temperatures and decreases in precipitation and the relevant changes in productivity.

Good (1998b) utilised these data and data from several bushfire events to assess the contribution of wildfires and planned management burns (prescribed burning) to Greenhouse gas emissions and global warming.

Early predictions on climate change and the possible impacts on snow conditions in Australian Alps were made by Slatyer (*et al.* 1984), Galloway (1988) and Busby (1988), among others. They predicted a dramatic decline in the total area receiving snow and a decline in total amount of snow. As noted above, the IPCC made early predictions on climate change and in its last assessment in 2001 presented scenarios for global warming for 1990–2100, with predicted warming from 0.7 to 2.5 °C by 2050. From this assessment, the Australian CSIRO Climate Impact Group estimated regional warming and precipitation values for Australia (CIG 1996). Under these scenarios, the 'best-case' scenario for snow is the least increase in temperature and the greatest increase in winter precipitation (see Whetton *et al.* 1996 and Hennesy *et al.* 2002 for a full discussion). For example, even a modest warming ('best-case scenario' of only +0.6 °C by 2050; Table 1) will result in a 27% reduction in the area that receives 30 days of snow per year in the Snowy Mountains and Victorian Alps (Hennesy *et al.* 2002).

Under the 'worst-case scenario' (Table 1), a reduction of 97% by 2050 is forecast in areas that have more than 60 days of snow cover a year. A reduction in snow cover of this scale will have an impact on the unique and biologically important flora and fauna of the region (Green 1998). Changes in the diversity and abundance of plants and animals may be particularly severe in Australia, because of the minimal area of true alpine habitat, and therefore the limited availability of high altitude refuge. The latter may disappear altogether under the worst-case scenario, with devastating effects on some alpine species. For example, Mt Kosciuszko is 500 to 600 m lower than the theoretical niveal zone (Slatyer *et al.* 1984), so there is no opportunity for an altitudinal shift in the alpine zone.

TABLE 1. CLIMATE CHANGE SCENARIOS FOR SNOWY MOUNTAINS AND VICTORIAN ALPS
from Hennesy *et al.* 2002

CHANGES IN:	BEST CASE 2020	BEST CASE 2050	WORST CASE 2020	WORST CASE 2050
Temperature	+0.2 °C	+0.6 °C	+1.0 °C	+2.6 °C
Precipitation	+3%	+8%	-8%	-23%
Reduction in area experiencing snow cover				
At least 1 day	9%	19%	37%	87%
At least 30 days	13%	27%	55%	93%
At least 60 days	15%	34%	60%	97%

CLIMATE CHANGE AND FAUNA

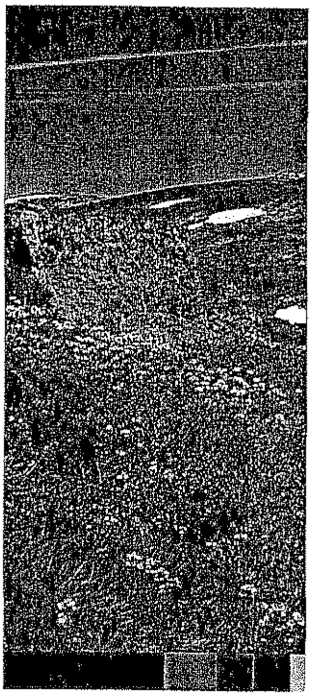


Photo: Roger Good, NSW Department of Environment and Conservation

Seasonal snow cover is recognised as a major determinant of the faunal composition of the subalpine and alpine areas of the Snowy Mountains above 1500 m (Green and Osborne 1994, 1998). Within the latitudinal band of south-eastern mainland Australia that encompasses the Snowy Mountains, i.e. the area between the coast and the inland western slopes, 25 species of mammals occur in areas of winter snow cover (Green and Osborne 1998). Most of these species are also common at low altitudes with two exceptions, the Mountain Pygmy Possum (*Burramys parvus*) and the Broad-toothed Rat (*Mastacomys fuscus*). In the Snowy Mountains, the Mountain Pygmy Possum is found only above the level of the winter snowline and the Broad-toothed Rat only above 1000 m (Green and Osborne 1994). In addition to native species, feral mammals, including foxes, hares and horses, are found in the mountains (Green and Osborne 1994). No bird species are confined to the mountains, but it is the composition of the avifauna, particularly the absence of some species found nearby at lower altitudes, which is a characteristic of the snow-country avifauna (Osborne and Green 1994). Of the 271 native species of birds occurring at sea level, only 66 species are found above 1500 m, of which only 13 are winter residents (Green and Osborne 1994).

PREDICTED IMPACTS OF CLIMATE CHANGE ON FAUNA OF THE SNOWY MOUNTAINS

Based on the pooled data from the Atlas of NSW Wildlife, a National Parks and Wildlife Service (NPWS) database, 35 species of mammals, six of which are feral, generally decline in number of records with increasing altitude (Table 2). For 20 of the species, including all the bats, the decline in number of records with altitude is likely to be unrelated to snow (Green and Osborne 1998; Group 1 in Table 2). For example, the decline in the seven species of tree dependent possum species at higher altitudes due to trees becoming smaller or absent at higher altitudes and the house mouse (*Mus musculus*) that might be excluded above the winter snowline from lack of suitable food (Green and Osborne 1998). For a second group of species (Group 2 in Table 2), exclusion or reduction in numbers above the winter snowline may be the result of competition with the more common higher altitude species that may derive a competitive advantage from the presence of snow (Dickman *et al.* 1983). The three successfully competing native species, Dusky Antechinus (*Antechinus swainsonii*), Broad-toothed Rat and Mountain Pygmy Possum are the only species that have been recorded as increasing in numbers with altitude. Finally, there is a third group of mammals (six native and four feral species; Group 3 in Table 2) where snow appears to be the major factor in the reduced numbers of records at higher altitudes (Green and Osborne 1998; Table 2).

TABLE 2. SPECIES OF MAMMALS THAT DECLINE IN NUMBERS OF RECORDS WITH INCREASING ELEVATION, THE PROBABLE REASONS FOR THE DECLINE, AND THE RELATIONSHIP OF THE DECLINE TO PRESENCE OF SNOW. (Data from the Atlas of NSW Wildlife, a NPWS database.)

DECLINING SPECIES	REASON FOR DECLINE
Group 1: Decline not snow-related in the short term	
Bats (11 species)	Reduction in flying insects
Possums (7 species)	Require trees
Koala	Absence of food tree species
House Mouse[a]	Lack of food for a specialist granivore
Group 2: Longer-term changes indirectly related to snow	
Dog[a]	Absence of large prey/competition with Fox[a]
Agile Antechinus	Competition with Dusky Antechinus[c]
Swamp Rat	Competition with Broad-toothed Rat[c]
Eastern Pygmy Possum	Competition with Mountain Pygmy Possum[c]
Spotted-tailed Quoll	Competition with Fox[a]
Group 3: Decline likely to be snow-related	
Kangaroos and Wallabies (3 species)	Mobility in snow/access to food
Wombat	Access to ground-based food
Echidna	Access to ground-based food
Bandicoot	Access to ground-based food
Cat[a]	Hunting method
Rabbit[a] Pig[a] Horse[ab]	Access to ground-based food

[a] Feral animals.

[b] Within the study area feral horses are not common below 1000 m.

[c] These species increase in numbers with increased altitude.

There is some evidence of an increasing altitudinal distribution of some mammals over the 30-year period to 1999. Wildlife Atlas records indicate a higher maximum altitudinal distribution particularly for the Red-necked Wallaby and for the four species of feral mammals (Table 3). Other evidence for increasing activity by feral mammals at higher altitudes supports this trend (Table 3). In the 1970s, Snowy Plains (1370 m) was regarded as climatically marginal for rabbits (Dunsmore 1974), yet during the summer of 1998–99 the NPWS was forced to institute a rabbit control program at Perisher Valley (1800 m) (Sanecki and Knutson 1998).

TABLE 3. MEAN ALTITUDE (M) OF THE THREE HIGHEST ALTITUDINAL RECORDS FOR MAMMALS IN THE ATLAS OF NSW WILDLIFE, A NPWS DATABASE, TOGETHER WITH OTHER SOURCES OF EVIDENCE FOR AN ALTITUDINAL SHIFT (SAMPLE SIZE IN PARENTHESIS).

DECADE	1970–1979	1980–1989	1990–1999	OTHER EVIDENCE
Number of records ≥1500 m	586	470	597	
Grey Kangaroo	1500(10)	1400(39)	1700(28)	
Swamp Wallaby	1233(3)	1267(16)	1700(32)	1, 2, 4
Red-necked Wallaby	1533(17)	1333(41)	1567(17)	
Cat[a]	1267(3)		1600(3)	1, 3
Horse[a]	1233(3)	1000(2)	1900(17)	1, 2
Pig[a]	1400(22)		1533(12)	1, 2
Rabbit[a]	1670(17)	1300(7)	1800(26)	1, 3, 5

[a] Feral animals. 1. Anecdotal records by local long-term residents. 2. Indirect evidence (dung or area of animal digging/vegetation disturbance). 3. Increased presence in predator scats. 4. Occurrence of tracks on regular snow transects. 5. Rabbit control required for first time at ski resort at 1800 m.

Among the macropods there is little evidence of altitudinal movements of Red-necked Wallaby (*Macropus rufogriseus*) and Grey Kangaroo (*M. giganteus*), Table 3. The few records of solitary individuals of these species at higher altitudes may be males dispersing or seeking mates, rather than grazing animals. For example, the Grey Kangaroo is a social species (Bennett 1995) but the high altitude records were all of individual animals. The situation with the Swamp Wallaby (*Wallabia bicolor*) is, however, different. While the other two species of macropods are grazers, the Swamp Wallaby is a browser and therefore seasonal snow cover will not severely reduce its access to food. Despite several years of extensive winter fauna surveys (Osborne *et al.* 1978) and further winter work through 1979 (Green and Osborne 1981), no tracks of Swamp Wallabies were observed in winter along the main access trail for these studies, whereas in recent winters (Green unpublished) Swamp Wallaby tracks have been observed on this trail on almost all weekly winter visits.

Additional support for the impact of snow cover on animal numbers comes from the response of species to years of shallow snow cover. In these years there is evidence for a reduction in populations of the three species of native mammal that increased in number of records with altitude. Populations of Dusky Antechinus (Green 1988) and Broad-toothed Rat (Green unpublished) declined in poor snow depth years, while in the Mountain Pygmy Possum population there was also a lowered recruitment (L. Broome pers. comm. 2000). The latter species depends upon snow cover for stable, low temperatures for torpor ('hibernation') (Walter and Broome 1998), whereas the two former species are active under the snow throughout winter (Green 1988) and are therefore more prone to predation by foxes (Green and Osborne 1981). Using a bioclimatic analysis and prediction system to examine present and predicted future animal distribution, Brereton *et al.* (1995) suggested a potential decrease in areas of suitable habitat for Broad-toothed Rats with global warming. Already the Broad-toothed Rat population is under pressure at Barrington Tops, 600 km north of the Snowy Mountains. The population studied there in the 1980s (Dickman and McKechnie 1985) was in serious decline by 1999 in the face of invasion by Swamp Rats (*Rattus lutreolus*) (Green 2000).

A similar process may occur in the Snowy Mountains with a reduction in snow cover. This is likely to reduce the competitive advantage of Broad-toothed Rats and may act synergistically with increased incursions of feral animals, particularly foxes, whose hunting is made easier by a thin snow cover (Halpin and Bissonette 1988).

In addition to the apparent changes in the distribution of some mammal species associated with changes in snow cover, migratory birds may also be affected. Among the migratory birds, the only observable change in timing of arrival, for those species for which there was a sufficient sample size, was one of an earlier arrival in the 1980s and/or 1990s compared to the 1970s. For the 11 bird species for which there were sufficient data (Table 4), the earliest arrivals were recorded in the 1990s for five species (four of these occurring in an earlier month) and the 1980s (generally differing by only a few days from the earliest date for the 1990s) in four. For two species – Grey Fantail (*Rhipidura fuliginosa*) and Silvereye (*Zosterops lateralis*) – there was no difference in arrival times across the three decades. While there has been a greater search effort through the 1990s by one of the authors (Ken Green), the search effort for the period 1971–1980 was boosted by a large fauna survey (CSIRO unpublished) and two studies of the avifauna (Longmore 1973; Gall and Longmore 1978). While the earlier arrival records detected in the 1990s might be ascribed to a greater search effort (152 records entered compared with 124 from August to October in the 1970s), the same explanation cannot be used for the arrival records in the 1980s. There was only half the number of records in the same period in the 1980s, and yet six of the nine species that varied in time of immigration were recorded earlier in the 1980s than the 1970s.

TABLE 4. TIME OF FIRST ARRIVAL OF MIGRATORY BIRDS AT OR ABOVE 1500 M AFTER WINTER TO THE END OF 1997. The earliest record for each decade is given and all other dates (maximum one per year) earlier than the earliest record in 1970–1979. Source: The NSW Wildlife Atlas, a NPWS database.

SPECIES	1970–1979	1980–1989	1990–1999
Number of records from August to October	124	65	152
Crescent Honeyeater	19 Oct	26 Oct	12 Sep, 17 Sep, 30 Sep
Olive Whistler	15 Sep	22 Sep	21 Aug
Flame Robin	2 Sep	17 Aug	21 Aug
Grey Fantail	19 Oct	26 Oct	23 Oct
Striated Pardalote	16 Sep	24 Aug, 15 Sep	30 Aug
Yellow-faced Honeyeater	18 Sep	26 Oct	12 Sep
Australian Kestrel	5 Nov	20 Sep, 26 Oct	30 Aug, 8 Sep, 23 Sep, 28 Sep
Fantail Cuckoo	25 Nov	21 Sep, 20 Oct	23 Oct
Red Wattlebird	14 Oct	13 Sep, 20 Sep	20 Sep
Richards Pipit	16 Sep	5 Sep	28 Aug
Silvereye	19 Oct	18 Oct, 20 Oct	22 Oct, 23 Oct


Photo: Roger Good, NSW Department of Environment and Conservation

The arrival responses of migratory birds are variable and may be dependent upon their foraging techniques. The species recorded as arriving earlier include three species of honeyeaters that are dependent on the flowering of shrubs (see also Osborne and Green 1992). The Australian Kestrel (*Falco cenchroides*) is largely dependent upon snow-free ground for foraging. The ground-feeding Flame Robin (*Petroica phoenicea*) and Richards Pipit (*Anthus novaeseelandiae*) arrive early in spring and feed on insects immobilised on the surface of the snow. The earlier presence of these insects is associated with, and is a response to, sufficient warmth at their point of origin for metamorphosis and flight. The Olive Whistlers (*Pachycephala olivacea*) and Striated Pardalote (*Pardalotus striatus*) glean active insects off shrubs and trees. Movements of Fantail Cuckoos (*Cuculus flabelliformis*) must be attuned to the breeding timetable of their hosts. The two species that appear not to arrive earlier despite changes in snow cover over the three decades are the Grey Fantail, which catches insects in flight, and the Silvereye, which undertakes long migratory flights, the timing of which may be independent of local events elsewhere.

There are obvious statistical problems with the data sets in examining changes in the altitudinal distribution of mammals and the time of first arrival of migratory bird species. These include large variations in sample size, sampling effort and sampling time. The use of the numbers of records of mammals ≥1500 m entered per decade and the number of records in the three-month period of influx of migratory birds as indices of climate change, while not perfect, do suggest that there is no great bias as a result of differential search effort. This report also does not state unequivocally, and should not be taken as inferring, that all of the changes in animal distribution (both spatially and temporally) are a direct result of observed changes in snow cover. For many of the changes there are possible and plausible alternative explanations. Changing land use in the Alps is, however, not one of those. During the course of this study period there have been no major changes in land use patterns at the higher altitudes to explain differences in animal distribution. The study area was declared a State Park in 1944 and summer grazing was withdrawn from the alpine area of the Main Range in 1946 and banned above 1360 m in 1958 (Good 1992). Any increased use by humans has largely been confined to the few ski resorts and access routes. However, the changes are those that might reasonably be hypothesised to result from reduced snow cover, and the observed change in snow cover is the only explanation that can account for all. Therefore, the patterns documented here could be a model for likely changes to animal distribution, and hence biodiversity, with predicted changes in snow cover. The data here is consistent with worldwide patterns for changes in spring events with climate change (Parmesan and Yohe 2003).

Further global warming resulting in a declining snow cover may therefore have a major impact upon the faunal composition of the alpine/subalpine areas of the Snowy Mountains, allowing greater access by feral animals and reducing the competitive advantage of the higher altitude species. As such, while possibly increasing the numbers of species in the Snowy Mountains, this process may reduce the regional biodiversity by the loss or serious reduction of populations of endemic species. Such a loss would be very significant at a local, regional, national and international scientific level.

CLIMATE CHANGE AND FLORA

The current climate change scenarios outlined in Table 1 will predictably affect the abundance and distribution of plants species in the alpine and subalpine regions of Australia. A detailed knowledge of the ecology of individual Australian alpine plant species is in most cases minimal, so it is only feasible to postulate about the impacts of climate change on the main plant communities and the few species for which detailed ecological information is available (Costin 1954, 1957, 1958, 1989; Costin *et al.* 1959, 1969, 2000; Carr and Turner 1959; Bryant 1971, 1971b; Edwards 1977; Keane *et al.* 1979; Mallen 1986; Mallen-Cooper 1990; Good 1992; Atkin and Collier 1992; Pickering 1993; Pickering 1997; Kirkpatrick and Bridle 1998, 1999; Good 1998a; Venn 2001; Pickering and Armstrong 2003). In this report we hypothesise about potential changes in the pattern of distribution and association of the 11 natural vegetation communities recognised by Costin (1954, 1957; Costin *et al.* 2000) in the largest contiguous alpine region in Australia, the Kosciuszko alpine area.

Climate change may affect the distribution of the plant communities directly through changes in temperature and precipitation, and indirectly through the depth and distribution of snow cover. Climate change may also have indirect effects through resulting longer growing seasons, changes in prevailing soil moisture and changes in vegetative competition (Good 1998a; Pickering 1998). The effects of climate change on the abiotic factors that are thought to determine the distribution of alpine plant communities will be further examined for the next three to five decades. For example, predicted climate change will alter a number of abiotic factors (e.g. duration of snow cover, the period of freezing/lethal temperatures and soil moisture regimes), variables that have been associated with the occurrence and distribution of several alpine plant communities (Costin 1954, 1957; Carr and Turner 1959; Ashton and Williams 1989; Kirkpatrick and Bridle 1998, 1999; Atkin and Collier 1992; Costin *et al.* 2000; Venn 2001). Changes in these factors due to human disturbance in the past (grazing, trampling) have led to some minor changes in the distribution of some communities. For example, as a result of cattle grazing small areas of tall alpine herbfield have been replaced by 'erosion feldmark'(Good 1972, 1992). This provides support for the link between abiotic factors and vegetation community distributions (Costin 1954; Wimbush and Costin 1979; Ashton and Williams 1989; Clarke and Martin 1999; Costin *et al.* 2000; Johnston and Pickering 2001).

PREDICTED IMPACTS OF CLIMATE CHANGE ON FLORA OF THE KOSCIUSZKO ALPINE REGION

Climate change will affect plant communities in the Kosciuszko alpine study area, but the extent of change and the vegetation responses exhibited will be influenced by the rate and degree of temperature and precipitation change. The over-arching pattern of change is likely to involve alterations in the distribution and species composition of the existing communities, primarily due to fundamental changes in the climatic factors that define their present distributions (Table 5).

TABLE 5. SUMMARY OF POTENTIAL CLIMATE CHANGE IMPACTS IN THE PLANT COMMUNITIES OF THE KOSCIUSZKO ALPINE AREAS

PLANT COMMUNITY	CURRENT CLIMATIC RANGE	PREDICTED CHANGES IN THE DISTRIBUTION OF THE PLANT COMMUNITY AS A RESULT OF CLIMATE CHANGE
Short alpine herbfield	Alpine	The reduction in late-lying snow patches may result in colonisation of some remnant areas of short alpine herbfield by tall alpine herbfield species. For smaller snow patches there could be complete loss of community, while in larger patches there will be a reduction in area occupied by this community.
Feldmark		
1. Windswept feldmark	Alpine	Potential increase in area of windswept feldmark if reduced snow cover in winter results in greater areas exposed to high winds. This could result in areas of stony erosion pavements being colonised by windswept feldmark.
2. Snowpatch feldmark	Alpine	Reduced area as windswept feldmark species will colonise the area in response to the reduction in the area of late-lying snow patches.
Tall alpine herbfield 1. *Brachyscome-Austrodanthonia* alliance	Alpine	Unlikely to be greatly affected while snow cover remains adequate, as this specialised community is restricted to areas that are subject to relatively rapid natural erosion.
2. *Celmisia-Poa* alliance	Alpine	Likely to increase in area while adequate (3-4 months) snow cover continues to occur. The community potentially could expand into areas currently occupied by mesic communities. They may be affected by increased herbivory, including grazing by feral animals, if rising temperatures cause changes in dominance of species within the community. Some areas currently with tall alpine herbfield may be colonised by shrubs.
Sod tussock grassland	Alpine Subalpine	Warmer nights, drier soils and greater soil aeration due to predicted climate change could result in increased growth of herbs and shrubs, resulting in the community becoming a heathland or grassy shrubland.
Groundwater Communities		
1. Fen	Alpine Subalpine Montane	Decreased precipitation and increased temperature may result in decreased run-off into fens leading to changes in competitive advantage of fen species, potentially resulting in replacement by sod tussock grassland species in drier sites.
2. Valley bog	Alpine Subalpine Montane	A reduction in soil moisture associated with climate change is likely to promote the replacement of valley bogs by sod tussock grassland species. If the reduction in snow cover is to the level experienced by subalpine vegetation, then valley bogs could be colonised by tussock grassland and heath communities.

PLANT COMMUNITY	CURRENT CLIMATIC RANGE	PREDICTED CHANGES IN THE DISTRIBUTION OF THE PLANT COMMUNITY AS A RESULT OF CLIMATE CHANGE
3. Raised bog	Alpine Subalpine Montane	Warmer drier conditions are likely to lead to the colonisations of raised bog areas by snowgrasses (*Poa* sps.) and other tall alpine herbfield species. If snow cover declines further, then it is possible that valley bog species may colonise wetter areas and shrubs may colonise drier areas.
Heath		
1. Epacris-Kunzea alliance	Alpine Subalpine Montane	Heath may colonise other communities, particularly replacing fen and bog species if conditions become warmer and drier.
2. *Oxylobium-Podocarpus* alliance	Alpine Subalpine Montane	Many of these shrub species may invade other communities such as tall alpine herbfields and sod tussock grasslands communities. However, this heath may itself be colonised by other subalpine species if snow cover declines to levels currently experienced in the subalpine zone.

It is predicted that some native species will benefit from climate change by colonising areas from which other species or communities have been lost as a result of changed environmental conditions. Shrub species are particularly likely to expand in range, along with some herbs and grasses of the tall alpine herbfield. The Kosciuszko endemic, for example Ovate Phebalium (*Phebalium ovatifolium*), may have the opportunity to increase in population number and extent of occurrence. Even some species from the restricted plant communities that are expected to decline may benefit, at least in the short to medium term. For example, White Purslane (*Neopaxia australasica*) and Silver Ewartia (*Ewartia nubigena*), species that are found in the short alpine herbfield and feldmark respectively, can colonise bare areas and so may increase in abundance with climate change. These species have increased in cover following previous disturbances, and often colonise areas associated with human disturbance (Edwards 1977; Keane 1977; Wimbush and Costin 1979; Good 1992).

The extent of changes in the distribution of plant species and communities will, predictably, be indirectly influenced by reduced snow cover. This is expected to cause an increase in the diurnal freezing and thawing of the alpine humus soils, with increased 'frost-heave' action in areas with exposed soils. A flow-on effect will be a decrease in organic matter decomposition rates and a resulting depletion of soil nutrients within the nutrient cycling regime of the alpine humus soils. This could greatly affect high biomass-producing plant communities, such as tall alpine herbfield and heath, leading to a reduction in their area of distribution. The alpine humus soils are low in nutrients and are only able to support high biomass production through the rapid growth, biomass accumulation, decomposition, and nutrient release to the growing plants. An important component of the soil organic matter decomposition is the soil micro-fauna and invertebrate populations, which will similarly be reduced in number and activity if soil temperatures are reduced in the autumn and spring and increased in summer.

Under past and existing climatic conditions, alpine vegetation is placed under moisture stress through the winter months (physiological drought) and for short but regular periods during summer (low soil moisture availability as a result of short seasonal rainfall deficits). An increase in mean summer temperature and decreased rainfall may exacerbate/extend the length of time of moisture stress, advantaging those species that are able to adapt to the moisture deficits and higher temperatures. Part of this adaptation will be the capacity of species to tolerate higher levels of solar radiation, particularly the increasing levels of ultraviolet light. Increased levels of ultraviolet light have already been shown to have a detrimental impact on the Corroboree Frog (*Pseudophryne corroboree*) (Green unpublished data).

If the scenario of reduced snowfall and snow cover but increased precipitation as rainfall eventuates, runoff may increase considerably with an increasing potential for soil and vegetation degradation. This may also influence the occurrence and distribution of plant communities, although most modelling predictions to date suggest a reduced total precipitation over southern Australia (Nathan *et al.* 1989).

RESPONSE OF SPECIFIC INDICATOR PLANT SPECIES

(i) Buttercups (*Ranunculus* species). During the grazing era, buttercups (*Ranunculus*) were noted as hybridising more than any other Family or Genus. Extensive hybridisation was attributed to grazing modifying the environment, resulting in favourable habitats for hybrids to grow and flower (Briggs 1986; Pickering 1993). With the cessation of grazing, hybrids have become less common, and intermediate habitats between those favoured by each species have declined (Briggs 1986; Pickering 1993). Any increase in hybridisation over the next 10 to 15 years could be a response to the impact of temperature increases and reduced periods of snow cover (T. Armstrong, pers. com. Landcare, NZ).

Of particular interest is the Anemone Buttercup (*Ranunculus anemoneues*) that survived grazing in isolated refuge sites. Only in the past 10 years has the plant population increased to any degree (Rath 1999). Importantly, the occurrences of new populations of plants have been in sites (snowpatch and dry sites) very different to that of all the refuge site conditions. If the drier sites are the type location for *R. anemoneus*, a change in temperature could further benefit the species with further increases in species occurrence, although at this time the moist to wet outwash areas in tall alpine herbfields is considered to be the type habitat.

(ii) The Alpine Marsh-marigold (*Caltha introloba*) would appear to potentially be one of the first indicators of changes in mean temperatures, as the species has adapted to the short growing season by the initiation of flowering under a snow cover (Wardlaw 1998). As soon as light intensity and penetration of the melting snow occurs, the development of the flower primordia is reinitiated and a large proportion of the plant population has flowers ready for pollination immediately as the snow cover disappears.

Predicted changes in snow depth and distribution will have some impact on the flowering process, with a possible reduction in total flower numbers and/or influence on seed set and seed viability (Wardlaw 1998).

(iii) The Sky Lily (Herpolerion novae-zealandae), another species with very specialised habitat requirements and low tolerances to changes in habitat conditions, will predictably be an early indicator of temperature changes. Flowering is initiated by a very narrow temperature regime and the flowers only persist for three to four hours while this temperature and associated humidity regime persists (Good 1992, 1998a; Costin *et al.* 2000).

An increase in mean temperature and a reduction in micro-habitat humidity conditions may result in a very reduced flowering and/or non-viability of any seed.

(iv) The Mountain Plum Pine (*Podocarpus lawrencii*) is the only podocarp in the Alps and is the longest lived plant of the alpine zone. Seed set is very closely linked to prevailing temperature conditions and, like the other species, changes in temperature may influence the effectiveness and viability of seed set.

The species has a growth habit that utilises large boulders and rocks for support and to provide micro-habitat temperature conditions benefiting its growth and survival (Costin *et al.* 2000). An increase in mean temperature could be indicated by new recruits of this species growing as free-standing shrubs not requiring the warm conditions provided by the rocks and boulders.

RESPONSE OF SPECIFIC INDICATOR PLANT COMMUNITIES

(i) Groundwater communities (bogs and fens) were destroyed or highly degraded as functional ecosystems during 150 years of domestic stock grazing (Good 1992, 1999; Costin *et al.* 2000). Less than 50% of the original bog and fen areas remain in the Alps, and of this area only approximately 30% is considered fully functional as groundwater communities. As with many other communities and species that persisted through the grazing era, the surviving functional fens and bogs are small in size and in marginal sites. A number have been rehabilitated to a functional capacity but their retention as functional systems will require careful management (Good 1999). An increase in mean ambient temperatures potentially could result in further loss of some of these rehabilitated bogs and fens as a result of changes in snowfall/snowmelt regimes and groundwater movement. The fen and bog community could be replaced by wet heath or sod tussock grassland (Pickering and Armstrong 2003).

(ii) Sod Tussock Grasslands occur in sites of shallow soils or poor surface drainage and fill a niche between the tall alpine herbfield on drier soils and the permanently moist to wet groundwater communities. With increased temperatures, the sod tussock grasslands could be colonised by tall alpine herbfield species and contribute to an increased area of the most extensive community currently occurring in the alpine zone: the tall alpine herbfield (Good 1998a). The sod tussock grassland on the other hand could colonise other sites as noted above.

(iii) Short Alpine Herbfield occurs in cold wet sites immediately below the bottom edge of snowpatches where cold snowmelt flows provide for permanently saturated soils and continuous cold runoff flows over the cold-water tolerant species. The area of short alpine herbfield was greatly reduced under the long-term pressure of domestic stock grazing and has never recovered to the full extent of its identifiable original area.

Over the past 10 years the number of species in the short alpine herbfield areas has declined and some species have been lost altogether from several sites (Good, unpublished data). Several previously large short alpine herbfield sites have been colonised by tall alpine herbfield, indicating that the longevity of snowpatches has already declined possibly due to changes in snowpatch distribution, depth or area.

Very minor increases in mean temperatures predictably lead to an increase in the rate of loss of the short alpine herbfield to the extent that short alpine herbfield could disappear as a unique functioning plant community.

(iv) Windswept Feldmark is the plant community occupying the smallest area in the Alps – less than one percent of the alpine zone (Good 1992; Costin *et al* 2000). The feldmark community occurs in the most exposed windswept scols of the main range of the Snowy Mountains, where the prevailing strong winds continually blow away any snow cover. The plant species in the community are well adapted to the continual wind ablation and extreme exposure to frosts in winter and high radiation levels in summer. Increases in mean temperature may not directly affect the community but changes in snow cover and rainfall may affect the community.

(v) The treeline is defined by the altitudinal level where the energy resources available limits the growth of trees – around the world this altitudinal position is at the 10 °C mean maximum summer temperature level (Slatyer 1976; 1978; 1989). Increases in global warming will raise this altitudinal level and increase the potential for the treeline to rise. The response of the snowgums (*Eucalyptus niphophila*) will be very slow due to the extreme weather conditions that prevail against recruitment at the treeline, hence the upward altitudinal movement of the treeline will not be an early indicator of climate change/global warming. Identifiable changes in the treeline as a response would not be expected for up to 100 years or more.

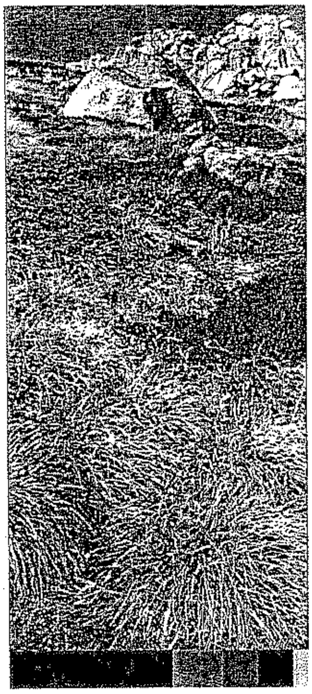


Photo: Roger Good, NSW Department of Environment and Conservation

POTENTIAL IMPACT OF CLIMATE CHANGE ON OTHER ALPINE AND SUBALPINE AREAS IN AUSTRALIA

Plant communities similar or identical to those occupying the main alpine region of Kosciuszko National Park, as well as other plant communities, occur in the alpine and subalpine regions of Tasmania and Victoria (Costin 1954; McDougall 1982; Kirkpatrick 1989; Kirkpatrick and Bridle 1998, 1999; Costin *et al.* 2000). Climatic conditions appear to be the primary factors associated with distribution of the different vegetation types in all of these regions (Kirkpatrick and Bridle 1998). Therefore, it is possible that climate change could alter the pattern and distribution of plant communities in all alpine areas in Australia and may involve reductions in long- lasting snow-patches and other factors determining the distribution of some specialised plant communities (Ashton and Williams 1989; Atkin and Collier 1992; Kirkpatrick and Bridle 1998, 1999; Venn 2001). However, alpine regions in Australia vary in total area, altitudinal range, current patterns of snow cover, composition of communities and existing intensities and types of human impacts (McDougall 1982; Ashton and Williams 1989; Costin 1989; Kirkpatrick 1989, 1997; Good 1992; Kirkpatrick and Bridle 1998, 1999; Costin *et al.* 2000; Venn 2001), so the overall patterns may be very different in each region. However, it is clear that reductions in the duration of snow cover are likely to affect all of the alpine regions in Australia.

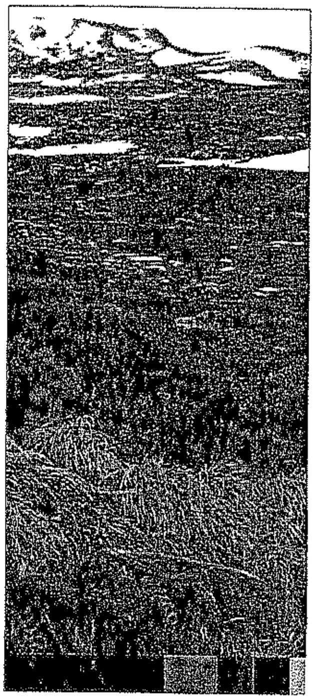


Photo: Colin Totterdell

LIMITATIONS IMPOSED BY CURRENT UNDERSTANDING OF THE ALPINE ENVIRONMENT

This study has intentionally examined the more direct responses of vegetation communities to primary climatic factors for two reasons. Firstly, it appears that climate is a crucial factor determining the distribution of the communities, with edaphic, topographic and biotic factors also important, but often broadly correlated with climatic variables (Costin 1954; Atkin and Collier 1992; Kirkpatrick and Bridle 1998; Körner 1999). Summer temperatures, rainfall, duration of snow cover and low temperatures in winter have all been proposed as defining factors for alpine communities in Kosciuszko National Park and other alpine areas (Costin 1954; Carr and Turner 1959; Wimbush and Costin 1979; Ashton and Williams 1989; Atkin and Collier 1992; Good 1992; Kirkpatrick and Bridle, 1998; Clarke and Martin 1999; Venn 2001). Therefore, changes in these variables are likely to alter the ecology of the Kosciuszko alpine ecosystem.

The second reason for the focus on physical, and specifically climatic factors, rather than biotic factors, is that information about biotic interactions at the community level is limited for the Australian Alps. For example, the composition and location of different soil biota has been proposed as an important factor affecting vegetation changes in alpine communities in response to climate change. Due to the limited information available about the role of soil biota in the ecosystem, it is difficult to speculate about the possible effects of climatically induced changes on the soil biota

Although a little more is known about the role of insects and other invertebrate animals in the alpine zone, particularly with respect to herbivory and pollination (Carr and Turner 1959; Inouye and Pyke 1988; Ashton and Williams 1989; Wilson 1994; Green and Osborne 1994; Pickering 1997; Stock 1999; Stock and Pickering 2002), the extent of the information is still inadequate for more detailed predictions. Therefore, it is clear that a better understanding of the potential impacts of climate change on this important and fragile ecosystem requires active research into the current ecology of this system. The research initiated in this project, will address the soil fauna and the soil surface invertebrates and the impacts climate change may have on species composition and distribution, as well as the activity levels of the fauna under different soil temperature regimes, vegetative cover and plant species composition.

CLIMATE CHANGE, TOURISM AND ASSOCIATED IMPACTS ON THE NATIVE BIOTA

In the Australian Alps, tourism and recreation is one of the largest land uses and greatly contributes to the regional economic base. However, tourism and recreation also has considerable adverse environmental impacts and is likely to interact with climate change, producing synergistic effects/impacts on the biota greater than that of either alone (Buckley *et al.* 2000; Scherrer and Pickering 2001). It has been recognised that research must not only focus on climate change impacts, but also recognise and examine interactions of predicted global warming and other factors that may negatively affect biota (Root *et al.* 2003).

TOURISM IN AUSTRALIAN SNOW COUNTRY

Although Australia is large in area and its population heavily urbanised, the area of 'snow-country' is disproportionately very small. The largest cities are close to the mountains and therefore the snow country is accessible to much of the population. There are annually more than 1.5 million visitors to the Australian Alps from a population of approximately 20 million (DNRE 2002; Mules 2002; Worboys and Pickering 2002; Pickering unpublished data). Ski tourism is now one of the principal economic activities in the Australian snow country, having outstripped other industries such as grazing and forestry (DNRE 2002; Young 2002). The ski industry contributes around $268m in Victoria and $300m in NSW to the local and national economy (DNRE 2002; Mules 2002). But tourism in the Australian Alps is more than just ski tourism/recreation. Until the mid-1980s, most visitors to the Australian Alps arrived during the winter months, with around 80% involved in skiing (Good 1992; Mackay 1983; Mackay and Alcock 1987; Virtanen 1993). More recently, however, the growth in winter activities has levelled off through saturation of the limited skiable snowfields and resort facilities, as well as the popularity of other activities (DNRE 2002). A few other winter activities such as snowboarding and self-sufficient winter wilderness touring have increased (König 1998a and 1998b). In addition, there has been a large increase in summer visitation rates, with more visitors coming in the non-snow period (DNRE 2002; Mules 2001). Most summer visitors are engaged in bushwalking/hiking, car touring/sightseeing, nature appreciation, camping, fishing, four wheel driving, mountain bike riding, and horse riding (Mules 2002; Worboys and Pickering 2002a). These changes are broadening the environmental impacts of summer recreational activities (Buckley *et al.* 2000).

INTERACTION BETWEEN CLIMATE CHANGE AND TOURISM

Current climate prediction models indicate a substantial reduction in the total area covered by snow and a substantial reduction in the duration of snow cover in many areas, including the ski resorts (Whetton 1998; DNRE 2002; Hennessy *et al.* 2000). Such reductions in snow cover and duration are likely to have a large impact on winter tourism in the Australian Alps. Poor snow seasons in the past have resulted in dramatic declines in visitation and hence incomes for resorts and associated commercial activities (Keage, 1990; König 1998a and 1998b; DNRE 2002). Surveys of people currently visiting resorts to ski or snowboard indicate that if snow cover declines, the majority would either give up skiing, ski overseas, or ski in Australia less often (König 1998b and 1998b). Overseas, similar issues regarding reduced snow cover and its impact on tourism, particularly at ski resorts, have been highlighted by König and Abegg (1997) and Elsasser *et al.* (2000).

The warming of the spring and autumn weather conditions, however, will provide a wider window of opportunity for non-snow-based tourism and recreation with a consequent increase in the non-winter visitor numbers and impact on the vegetation, soils and native animal populations (Buckley *et al.* 2000; DNRE 2002; Worboys and Pickering 2002a). Visitor activities are also likely to change as ski-resorts diversify and focus more on activities such as conferences, education and health tourism, as well as on adventure sports (Keage 1990; Koning 1998; Buckley *et al.* 2002; DNRE 2002; Worboys and Pickering 2002a). These changes in tourism activities, timing and intensity, together with climate change, will also change the types and intensity of tourism impacts on the biota.

For example, some of the direct impacts of tourism in the Australian Alps include compaction of soil, erosion, trampling of vegetation, urine and faecal contamination of waterways, disturbance to wildlife, noise pollution, and increased feral animal activity (Edwards 1977; Keane *et al.* 1979; Hardie 1993; Virtanen 1993; Good and Grenier 1994; Good 1995; CDT 1997; Parr Smith and Polley 1998; Arkle 2000; Buckley *et al.* 2000; Scherrer and Pickering 2001; Worboys and Pickering 2002b; Pickering *et al.* 2003a). The infrastructure provided for some tourism and recreational activities, including walking tracks and huts, are contributing to impacts such as compaction of soil, clearing of vegetation, the introduction of alien plants, leaching of nutrients into adjacent areas, and visual impacts (Virtanen 1993; Good and Grenier 1994; Johnston and Pickering 2001; Pickering *et al.* 2003a, 2003b).

To highlight the potential negative effects that are predicted to arise from climate change together with the impacts from increasing visitor numbers and recreational activities, two significant tourism-impact scenarios have been examined. First, we examine the impact of increasing levels of snow manipulation by ski-resorts operators to ameliorate the impact of poor snow years that will result from global warming. Second, we examine the impact of predicted climate change on the abundance and diversity of weeds in the Australian Alps.

SNOW MANIPULATION AS A RESPONSE TO REDUCED SNOW COVER AND ITS IMPACTS ON THE BIOTA

Snow manipulation techniques and other tourism activities and infrastructure have, and will continue to have, important direct and indirect negative effects on the natural environment, particularly as they predominately occur in high conservation environments such as alpine national parks (Buckley *et al.* 2000; Pickering and Hill 2003).

Already, as a response to the less consistent snow conditions which are the result of the slight increases in mean temperatures (Green pers com), there has been strong competition between resorts for a share of the tourism market based on the quality of the snow cover they provide (Keage 1990; PBPL 1997; König 1998a and 1998b; DNRE 2002). This has resulted in the expenditure of considerable effort and money on improving the quality and extent of snow cover at resorts (PBPL 1997; NPWS 1998a,b; DNRE 2002; Pickering and Hill 2003). With decreasing snow cover and increasing temperatures predicted, there is likely to be even further reliance on snow manipulation techniques to maintain an adequate snow cover by resorts in Australia and overseas (König and Abegg 1997; Elsasser *et al.* 2000; DNRE 2002; Hennesy *et al.* 2002). Predictions for climatic change at resorts in the Australian Alps indicate that there will be dramatic changes in the duration and depth of natural snow cover (Whetton 2002).

Traditionally resorts have improved snow conditions by slope grooming during the summer and snow grooming and snow harvesting in winter (Pickering and Hill 2003). Slope grooming in summer alters the vegetation, soils and topography on major ski runs to improve the quality of the snow pack in winter (Keane *et al.* 1980; Graham-Higgs and Associates 1993; a,b,c, 1994). In addition, resorts groom much of the snow on downhill skiable areas to ensure a durable and even cover (Keane *et al.* 1980). Snow harvesting from snow patches (snowdrifts) away from the ski slopes also contributes to snow depth changes and the longevity of the source snowpatches. This contributes to changes in environmental conditions for the native biota under the source snowpatch and at the deposition sites. More recently, snow fences and other artificial structures have been used to reduce wind scour and accumulate snow in specified areas (König 1998b; PBPL 1997).

The introduction of artificial snow-making technology to nearly all large-scale downhill skiing resorts in Australia in the 1980s accelerated the impacts of changed snow conditions (Grenier 1992; Pickering and Hill 2003). Snow-making involves delivering pressurised water onto ski slopes during periods of below freezing temperatures, often with the addition of protein nucleators to promote ice crystal formation (O'Brien and Shepherd 1985; Brown 1997).

There has been little research to date in Australia on the impacts of snow manipulation on sensitive subalpine and alpine communities and threatened species (Pickering and Hill 2003), even though most ski-resorts are next to, or within, the National Parks. Research overseas, however, indicates that snow manipulation results in a cascade of changes and impacts that can negatively affect plant communities, fauna habitat, individual species of flora and fauna, soils and soil biota, hydrological regimes, and contaminate ski areas with pathogens and weed propagules (Balderin 1983; Kattelmann 1985; Watson 1985; Mosimann 1985; Tsuyuzaki 1990, 1991; Tsuyuzaki and Hokkaido 1994; Urbanska *et al.* 1999; Ruth-Balaganskaya 2000; Pickering and Hill 2003).

IMPACTS OF SKI-SLOPE DEVELOPMENT

Initially, impacts arise from direct physical alteration of the terrain during ski-slope development (clearing vegetation, removing rocks, installing drainage systems, importation of soil, seeding areas etc) undertaken in the summer months. Environmental Impacts Statements (EISs) prepared for development works within Australian ski-resorts list a series of direct impacts of slope development and summer slope maintenance. These include changes in natural appearance, soil compaction, soil erosion, and changes in plant species composition, hydrology (groundwater and surface water regimes) and flooding. The most severe impacts are found on slopes that have been subjected to the most intensive reshaping and smoothing (slope grooming) (Keane *et al.* 1980; Good and Grenier 1994; Good 1995).

Overseas studies also report a number of secondary impacts resulting from ski-slope development and use. For example, the removal of natural vegetation decreases the water holding capacity of soils and increases runoff during rain events, resulting in generally lower soil moisture. These changes are reported to have dramatically changed the occurrence and distribution of vegetation communities on the ski-slopes, surrounding areas and associated valley floors, leading to major changes in plant community composition (Mosimann 1985; Watson 1985). Other secondary impacts include changes in soil biota including mycorrhiza, increased soil temperatures in summer, decreased temperatures in spring and autumn, and drier conditions in summer (Mosimann 1985; Watson 1985). Even minimal slope grooming, involving trimming and removing trees, has been shown to affect the ecology of the understorey species in subalpine woodland areas. For example, decreasing the tree canopy increases the amount of light reaching the understorey, which in turn influences the composition of plant communities (Keane *et al.* 1980; Tappeiner and Cernusca 1989).

In the Australian Alps, ski-slopes have been cleared of snowgums except for small isolated islands of trees retained for habitat maintenance and to assist snow accumulation. Observations of these remnant islands of trees indicate that they are slowly declining as the trees succumb to changes in the surface and groundwater regimes and changes in the snow cover profile (Good, author obs.).

Photo: Roger Good, NSW Department of Environment and Conservation

IMPACTS OF SNOW-GROOMING

The impacts of snow-grooming machines have been extensively studied in overseas subalpine and alpine areas, and results indicate that snow-grooming causes significant degradation in the vegetation and soils of the ski-slopes (Fahey and Wardle 1998). The impacts occur as (i), impacts that are the direct consequence of physical damage by vehicles on the vegetation and soils; and (ii), impacts as a result of snow compaction and redistribution.

The majority of studies have also examined the impacts of oversnow vehicle use on vegetation, with most damage occurring when little or no snow cover is present (i.e. at the beginning or end of the season). Under these conditions there is increased mechanical damage to vegetation, greater compaction of vegetation and soil, and decreased water infiltration rates into the soil resulting in increased bare ground and risk of soil erosion (Watson *et al.* 1970; Wanek 1971; Greller *et al.* 1974; Baiderin 1980; Felix and Raynolds 1989). Changes to soil chemistry were also observed with higher soil pH, depleted calcium, potassium and phosphorus, and increased levels of nitrates and ammonium (Kevan *et al.* 1995). The high levels of disturbance were also noted to result in changes to species composition, such as the replacement of mosses with sedges and prostrate shrubs with grasses, while all levels of disturbance resulted in decreased vegetation cover (Emers *et al.* 1995).

Increased snow compaction is a major objective of most snow-grooming operations, and increased density and hardness of the snowpack generally occurs and has been widely demonstrated (e.g Wanek 1971; Neumann and Merriam 1972; Baiderin 1980, 1983; Kattelmann 1985; Racine and Ahlstrand 1991; Fahey and Wardle 1999b). Woody, erect species such as shrubs and low trees are among the most susceptible to direct damage from snow compaction (Emers *et al.* 1995; Felix *et al.* 1992; Forbe 1992). Herbs and grasses, by contrast, often die back in winter, with buds often protected at or below the surface (Greller *et al.* 1974). As a result they are less likely to experience mechanical damage associated with snow compaction.

Changes in snowpack properties as a result of snow compaction also cause an array of secondary impacts. Compaction increases the thermal conductivity of snow and reduces insulation capacity. This has been shown to lead to reductions in soil temperatures with increased frost penetration of the soil (Wanek 1971). This was found in overseas studies to cause a five-to-seven fold reduction in soil temperatures and a seven-to-eleven fold increase in frost penetration into the soil beneath compacted snow (Baiderin 1980, 1983).

Flower and vegetative buds often occur along branches of woody plants and damage can occur to meristematic tissue by the lower temperatures found in compacted snow. Herbaceous species are also susceptible to freezing soils and changes in snowmelt patterns in the spring. Studies overseas have found that secondary impacts of snow compaction include decrease in the rate of organic material decomposition with decreased temperatures, a reduction in the number of soil bacteria and fungi involved in nutrient recycling (Neumann and Merriam 1972; Meyer 1993) and often oxygen depletion/deficiency in the soil (Newesely *et al.* 1993).

Changes in snow-pack characteristics can result in a later snowmelt in spring, thus decreasing the length of the growing season (Neumann and Merriam 1972; Keddy *et al.* 1979). For example, snow retention can delay the onset of flowering, resulting in a shortened flowering season for many plant populations (Baiderin 1983). This can cause changes in the composition of plant communities, with the proportion of spring and summer flowering species declining as autumn flowering species increase (Baiderin 1980). Delayed snowmelt has also been shown to change soil carbon-nitrogen ratios (Walsh *et al.* 1997). These types of changes have been shown to differentially affect plant-growth characteristics and can alter the composition and distribution of plant communities (Neumann and Merriam 1972; Masyk 1973; Felix *et al.* 1992; Forbes 1992).

The compaction of snow also eliminates the subniveal space (natural space between the soil surface and bottom layer of the snowpack), restricting the movement of small mammals under the snow (Baiderin 1983). This is particularly significant in the Australian subalpine/alpine areas as the small mammal species remain active in the subniveal space through the winter months, even though they are in a state of torpor (reduced metabolic and body activity) (Green and Osborne 1994; Green 1988).

There has been little empirical research in Australia examining the effects of snow manipulation on flora or fauna. Ski slope construction, slope grooming and snow grooming at Perisher Valley have been found to have altered soil structure and composition (Cousins 1998; Growcock 1999). A study of a super-groomed, revegetated ski slope has been observed as having a thin mineral soil with minimal organic content, in contrast to the deep peat soils found on similar undeveloped slopes. Vegetation on the ski slope was found to be dominated by Carex species and to have a high percentage of introduced species. Most notable was the absence of Sphagnum on the developed sites where it was previously dominant on the undisturbed slope. As vegetation and peat soils had been removed from the ski slope, the hydrology was also altered, with increased infiltration rates but lower water holding capacity (Growcock 1999). This increased the erosion potential during snowmelt period. Conversely peat soils and the associated vegetation on the undeveloped slopes protected those sites from erosion (Wimbush and Costin 1985; Growcock 1999).

The indirect impacts of snow-grooming do not seem to have been specifically examined in Australia, even though grooming occurs over large areas of resorts and secondary environmental impacts appear to have important ecological implications for the native vegetation.

IMPACTS OF SNOW-HARVESTING

To improve skiing opportunities, snow conditions (depth and distribution) are often increased by snow-harvesting (i.e. stockpiling and redistributing snow). Overseas research has shown that this often results in delayed plant development and growth retardation. Increased depth also decreases the amount of light that penetrates snow and can delay germination of seeds (Richardson and Salisbury 1977). Additionally some species, such as evergreen perennials, biennials and winter annuals, continue photosynthesis under snow, a characteristic that may be critical to their survival. As the changes in snow depth differentially affect plant species, the composition of plant communities may be considerably modified (Richardson and Salisbury 1977).

Increased snow depth has also been found overseas to delay the onset of snowmelt, with the soil under deeper snow found to have reduced organic content, water content, nitrogen, phosphorous and acidity (Stanton *et al.* 1994). Species richness and total vegetation cover were also noted to decrease in sites with delayed snowmelt (Stanton *et al.* 1994).

ARTIFICIAL SNOW-MAKING

While it has been suggested that snow-making will result in unacceptable changes to flora and water quality in the Australian Alps (Good and Grenier 1994; Good 1995), there have been only one or two studies, that the authors are aware of, that have investigated the composition and structure of artificially made snow. Cole and Hallam (1999) investigated some effects of artificial snow, made with the snowmaking additive Snomax on alpine vegetation. However, the study was largely limited to an examination of microbial differences between leaf surfaces following cover with natural and artificial snow. While no changes in microbial damage to vegetation were found, some of the conclusions on microbial damage do not appear to be supported by their data (McDougall 2000).

It has been suggested that the chemical composition of artificial snowmelt water may differentially affect growth characteristics of some ground cover species (Holaus and Parti 1993; Jones and Devarennes 1995), but this has not been evident as yet in the Australian Alps (Good and Green, author obs.). Some species have been observed to be more abundant adjacent to natural snow meltwater, while others preferred artificial snow meltwater (Holaus and Parti 1993; Jones and Devarennes 1995).

THE INFLUENCE OF PREDICTED CLIMATE CHANGE ON EXOTIC PLANT AND WEED OCCURRENCE

The native flora of the Australian Alps has been derived from three sources: Australian lowland species adapted to alpine conditions; species from other alpine regions around the world; and cosmopolitan species (Barlow 1988). A fourth, more recent, source of taxa has been alien plants (Mallen 1986). Many of these alien plants are environmental weeds and pose a serious threat to the ecology of the Australian Alps (Carr *et al.* 1992).

The negative environmental impacts of alien plants include the displacement of native species, modification of primary ecosystem functioning, and modification of disturbance regimes and post-disturbance communities (Prieur-Richard and Lavorel 2000). Weed invasions can also accelerate the rate of soil erosion, alter other geomorphic processes, alter biogeochemical and hydrological cycles, alter fire regimes, prevent recruitment of native species, and accelerate extinction rates (Hobbs 1989; Mooney and Drake 1989; Carr *et al.* 1992).

Photo: Colin Totterdell

Within the Kosciuszko alpine and subalpine zones above 1500 m, a total of 175 alien vascular plant species have been recorded (Johnston and Pickering 2001). An examination of data from only those surveys conducted in the last five years (Pearson 1997; Ingwerson 1999; Duncan 1994; McDougall and Appleby 2000) indicates 140 alien species are currently present in the Alps.

Currently species representing 41 families and 122 genera are recorded for the area (Johnston and Pickering 2001). The number of species, genera and families varies between the States. New South Wales, with the largest contiguous alpine and subalpine area has 165, the highest number of recorded alien species. Victoria, with a slightly smaller area, has 117 plant species, and only 10 species have been recorded for the small alpine and subalpine areas of the ACT, although this is recognised as an underestimate due to the limited sampling of the area (Johnston and Pickering 2001). Less than 50% of the total recorded number of alien plant species currently occurs in the alpine zones. However, several species have extended their distribution into the alpine zone in very recent years, such as the invasive weed yarrow (*Achillea millefolium*). Pellet Clover (*Trifolium ambiguum*), originally introduced by the Soil Conservation Service as a rehabilitation species after the removal of grazing, has over recent years spread rapidly through much of the alpine area after remaining 'dormant' since the 1960s. The drier and warmer conditions experienced over recent years may have initiated the surge in growth and distribution through effective flowering and seed set (Good, author obs).

Although these recent warmer and drier conditions may only be a short-term perturbation in the mean long-term alpine/subalpine temperatures and precipitation, the response of several alien plants indicates the way in which plants in the Australian Alps may respond to global warming. It is interesting to note that mean summer temperature at the treeline on South Ramshead in February (the warmest month and normally expected to be about 10°C) has over the past three years been in the order of 12.5 to 13°C (Green, unpublished data).

Many alien plants are associated with specific types of land use in the Australian Alps. Based on their location, alien plants are categorised in this study as 'grazing weeds', 'rehabilitation weeds', 'resort weeds', and 'roadside and path weeds' (Johnston and Pickering 2001), with many species associated with more than one type of land use. There are 136 species of alien plants recorded along roadsides and paths in one national park alone (Mallen-Cooper 1990; Pearson 1997). This type of disturbance could account for just under 80% of alien species found in the Australian Alps (McDougall and Appleby 2000; Johnston and Pickering 2001). The next largest group is the 'resort weeds', with 58% of species found in and around resort buildings and other infrastructure. Without adequate control, roadside and resort weeds can act as sources of propagules for dispersal into surrounding vegetation (Mallen-Cooper 1990). Just over 20% of alien species already appear to be independent of the need for human disturbance to provide suitable habitats, having become 'naturalized aliens' (Johnston and Pickering 2001).

IMPACTS OF CLIMATE CHANGE AND TOURISM ON WEED OCCURRENCE

Predicted climate change will directly contribute to an increase in the distribution and diversity of alien species in the subalpine and alpine areas of the Australian Alps (Good 1998a; Buckley *et al.* 2000; Pickering and Armstrong 2003). As summer tourism and recreational activities are increasing (Good 1992; Worboys and Pickering 2002a) with a commensurate increase in additional support facilities, the weed problem will be further exacerbated (Usher 1988; Hodkinson and Thompson 1997; Pickering *et al.* 2003b). Developers and conservation organisations will have to make informed decisions about the appropriate levels of allowable disturbance, and hence potential weed invasion, when considering the impacts of future developments.

Decreasing native and alien plant diversity with increasing altitude is characteristic of many alpine and subalpine areas including the Australian Alps (Mallen-Cooper 1990; Körner 1999; Costin *et al.* 2000). Where climatic conditions are the major limit on the upward expansion of species, then the distribution and abundance of alien plants at a given altitude is likely to increase if snow cover declines and average temperatures increase.

Evidence in support of this comes from experiments on the germination and establishment of alien seed sown into natural plant communities in the Kosiuszko alpine zone. Species of alien plants currently limited to subalpine areas were able to germinate and grow at higher altitude, particularly following disturbance (Mallen-Cooper 1990). However, they were unable to reproduce due to the severity of climatic conditions (Mallen-Cooper 1990). Therefore, changes in climatic conditions, along with disturbance, are likely to enhance the establishment and spread of these and other weeds.

SUMMARY OF PREDICTED IMPACTS OF CLIMATE CHANGES ON BIOTA

Climate change is the major threat to the natural ecosystems in the Australian Alps and predictably will result in changes in the occurrence and distribution of plant communities, sensitive species and the functionality of several communities, e.g. groundwater communities. The occurrence and distribution of the alpine/subalpine native fauna will be directly affected by the changes in distribution and structural components of the plant communities, particularly for the rare and sensitive small mammals dependent on particular habitat(s) for survival through the extremes of winter.

The degree and extent of the impacts of global warming on the native biota are impossible to quantify based on the current available data, but studies have been initiated as part of this project to fill the knowledge gaps.

The impacts of climate change, particularly that of global warming, will be numerous and will, or may, be exacerbated by the public responses (tourism and recreational activities) to consequent changes to snow conditions and landscape changes (vegetation types). Much of the alpine zone is still recovering from the disturbance impacts of a century of domestic stock grazing, while an increasing demand for recreation infrastructure are intensifying the disturbance factors in the ski-village areas. However, the impacts of grazing and tourism have been, or can be managed by, altering the focus of visitors, their expectations and behaviour, or by providing alternative experiences within the alpine parks. This will, however, be a challenge for the land managers. The same approach will not work for climate change. Predicting the magnitude of the changes in occurrence and distribution of plant and animal habitats will be crucial to the maintenance of representative areas of each vegetation/animal habitat area. This will involve the prediction of what vegetation communities may benefit and those that will be negatively affected, what communities or species will replace an existing community(ies), and what will be the relative areas of each. Tall alpine herbfield may replace short alpine herbfield and sod-tussock grassland, but tall alpine herbfields could also be replaced by shrubland (heaths) where further drying of the alpine humus soils occurs. Similarly, the very small feldmark communities could extend their area of occurrence by colonising areas that are, or will become, at greater risk of erosion.

Impacts of global warming will be detrimental to some faunal species but beneficial to others. The major impact of global warming on the alpine fauna initially is expected to be as a result of alterations to the snowpack. A slowly melting snowpack provides water for animal activity well into the summer – regular water that cannot be provided by infrequent summer rains. Snow itself provides protection for subnivean animals against winter cold and a barrier against predators. Animals dependent upon snow for protection or for excluding less well-adapted species will therefore be disadvantaged. Phytophagous animals (mainly insects in the alpine zone), however, are dependent upon the amount of primary productivity. This is quite low in alpine areas, with only deserts being lower because of the reduced period of the year available for growth, low temperatures and occasional drought stress. These may increase with global warming. The complexity of changes and interactions make it difficult to predict in which way the ecosystem will shift. What is known, however, is that there will be an increased altitudinal distribution of many species (possibly resulting in the loss of some endemic forms) and an earlier return to the mountains of migratory forms.

The threat from climate change is global in nature, with human activity causing the change also on a global scale. Therefore, an organisation such as the NSW National Parks and Wildlife Service, which has a mandate to protect biodiversity within the park, may increasingly have to address the impacts of climate change on the natural environment.

Having recognised the importance of climatic warming in the Australian Alps, particularly in the alpine zone, a series of field evaluations of predictions have been established within Kosciuszko National Park. The aim of these evaluations is to establish a comprehensive monitoring program of the impacts of global warming on winter snow and ice conditions and summer mean temperatures, and how these may/will affect the distribution of plant communities/animal habitats, animal populations and the survival of rare plant and animal species.

Further, there is collaboration with international mountain climate change studies such as the GLORIA (Global Observation Research Initiative in Alpine Environments) and the Global Mountain Biodiversity Assessment (GMBA). GLORIA is an international coordinated research initiative that monitors the impact of climate change on mountain biota around the world (Pauli *et al.* 2001). This involves establishing long-term observation networks with standardised monitoring settings in all major mountain systems, including five in Australia (see www.gloria.ac.at).

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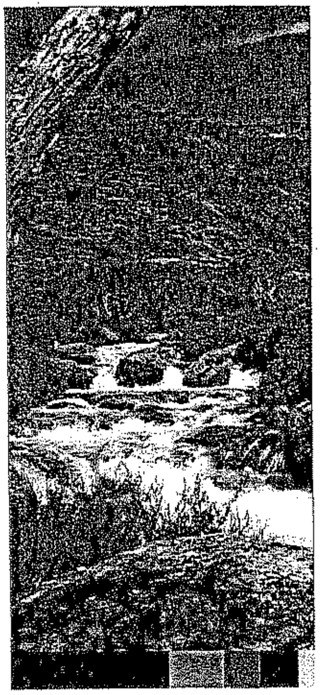

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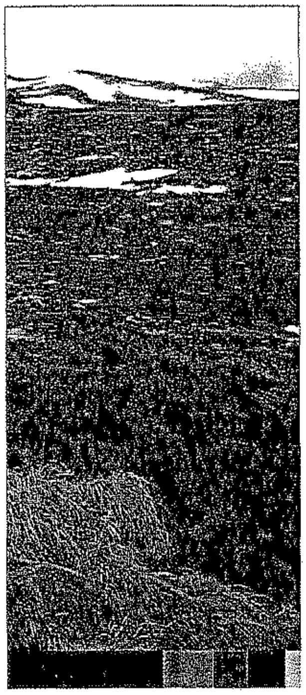

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