Peat-forming bogs and fens of the Snowy Mountains of NSW

Technical Report

Office of Environment & Heritage
NSW National Parks & Wildlife Service

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Front cover: Alpine shrub bog and fen in the Cup and Saucer area, upper Geehi River. Photo: G Hope

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SUMMARY

Bogs and fens are common in the Snowy Mountains of south-eastern New South Wales (NSW) and form up to 2.5% of the higher altitude land cover in Kosciuszko National Park. At lower altitudes peat deposits beneath extensive sedge fens fill broad valleys on gentle slopes. With increasing altitude the hummock moss, *Sphagnum cristatum*, contributes to shrub-rich montane, subalpine and alpine bogs which follow drainage lines and seepage areas on slopes and saddles. These peatlands are vital areas of moist habitat and of high scientific significance biogeographically. Additionally, their slowly accumulating peat is an archive of past change in vegetation and fire regimes. This peat and associated organic-rich mineral soils are a significant carbon store. While similar fens and bogs occur in Victoria and the Australian Capital Territory (ACT), the occurrences in the Snowy Mountains represents the most extensive expression of peatlands in mainland south-eastern Australia with major environmental significance as habitat and as regulators of water quality. The peatlands have been badly affected by cattle grazing and fire since European settlement of the region commenced in 1823. Some recovery is evident within protected areas but serious fires in 2003 reversed this process in many areas.

This study provides the first comprehensive mapping of the region's peatlands. It has been completed by using aerial photography and satellite imagery, supplemented by field checking, to create a spatial database of the mires. The boundaries generally reflect the situation in February 2003, immediately after a major fire prompted the collection of high resolution aerial photographs of the peatlands. The surface extent of the peatlands is combined with data on the depth of peat and its carbon content to estimate peat volumes and carbon storage. The accumulation history of the mires provided by a 30-year program of coring and radiocarbon dating was used to estimate the long term rates of peat accumulation and carbon sequestration. This report provides the first quantified measurements of peatland extent, peat volume and peatland carbon storage for the Snowy Mountains.

The 9120 individual peatlands in the Snowy Mountains region total 7985 ha, of which 6037 ha is in Kosciuszko National Park, 556 ha in the ACT, and 1392 ha in other reserves or on leasehold or freehold land. Some 72% is smaller than 0.5 ha. The 3656 ha of *Sphagnum* shrub bog in Kosciuszko National Park can be compared to the 2713 ha of bog in alpine Victoria and the 2865 ha of *Sphagnum* moss communities that occur above 800 m in Tasmania.

The Snowy Mountains bogs and fens preserve 49 million cubic metres of peat, of which 27.1 million cubic metres is in bogs and moorlands and 21.9 million cubic metres is in sedge fen. The estimated total carbon store is 3.55 million tonnes. Measuring peat growth over the past 100 years shows that the historical carbon sequestration rate is only 4950 t C/year for the entire peat estate. This net carbon storage rate of 0.8 to 1.6 t C/ha/year is comparable to the rates found in temperate mires in other parts of the world. Peat sections covering the last 3000 to 4000 years indicate that the millennial-scale rate of long-term storage is 2340 t C/year (53% of the historical rate); part of this lower net rate may represent losses caused by grazing and fire.

Most of the peatlands exhibit damage from the period of grazing last century, but those at higher altitudes are recovering strongly and recolonising erosion areas. The peatlands are vulnerable to hydrological changes caused by grazing and trampling by large mammals such as horses. They are also sensitive to climate change, as they are near their climatic limits and have been greatly stressed by past disturbance and fire. Recovery of the peatland vegetation will take several decades, but replacement of lost peats will be a much longer process. For this reason, active management of the hydrology, surface stabilisation, and reduction of disturbance are essential to restore peatlands and maintain their resilience to natural change.

The report recommends further research in ecology and peatland processes to inform management. Programs of training for managers and education for the public are also needed.

ACKNOWLEDGMENTS

Mapping of the NSW bogs began in 2005, when it was funded by a research grant from the Parks and Wildlife Group, Office of Environment and Heritage (P&WG). The original remit was to map the outlines of peatlands in Kosciuszko National Park, but we have indulged our curiosity by extending the survey to the Snowy Mountains region as a whole and attempting a more detailed analysis of vegetation, peat types and history. This expansion has extended the length of the project by 2 years, and the tolerance of various responsible officers in P&WG has been severely tested, for which we apologise. Permission to undertake the field component was provided to the authors by Kosciuszko National Park. We are indebted to Dave Darlington, Rob Gibbs, Andrew Miller, Elouise Peach, Geoff Robertson and Matt White for authorisations, advice and substantial field support. We are particularly grateful to Genevieve Wright for managing the project on behalf of P&WG.

The geographical information system (GIS) mapping was developed for both this and a parallel project on the peatlands of the ACT by Rachel Nanson, with additions by Iona Flett and Peter Jones and advice from Lyn Finch (Office of Environment and Heritage) and Tony Sparks (Ecowise). We are grateful for help with the field survey from Iona Flett, Roger Good, Simon Haberle, Ben Keaney, Justine Kemp, Colin de Pagter, Bren Weatherstone, Jennie Whinam and Genevieve Wright. Barry Cooper and Jim Kelton provided valuable information about Tomneys and MacPhersons plains in the Bago State Forest area.

This report builds on several decades of mire studies by palaeoecologists and ecologists from the Australian National University, P&WG, the Commonwealth Scientific &and Industrial Research Organization (CSIRO), the NSW Soil Conservation Service and the Tasmanian Department of Primary Industry, Parks, Environment and Water. We have greatly benefited from discussions on the ecology and palaeoecology of the mires with John Banks, Mark Butz, Geoff Cary, Robin Clark, Fiona Coates, Alec Costin, John Dodson, January Finn, Roger Good, Ken Green, Kate Harle, Dave Hunter, Joe Jennings, Peter Kershaw, Michael Macphail, Merna McKenzie, Tony Martin, Scott Mooney, Stuart Pearson, Warwick Papst, Nick Porch, Arne Tolsma, Alan Wade, Janet Williams, Dane Wimbush, Gen Wright, Jennie Whinam and Phil Zylstra. We owe a debt to Keith McDougall (Biodiversity Conservation Section – South) for his comprehensive floristic surveys at Kosciuszko and the Victorian Alpine National Parks.

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INTRODUCTION

The Snowy Mountains of south-eastern Australia are home to numerous small peatlands that are unusual in forming organic-rich soils that are preserved through waterlogging, acidity and cool temperatures. The peatlands have characteristic vegetation that sharply distinguishes them from the surrounding woodlands and grasslands; they so can be seen as islands of moist habitat within the forests and subalpine woodlands. Peatlands support a limited number of hummock moss shrubland, sedgeland and other sedge-like plant communities, often interspersed with small pools. The peatlands provide significant environmental benefits to the natural environment. They are important as an animal habitat: they provide green feed and water during dry periods to a range of grazers and invertebrates and support some wetland species such as freshwater crayfish, frogs, skinks, birds and rodents (Lintermans and Osborne 2002). The moist peat preserves living rootstock after fires, so that peatlands offer the earliest resprouting after fire. This is of crucial importance to small grazers. Peatlands intercept rainfall, trap sediment, remove nutrients and store water, gradually releasing high quality flows to rivers. Unfortunately, with grazing, many peatlands have become compacted or eroded over the past 150 years and have become less effective as storages owing to the low hydraulic conductivity of humified peat (Grover *et al.* 2011). However, peatlands are still very long-term carbon stores, comparable under the best conditions with temperate forest ecosystems (Keith *et al.* 2009), and they are capable of high short-term carbon sequestration rates that match values for forest.

Although the peatlands of the Australian Alps have been studied for a long time, most systematically by Alec Costin as part of his ground-breaking survey of ecology and soils of the Monaro (Costin 1954), no detailed mapping of peatlands has previously been attempted in the Snowy Mountains region of New South Wales (NSW). Peatlands above 800 m in the Australian Capital Territory (ACT) (Hope *et al.*2009) and above 1000 m in highland Victoria (Lawrence *et al.* 2009) have recently been mapped, and data are available at a 1:25,000 scale for Tasmania. Although the Victorian and Tasmanian peatlands are classified differently from the ACT/NSW system, all GIS data are based on floristic mapping and should therefore be compatible among states and territories.

This report describes the mapping of the significant peatlands of the Kosciuszko National Park and neighbouring areas and defines the criteria used to prepare the GIS data base of mire extent. (Note that the term 'mire' is used here to describe peat-forming wetlands of all types.) We have now mapped approximately 8250 individual mires (with an extent of 7438 ha above 700 m) in the Snowy Mountains region (Table 1).

Table 1. Peatlands noted in surveys and nominations

Area (bioregion)	Peatlands	Mire area (ha)	ANCA 2001	Ramsar
Kosciuszko NP	7336	6037	3	1
NSW Alps (AA)	7142	5553	3	1
NSW Southern Highlands (SEH)	1137	1879	8	0
ACT Alps (AA)	25	227	2	1
ACT highlands (SEH >700 m)	33	347	1	0
Victoria >1000 m (AA+SEH >1000 m)	1377	2713	11	0

AA, Australian Alps; SEH, South East Highlands (Snowy Mountains region). ANCA (the Australian Nature Conservation Agency) provided a census of Australian wetlands. Ramsar is a listing of wetlands of international significance.

The total area includes 773 ha of large *Carex* fen peatlands below 1250 m and 3778 ha of alpine and subalpine *Sphagnum* shrub bogs. This compares with 58 peatlands totalling 574 ha in the ACT. (Hope *et al.* 2009) and 2713 ha of mainly subalpine *Sphagnum* shrub peatlands in the south-eastern highlands of Victoria above 1000 m (Lawrence *et al.* 2009).

It is clear that the Snowy Mountains preserves the richest area for montane and subalpine mires in Australia. This is strongly related to the mountains of the south-east providing the most important catchment and source of water that runs coastwards and to the Murray Basin (Worboys *et al.* 2010). Other montane *Sphagnum*-shrubland-dominated peatlands occur on the crest of the coastal scarp between Sydney and Bombala and in the Blue Mountains, Barrington Tops and New England areas (DEWH 2005, Whinam and Hope 2005).

The montane peatlands and swamps of the South East Highlands and Australian Alps bioregions were listed in NSW as an endangered ecological community in December 2004 on Schedule 1, Part 3 of the *Threatened Species Conservation Act 1995* (NSW). Additionally, in 2008 the Alpine *Sphagnum* Bogs and Associated Fens ecological community was listed as Nationally Endangered under s. 266B of the *Environment Protection and Biodiversity Conservation Act 1999* (DEWHA 2009). The areas of this community are: ACT 137.1 ha, NSW 3778.1 ha, Victoria 2713 ha, and Tasmania 2865 ha.

In a national survey of wetlands by the Australian Nature Conservation Agency (ANCA 2001), two regions, the South East Highlands and the Australian Alps of south-eastern Australia, were defined as interim biogeographic regions. These are equivalent to montane (>500 m) and subalpine (>1300 m) zones. The ANCA report extracted data from an earlier survey of montane peatlands in the ACT and southern NSW (Hope and Southern 1983), but the survey results are incomplete.

One mire in the ACT, the Ginini Flats subalpine bog complex, has been described as an exceptional example of a subalpine *Sphagnum* bog and is Australian Ramsar Site 45. (Ramsar sites are wetlands of international importance, designated under the Ramsar Convention.) Part of the listing reflects the importance of this site as breeding habitat for the highly endangered northern corroboree frog, *Pseudophryne pengilleyi* (McElhinney and Osborne 1995). It is surprising that no other peatlands in the NSW or Victorian alps have been listed on the Ramsar List of Wetlands of International Importance, because there are above-treeline mires and mire vegetation communities in NSW at Mt Kosciuszko that are not replicated in the ACT or Victoria. However, Blue Lake (Australian Ramsar Site 48) is listed as a 348-ha area, in part for its alpine wetland values:

> Criterion 3: The Blue Lake Ramsar site contains the only high altitude alpine wetlands in Australia. The site also supports populations of plant and animal species important for maintaining the biological diversity of this particular biogeographic region (http://www. environment.gov.au/cgi-bin/wetlands/ramsardetails.pl?refcode=48).

We show here that this statement is inaccurate, as it ignores other peatlands within the Kosciuszko alpine zone.

No montane sedge fen in the Australian Alps has been listed as a Ramsar site to date. To the south, Jacksons Bog, near Bombala, NSW, is listed as an example of 'Temperate Highland Peat Swamps on Sandstone'. This is an ecological community that is regarded as endangered under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* and the NSW *Threatened Species Conservation Act 1995*.

A few of the Kosciuszko mires have been studied in order to understand their long-term stability as part of catchment vegetation (Costin 1972, Costin *et al.* 2000, Martin 1986a, 1986b, 1999) and their community dynamics through time (Clarke and Martin 1999, Whinam and Chilcott 2002, Whinam *et al.* 2003b). The peatlands have been shown to be sensitive indicators of environmental change, as demonstrated by recent changes in vegetation and hydrology in response to fire and rehabilitation (Good 2004, Good *et al.* 2010b, Hope *et al*. 2005, Wimbush and Costin 1979, Whinam *et al*. 2010). In addition to having ecological value, peatlands are scientifically valuable because they preserve their own history in the accumulating peat. Organic matter can be dated with radiocarbon to provide a record of peat accumulation. Analysis of inorganic components, pollen, charcoal, fossil plants and insects, and other proxies, can indicate the condition of the mire and its surrounds in the past. These archives provide evidence of the long-term fire history and the past record of climate change (e.g. Dodson *et al.* 1994, Kemp 1993, Martin 1986a, 1999, Mooney *et al.* 1997, Raine 1974, Thomas 1991). Hope *et al.* (2009) reviewed several of these sites in relation to the more intensive network of palaeoenvironmental records from the ACT mountains.

An important aspect of mires as archives is that they not only store organic matter on millennial timescales but can also potentially release large carbon stores to the environment. Mean net peat accumulation rates can be derived from dated sections. These rates can be converted to long-term carbon sequestration rates if the peat bulk density, water content and carbon content are measured. This report provides the first estimates of the carbon store and historical carbon sequestration rates of the mires of the Snowy Mountains region.

PEATLANDS AND MIRES

Definitions of organic deposits are complex and highly variable internationally (Bridle 1994), because such deposits can be viewed as sediments or soils and as biological or hydrological systems. Classifications of peatlands may include the physical peat typology, floristics of the mire vegetation, topographic setting, water and nutrient inputs and chemistry (Moore 1984). Peat is one of several types of organic sediment that form from the dead remains of plants, both large and microscopic, almost always accumulating in permanently waterlogged conditions under which breakdown is hindered. The presence of a high proportion of organic material creates reducing conditions that exclude microfauna and prevent aerobic microbial action, and the porous, relatively light matrix retains water readily. This moisture allows continued accumulation of organic matter. Peat is not just dead sediment; it is also a component of a living ecosystem, the net production of which forms the substrate on which the living part depends. The surfaces of organic deposits such as peat provide specialised habitats for plants and animals tolerant of aquatic, or wet, reducing and often acid conditions. An organic deposit preserves some of the remains of plants and animals that have lived there through the period (or periods) over which the deposit forms.

Organic breakdown (humification) tends to produce similar material from diverse original sources. Typically, the proportion of fibrous peat in a deposit decreases with depth, and both Clymo (1984) and Clark (1986) argue that this reflects continuing breakdown in a deposit, so that older materials are more humic (and represent slower net accumulation). However, more fibrous horizons may occur under humic ones, and these mark a period of rapid growth in the peatland in the past. Charman (2002) distinguishes a shallow upper layer that has a fluctuating watertable, the acrotelm, from a lower, permanently waterlogged layer, the catotelm. Mire vegetation has its roots in the acrotelm, and biological activity is greatly reduced in the catotelm. In this scheme, many peatlands in valleys in Australia have very deep acrotelm horizons, reflecting considerable drying out in droughts, and catotelms consisting of fully humified peat (Isbell 1996). There is, however, no requirement that all the peats in the catotelm be humified and of low hydraulic conductivity, as asserted by Grover *et al.* (2005). Many peat sections in arctic or tropical peatlands are fibrous throughout.

The vegetation forming the organic material varies according to the availability of mineral nutrients in the water. At one extreme, bogs dominated by slow growing mosses occur in very wet, cool climates in sites where ground water is minimal, so that growth depends on nutrients brought in with rainwater. If increased nutrition, for example from ground water, is available, shrubs, grasses and sedges will invade and co-exist with the moss, or exclude it. The growth of peat at the wettest places tends to block stream lines and form shallow ponds over time, retaining water in the mire. *Sphagnum* moss is particularly able to do this and can form a raised bog, well above the regional watertable. Other swamp plants, such as sedges and restiads, also act to create string bogs by creating peat dams. If the watertable occurs at the surface for a substantial time, many shrubs will not survive, and shallow-rooted sedges, twig rushes and similar plants will form an open cover. Finally, in deeper water, aquatic species such as cumbungi (bulrushes), reeds, sedges, waterlilies, strap rushes and pond weeds will dominate, and the organic material will contain plant debris and algal muds. Dynamic growth of peatlands can thus result in the formation of a mosaic of communities. These processes are set back by disturbance or changes in water supply due to drought, fire or drainage, and the peat can be humified or destroyed (Hope 2003).

Peatland definitions in this report

We use the term ‘**peatlands**’ to indicate terrestrial sediments in which organic matter exceeds 20% dry weight and the depth is generally greater than 30 cm. This is conservative by European measures (Whinam and Hope 2005), but even our definition would exclude some mires, such as Tasmanian buttongrass moorland. These may have shallower peats (15 to 25 cm), but they must be included as peatland because they form extensive organic terrains.

Many terms exist to describe peaty wetlands: for example, bog, fen, mire, moor, marsh, morass, mossbed, swamp and swamp forest. Of these, only bog, fen and moor have specialist definitions as types of vegetation (Bridle 1994, Charman 2002, Hope 2006, Whinam and Hope 2005):

Bog: Characterised by complex vegetation with little free water surface. The water is stagnant and the soil is usually acidic (pH 4 to 5) and of low nutrition, as it generally depends on rainfall for minerals.

Fen: Simple vegetation, often with some open water. Fens are fed by surface flow and ground water; mineral matter is often present, providing better nutrition than in bogs and creating a mildly acidic to neutral peat (pH 5 to 6). May include some woody vegetation.

Moor: Simple sedge, rush or open sedge shrubland with shallow muck or fibrous peats forming an organic soil, often on slopes. Nutrition is supplied by surface flow and mineral substrate. Moors are acidic to mildly acidic (pH 4.5 to 5.5).

Mire: Includes all the above as actively peat-forming systems. **Topogenous mires** are those formed in low points in the landscape that collect runoff and ground water. **Ombrogenous mires** depend on rainfall for their water and in high rainfall areas can occupy slopes and crests.

Peatland: A landform formed from organic-rich sediment that may be actively accumulating or inactive (relict).

In the absence of data on nutritional status, the terms are best used in relation to the structure of the major vegetation community on the site. This approach contrasts with that of some European authors who restrict the term ‘bog’ to communities that are fed by rain alone (also termed ombrogenous or cloudfed bogs, i.e. supported solely by precipitation) (Charman 2002, Clymo 1984, Whinam and Hope 2005). In an analysis of a 230-cm profile in a *Sphagnum* shrub bog at Wellington Plains, Victoria, Grover *et al.* (2005) found that the pH range and nutritional status of the peat agreed well with Netherlands and Canadian measurements for ombrogenous bogs. Lawrence *et al.* (2009), in reviewing subalpine peatlands in Victoria, state that terms like bog, fen, mossland and mossbeds have become confused; they prefer the term ‘peatland’ to cover the range of plant communities present. The problem with this is that peatland is generally understood to be a substrate, not a vegetation formation. We use ‘mire’ as the equivalent term to ‘peatland’, which implies a wetland vegetation on an organic substrate.

In south-eastern Australia, bogs may have cushion plants, including mosses, and often low shrubs or even trees. They have an uneven surface of hummocks and hollows. Fens have graminoid (grass-like) plants, especially sedges (Cyperaceae) or rushes (Restionaceae, Juncaceae, Typhaceae, Xyridaceae). The surface is usually level. However, grass or sedge-dominated bogs are known; an example is *Gymnoschoenus* (button-grass) bog, in which densely packed graminoid hummocks up to 2 m high provide a complex structure. In Tasmania, extensive montane button-grass bog extends over large, often sloping, areas on shallow peats, so it is also called moor (Whinam and Hope 2005).

Almost all peatlands in the Snowy Mountains are topogenous mires, meaning that they require slope runoff and ground water to exist and hence occupy the bases of slopes in saddles, wet slopes and valley floors. However, some areas on *Sphagnum*-dominated bogs have no overland flow and are raised above the surface flows; they may therefore represent embryonic ombrogenous bogs. In the wettest parts of the Kosciuszko Main Range a peat layer is draped over slopes (blanket bog) in which steps and rises indicate slope creep. Investigation of the formation of many mires shows that a basal layer of humic peat and peaty clay, which water cannot penetrate (i.e. an aquaclude), causes site waterlogging and allows the peatland to form and spread. This creates a perched watertable that cannot access the mineral substrate, leading to bog-like conditions (Grover *et al.* 2005). If this layer is disrupted, bogs may not be able to reestablish on former sites, or they may be replaced by fen.

The environment of the Snowy Mountains

The Snowy Mountains and the associated northern extensions such as the Brindabella Ranges are part of the mountain areas collectively known as the Australian Alps (Worboys *et al.* 2010). They were formed by uplift in the late Mesozoic to early Cainozoic period (90 to 50 Ma ago), possibly as result of the opening of the Tasman Sea. The ca. 320 Ma Palaeozoic rocks that were uplifted include sediments and metasediments that had been affected by extensive Siluro-Devonian granites and rhyolitic volcanics. Some metamorphic rocks, including shale, slate, quartzites, schists and gneiss, are also present. In the late Cretaceous and early Tertiary, basaltic eruptions occurred across the area, leaving scattered basaltic landscapes. Although much of the Snowy Mountains has plateau-like surfaces, these have been strongly eroded to form steeply incised valleys. Typically, drainage is dendritic, but in granite areas jointing often controls stream direction. Across the plateaus, streams have gentle gradients before entering gorges and descending rapidly to the major streams of the Murray, Tumut, Goodradigbee and Murrumbidgee rivers, which are part of the Murray-Darling drainage basin, and the Snowy River, which flows south and east to the Tasman Sea.

Soils and regolith are comparatively thick, the result of lengthy weathering, organic accumulation and moderate slopes (Costin 1954). Slopes are often mantled in gravelly clay deposits that developed during cool periods of alluvial fan development with periglacial action at higher altitudes (Barrows *et al.* 2004). The deep regolith and substantial valley fills provide an excellent water store that maintains stream flows and spring lines.

The climate is influenced by the position of the mountains on the western side of the south-eastern highlands. Rainfall is intercepted from frontal systems coming from the west, with highest precipitation on the western range crests and drier conditions to the east; rainshadows form at lower altitudes. Precipitation varies from more than 2000 mm at Mt Kosciuszko to about 800 mm at 1000 m on the eastern slopes and 450 mm in the gorge of the Snowy River. The highest precipitation, associated with high cloudiness and extended snow cover, occurs above 1750 m along the Main Range from Mt Jagungal to Mt Kosciuszko. Rainfall distribution has a moderate winter peak there but tends towards equal summer and winter totals to the north and east. Convectional rain occurs as thunderstorms or as a result of troughs in summer. Winter snow cover above 1400 m lasts for 1 to 3 months, with big variations among years. Temperatures are cool temperate, with severe frost at all altitudes through winter. As in the rest of Australia, high inter-annual variability is characteristic (Costin *et al*. 2000).

Vegetation communities on the mires of the Snowy Mountains

Keystone species

The plant communities of peat-forming mires have simple floristics and share many species in a total flora of about 250 species (Helman *et al.* 1988, McDougall and Walsh 2007). In the total flora of mire obligate or tolerant plants are a few keystone species that control the structure and function of a community, being always present. Each can influence some aspect of the community, such as water-holding ability, pH, flammability or ability to exclude competition. Four species and three groups of related taxa are described here and are illustrated in Figures 1 and 7 to 15.

Sphagnum cristatum is a hummock- or cushion-forming moss with a very open structure that can hold up to 20 times its own weight of water, which it maintains at an acid pH, and tolerates very low nutrient status, thus limiting competition. It is capable of blocking watercourses and building domes by wicking up moisture. The living moss requires 30% to 70% shade, but during a favourable season it can expand rapidly, adding several centimetres to the cushion. In the Snowy Mountains it spreads vegetatively along streams or by animal and bird dispersal, as it only rarely sporulates in this region. It is fire sensitive, being completely killed by a light fire in overtopping shrubs and herbs. Whinam *et al.* (2003b) note that the moss is near its climatic limits in the Snowy Mountains, being unable to survive days of high temperature, low humidity and high radiation in summer, except at high altitude in shaded aspects with a good water supply. However, there are *Sphagnum cristatum* shrub bogs in the Barrington Tops and New England.

Empodisma minus (formerly *Calorophus minor*) is a grass-like twig rush in the Restionaceae family that always accompanies *Sphagnum* in shrub bogs but also dominates fens on the margins of bogs. It is important structurally because it forms a tough cohesive mat of roots and underground stems that readily resprout after fire. Because the mat resists erosion it can impede stream flow and create ponds. The resprouting root mat reduces the potential damage caused by fires and explains why peatlands persist on sites subject to repeated burning. It is often associated with a more robust restiad species, *Baloskion australe* (formerly *Restio australis*), and vegetation dominated by these plants is sometimes termed ‘restiad bog’. However, structurally this community often occurs on slopes on shallow peat, where it can be termed a moor. *Empodisma minus* extends from Queensland to Tasmania and is also important in New Zealand mires (Hodges and Rapson 2010, Nieveen and Schipper 2005).

Carex gaudichaudiana is a grass-like sedge (Cyperaceae) that is scattered in bogs but dominates fens on periodically inundated peat. Like *Empodisma*, it readily resprouts after fire and stabilises burnt fens within a few weeks. Its dense sward can be 50 cm deep, and it forms an effective filter, spreading water out across valley floors. It is an early pioneer of shallow ponds. It forms fens throughout montane Australia, New Zealand and the sub-Antarctic and extends to subalpine New Guinea.

The bog epacrids *Epacris paludosa, Epacris brevifolia, Epacris microphylla, Epacris glacialis* and *Richea continentis* are long-lived mire shrubs in the Ericaceae (heather) family (formerly Epacridaceae). They can tolerate acid pH and colonise *Sphagnum* hummocks. They can grow to 120 cm and suppress *Sphagnum* when very dense. They are easily killed by fire and do not resprout, replacing themselves by seedlings. *Epacris paludosa* has a wide altitudinal range but *R. continentis* is confined to the subalpine and alpine bogs.

The bog myrtaceous shrubs *Baeckea gunniana*, *Baeckea utilis* and *Callistemon (Melaleuca) pityoides* form a second group of low mire shrubs in the Myrtaceae family, but unlike the epacrids they readily resprout from the base after light fires. *Baeckea gunniana* occupies high altitude bogs, and the very similar *B. utilis* is more common at lower altitudes. A taller teatree, *Leptospermum lanigerum,* occupies subalpine and montane mire margins. All species are readily flammable and probably carry fire onto *Sphagnum* shrub bogs.

Poa costiniana is a medium-sized tussock grass that is commonly found scattered in bogs and dominates sod tussock on the margins. It reseeds profusely and can resprout if lightly burned. It will invade mires if these are dried out and is an indicator of mires becoming degraded. Other *Poa* species, *Poa clivicola* and *Poa helmsii*, often contribute in the same way, with the larger tussock *Poa labillardierii* being common at lower altitudes on fen margins.

Vegetation communities

A landmark review by McDougall and Walsh (2007) provides a floristic plot-based census of the treeless vegetation communities, including mires, in Victoria, NSW and the ACT above 1000 m altitude. The authors discern two types of *Sphagnum*-shrub wet heathlands (one alpine and the other subalpine), distinguished mainly on structural grounds. The higher community, *Richea continentis – Carpha nivicola – Sphagnum cristatum* wet heathland, has low shrubs fitted into the moss cushions, whereas the lower altitude community, *Baeckea gunniana – Callistemon pityoides – Sphagnum cristatum* wet heathland, has tall shrubs overtopping and sometimes excluding *Sphagnum*. In a study of ACT mires, Hope *et al.* (2009) subdivided the subalpine *Sphagnum* formation into two distinct communities that differentiated a simpler *Sphagnum* shrub heathland lacking alpine taxa that extends to montane altitudes. There is undoubtedly considerable variation in the *Sphagnum* wet heathlands, as Whinam *et al.* (2003a) found 12 distinct species assemblages in their study of montane Victoria. The ACT study also recognised a variable sedgeland transitional to open low shrubland (moor) community dominated by a twig rush, *E. minus*, on shallow slopes. This was not listed by McDougall and Walsh (2007), as they regarded it as a form of wet heath (K.

McDougall, OEH 2010 pers. comm.), but it is widespread. In Tasmania and Victoria. *Sphagnum* can contribute to herbfields and fens (Kershaw *et al.* 1997), but these herbfields are very minor in the Snowy Mountains. In this report we have based our analysis on the mire plant communities described in Table 2.

Table 2. Vegetation communities forming peatlands in Kosciuszko National Park and adjacent areas

	Community name	McDougall & Walsh 2007 classification	NSW altitude range (m)	Substrate	Av. peat depth (cm)
1	*Richea continentis – Carpha nivicola – Sphagnum cristatum* alpine shrub bog	*Richea continentis – Carpha nivicola – Sphagnum cristatum* wet heathland	1600–2050	Sandy humic peat	25
2	*Sphagnum – Richea – Empodisma* subalpine shrub bog	*Baeckea gunniana – Callistemon pityoides – Sphagnum cristatum* wet heathland	1400–1800	*Sphagnum* peat	80
3	*Sphagnum – Epacris paludosa* Medium-altitude shrub bog	*Baeckea gunniana – Callistemon pityoides – Sphagnum cristatum* wet heathland	600–1450	*Sphagnum* peat	65
4	*Empodisma minus* restiad moor (fen/herbfield)	Allocated between wet heathland and grassland depending on shrub cover	>950	Humic peat and peaty silt	30
5	*Carex gaudichaudiana* fen	Fen	700–1950	Fibrous sedge peat	300
6	*Phragmites – Typha* tall sedgelands (fen)	Not in report	500–1000	Organic muds, clayey sedge peat	220
7	*Poa* sod tussock grassland (fen)	Subalpine valley grassland	700–1750	Humic silty clay	10
8	*Lobelia surrepens – Ranunculus millani* herbfield	*Lobelia surrepens – Ranunculus millani* herbfield	1090–1770	Organic clay	10
9	*Myriophyllum* aquatic fen (herbfield)	Aquatic	1000–1950	Organic muds	15
10	*Leptospermum lanigerum* tall shrubland	Woodland: Not in report	1000–1600	Humic silty clays	15

These communities generally conform with vegetation alliances and associations recognised by Costin (1954) for the Monaro and Snowy Mountains and by Helman *et al.* (1988) for the upper Cotter River catchment in the ACT. Gellie (2005) describes the montane fens and montane shrub bogs (communities 3, 5 and 6) as Southern Tablelands swamps / open woodlands and the associated riparian Southern Tablelands swamp grasslands. In Victoria a range of names have been used for mire communities, but these can be reduced to alpine wet heath, wet heath and *Carex* fen (Lawrence *et al.* 2009), which align respectively with communities 1, 2 and 5. Of the 10 communities in Table 2, only communities 1 to 6 are peat-forming and have been included in the mapping, with *Phragmites – Typha* fen being included with *Carex* fen to make five mapping units. The seventh community, *Poa* sod tussock grassland, generally grows on humic mineral soils on the margins of the peat-forming mires, commonly invading peatlands when these experience loss of organic content due to fire or drainage. Communities 8 and 9 are common but not extensive, as they are restricted to ponds and riparian habitats, whereas 10 occupies wet gullies sheltered by woodland. Other wetland vegetation has been defined (particularly other wet heaths), but these communities generally do not form peat.


Figure 1a. *Sphagnum cristatum* cushion with emergent epacrid shrubs *Richea continentis and Epacris glacialis* and graminoids *Carex gaudichaudiana and Empodisma minus*. 1915 m, Swampy Plain River, Main Range. Photo: Geoff Hope


Figure 1b. Alpine *Sphagnum* shrub bog with *Richea continentis* developed on fan gravels on Swampy Plain River, Main Range, February 2010. Photo: Genevieve Wright


Figure 1c. Alpine *Sphagnum* shrub bog is characterised by a sedge, *Carpha alpina*. 1800 m, Mt Jagungal, Upper Geehi River. Photo: Bren Weatherstone


Figure 1d. Alpine *Sphagnum* shrub bog with well-developed pond and stream patterns. 1740 m, Geehi River, March 2007. Photo: Geoff Hope


Figure 1e. Subalpine *Sphagnum* shrub bog with emergent shrubs and lines of *Baloskion australe* along drainage lines. 1530 m, Cascade Creek, northern Charcoal Range, March 2010. Photo: Geoff Hope


Figure 1f. Cushions of *Astelia alpina* in a sward of *Baloskion australe.* Cascade Creek, Charcoal Range. Photo: Geoff Hope

Figure 1g. Montane *Sphagnum* shrub bog with flowering *Epacris paludosa*. 1225 m, Sally Tree Creek, Currango Plain, January 2007. Photo: Rachel Nanson

Figure 1h. Montane *Sphagnum* shrub bog dominated by *Baeckea utilis*. 1185 m, Paddys River Bog, Bago State Forest, February 2011. Photo: Geoff Hope

Figure 1i. *Empodisma minus* moor. 1710 m, Plains of Heaven, February 2010. Photo: Geoff Hope

Figure 1j. *Empodisma* moor on former shrub bog. 1570 m, Grey Mare fire trail. Photo: Bren Weatherstone

Figure 1k. *Empodisma* moor on a saddle at 1275 m, Dairymans Flat, near Tantangara, January 2009. Photo: Bren Weatherstone

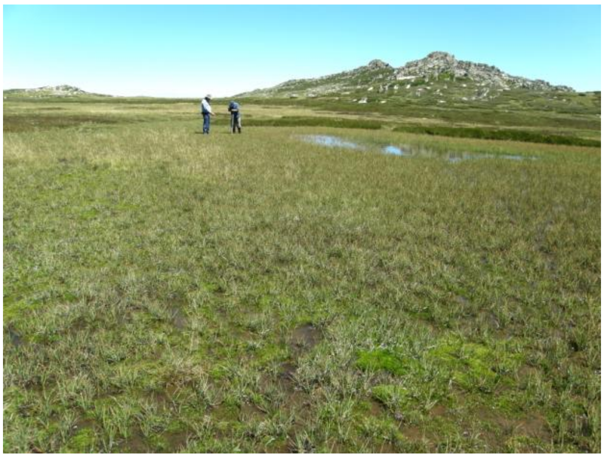

Figure 1l. Alpine *Carex gaudichaudiana* fen, 1910 m, Swampy Plain River, February 2010. Photo: Genevieve Wright

Figure 1m. The largest *Carex gaudichaudiana* fen in Kosciuszko NP, Mosquito Creek. 1225 m, Currango Plain. Photo: Matiu Prebble

Figure 1n. *Poa* tussock grassland replacing shrub bog at 1795 m, upper Geehi River, March 2007. Photo: Geoff Hope

Figure 1o. Pond and flark complex (cross-slope fens and ponds) in tussock grassland and moor. 1640 m, Ramshead Range near Diggers Creek, February 2010. Photo: Geoff Hope

Richea continentis – *Carpha nivicola* – *Sphagnum cristatum* alpine bog (alpine *Sphagnum* shrub bog, or ASSB). These bogs are very variable, with a dense flattened canopy with emergent tufts of the robust sedge *Carpha alpina*. A mosaic of *Astelia, Sphagnum, Richea* and *Epacris* often follows drainage lines or build-up of rounded cushions, with numerous ponds and small patches of *Carex* fen in hollows. The community rarely occupies deep peats and is often on 10 to 15 cm of peat over sands and gravels (Figures 1a to 1d). It is difficult to map from remote sensing, owing to its similarity to other dwarf shrublands on dry slopes.

Sphagnum – *Richea* – *Empodisma* subalpine shrub bog (subalpine *Sphagnum* shrub bog, or SASSB). This is a variable community, with the *Sphagnum* moss cover varying from nil to 90%. It has a hummock form, with hummocks generally 40 to 70 cm high under dense or open emergent shrub cover (Figures 1e, 1f). *Richea continentis* is prominent on unburned bog, together with other shrubs such as *Epacris* and *Baeckea* species. Small moss-edged ponds are common, often fringed by the larger restiad *Baloskion australe* and *Astelia alpina*. *Empodisma minus* and *Carex* spp. are always present and may form fen areas within the bog complex. Subalpine *Sphagnum* shrub bog is best developed at the bases of valley sides, where flow-on and ground water are abundant. It may be patchy on valley floors or localised to seepage sources.

Sphagnum – *Epacris paludosa* medium-altitude shrub bog (MSSB) is less diverse than high-altitude shrub bog, because several high altitude species such as *Richea continentis*, *Epacris brevifolia* and *E. glacialis* are absent. The bog occupies wet gullies and spring lines, often under the woodland canopies, but it can be extensive on stream terraces. Hummocks are sometimes widely spaced, and shrubs may form an open layer up to 2 m high (Figures 1g, 1h). Stands of *Epacris paludosa* with peat mounds covered by *Empodisma* but lacking *Sphagnum* are widespread and show that the shrub bog community was formerly much more extensive.

Empodisma minus restiad moor (EM) is formed by a sward of *Empodisma* with scattered shrubs and herbs (Figures 1i to lk). *Baloskion* and *Euphrasia* are usually present, with daisies and scattered sedges, particularly mat-forming *Oreobolus distichus* and *Oreobolus pumilio*. This community is capable of occupying wet slopes (where it is essentially a moor) and often marks the boundary between wetland and dryland vegetation. On many sites it is probably successional to shrub bog but maintained by fire. *Empodisma minus*-dominated bogs are common in New Zealand (Whinam and Hope 2005).

Carex gaudichaudiana fen (CF) is ubiquitous in all wet situations at all altitudes, often forming small patches in wet tussock grasslands and *Sphagnum* shrub bogs, or a ribbon of fen along stream banks (Figure 1l). This fen forms the largest mires in the Snowy Mountains at generally medium altitudes (800 to 1250 m), where a stand of grass-like *Carex* is the main structural cover and other plants such as *Carex appressa*, *Elaeocharis acuta*, *Phragmites australis* and *Lythrum salicaria* occur along shallow drainage lines (Figures 1m, 1n). *Carex gaudichaudiana* fens are widespread in south-eastern Australia, New Zealand and the mountains of New Guinea (Whinam and Hope 2005).

Poa sod tussock grassland invades dried-out peat and can withstand waterlogging. In general, a dense stand of 30- to 60-cm-high tussocks is found on dark grey humic silts (gleyed soil), but grassland has been recorded on peat and often dominates areas of drained peat. The *Poa* grassland is dense, with the tussocks interleaved, and scattered Asteraceae (daisies) and other herbs such as *Empodisma minus* are often present (Figure 1o). The sod grasslands are complex and may be subdivided into several communities (Costin 1954); they have sharp boundaries to grasslands on well-drained sites.

Several areas on saddles in the mountains are intermittently flooded and form small ephemeral shallow ponds, such as Shelf Lake in the Mt Scabby Nature Reserve (Hope 2010). McDougall and Walsh (2007) found *Lobelia surrepens* – *Ranunculus millanii* herbfield dominating small hollows. The more ponded sites have an aquatic vegetation of *Myriophyllum*, sedges and patterned tussock grassland, with occasional waterlilies. The linear cross-slope ponds are termed flarks (Backeus 1989) and are often surrounded by tussock grasslands (Figure 1p). Some of those examined have very shallow sandy soils and may be formed by periods of deflation by wind, but for others the origin is not known.

Fauna

The fauna of the montane and subalpine mires has not been studied in any detail, and the invertebrate fauna is incompletely surveyed. Frog species have received the most attention owing to the dependence of the southern and northern corroboree frogs, *Pseudophryne corroboree* and *P. pengilleyi*, on pools within *Sphagnum* shrub bog as breeding sites for eggs and tadpoles. The adult frogs live in adjacent snowgum woodlands but are in serious decline as a result of infection by chytrid fungi. Other frogs, including the common eastern froglet *Crinia signifera* and the southern toadlet *Pseudophryne dendyi*, are also found in *Sphagnum* bogs. The broad-toothed rat, *Mastacomys fuscus*, largely lives in wet heaths on the margins of bogs and their surrounding grasslands, making runways through the moss hummocks. Also present are skinks, including the eastern three-lined skink, *Bassiana duperreyi*; the bog skink, *Pseudemoia rawlinsoni*, and the alpine water skink, *Eulamprus kosciuskoi*. This fauna attracts snakes, particularly the highlands copperhead, *Austrelaps ramsayi*, and the white-lipped snake, *Drysdalia coronoides* (Bennett 2011, Linter mans and Osborne 2002).

The lower altitude sedge fens support water birds and provide grazing for kangaroos and the swamp wallaby, *Wallabia bicolor*. The eastern long-necked turtle, *Chelodina longicollis*, and some fish species such as the mountain galaxias, *Galaxias olidus*, follow stream lines. Eastern tiger snakes, *Notechis scutatis*, often visit the fens in search of frogs.

A colourful inhabitant of bogs is the blue burrowing spiny crayfish, *Euastacus rieki*, which forms burrows through the peat and can penetrate muds to reach underlying gravels. All of these faunas may have an important effect on the hydrology of the peatlands. The well-insulated moss hummocks provide a great habitat for ants – particularly black ants, the *Ochetellus glaber* group, and the unforgettable yellow-pincered jumper ant, *Myrmecia croslandi*. A wide range of other invertebrates occurs in bogs and fens, including leeches, beetles, daphnids, other insects and cladocerans, but these have not been comprehensively studied. This also applies to the microfauna, such as amoebae (Seamer 2007).

MAPPING PEATLANDS

Mapping techniques

We aimed to map all peatlands in the upper montane, subalpine and alpine areas of the northern (NSW and ACT) portion of the Australian Alps. The mapping of mires has been developed by using orthorectified aerial photographs, provided by the Office of Environment and Heritage (OEH; previously the Department of Environment, Climate Change and Water) and acquired after the January 2003 bushfires over the period February to March 2003. These materials have been supplemented by Google Earth cover of more recent imagery, generally acquired between March 2004 and July 2006.

The advantage of using the post-fire imagery is that burnt *Sphagnum* shrub bog shows up clearly and the lack of tree or shrub canopy reveals many bog areas that would have been concealed before the fires. A concurrent disadvantage is the difficulty in separating burnt fens from surrounding tussock grasslands. Pre-fire reference was provided by 1:25 000 contour and photomosaic mapping. The 2004 to 2006 Google Earth images displayed some regeneration and so were particularly useful where the resolution of the photographic images was poor, or where an open mire area had been reduced to a featureless black zone. Stereoscopic high-resolution photography from 2008 to 2009 was not available, but tests against our mapping show it has the potential to improve boundary placement.

Mapping took place at three levels:

Level 1

No data currently exist for comprehensive identification of both the location and number of mires in the Australian Alps and neighbouring regions. Point location is a first step in quantifying the extent of these features for both threatened species habitat and for budgeting catchment hydrology. The first level of mapping has therefore identified mires by using **points** based on:

- the identification of bog sites by **visual scanning** of the orthorectified images at varying scales, depending on the quality of the aerial photography
- the use of **existing point datasets,** including the corroboree frog point dataset (created by Dave Hunter, OEH) and the montane peatland database (based on the work of Hope and Southern 1983, and subsequent work). A total of 700 mires have been identified at this level.

These ‘point bog’ datasets were used at the conclusion of the first iteration of the peat map (in June 2010) to assess map accuracy and to ensure that known peat areas had been identified.

Level 2

The total volume of peat and other organic sediments in each mire can be used to estimate the total water-holding capacity of the bogs and to derive an estimate of carbon storage. To this end, the second level of bog mapping entailed **digitising mire boundaries** at 1:3000 scale. All significant mires (generally larger than 0.2 ha) in the study region were mapped by using this method; they totalled more than 5000 individual mires, including shrub bogs, moors and fens. Mire areas were determined from the sum of all shape files for individual catchments, although the mires might have been in several discrete patches within an area.

Many peat areas were delineated on the map by extrapolation from the appearance of known peat areas nearby. The texture, colour and vegetation of one known peat area could be reasonably assumed to have similar visual characteristics in nearby areas.

Mean peat depths were determined from core transects across characteristic mires. Mire volume was then based on this peat stratigraphy, extrapolated to model the mire as a three-dimensional shape. Probing and coring were limited to visited mires and have so far provided only a general picture of probable peat volumes. Analysis of peat and sediment samples of cores can provide values for water and carbon content, which can be used to estimate total carbon.

Level 3

The boundaries of simplified vegetation units within the total peatland extents were mapped for a limited number of larger peatlands. This included sod tussock grassland as a wetland unit.

Field validation/checking

Only a small proportion of the mire areas in the region have been ground truthed to allow actual boundaries to be checked against the mapping using handheld and differential GPS devices. However, inspections have been spread across the region to characterise mire situations across the altitude and geographic setting in the Kosciuszko National Park and surrounds. Peat type and depth have been checked by probing and coring with a D-section corer. Boundaries have also been amended and additional sites added with advice from OEH, P&WG staff, especially Rob Atkins, Roger Good, Ken Green, Dave Hunter, Eloise Peach and Genevieve Wright.

In addition, several aerial surveys were conducted by Helisurveys for P&WG in the Jagungal, Main and Charcoal Range areas of Kosciuszko National Park and the Scabby Nature Reserve (NR), as well as ground-based expeditions to Cup and Saucer, Tin Mine, Happy Jacks, Currango, Eucumbene, Kiandra, Long Plain, Nungar Plain, Tomneys Plain and Scabby NR by the authors, together with Iona Flett, Roger Good, Ben Keaney, Trish MacDonald, Bren Weatherstone and Jennie Whinam. Mires were photographed and margins mapped, with depth and peat stratigraphy determined where possible.

Some of the survey work has been associated with the program carried out from 2003 to 2009 to assess fire damage and repair the hydrology of burnt mires (Carey *et al.* 2003, Good 2006a, Growcock and Wright 2006). In addition, a post-fire monitoring program (Hope *et al.* 2005, Whinam *et al.* 2010) has resulted in repeated visits since 2003 to assess mire condition and remeasure permanent plots at Pengillys Bog and Guthries Bog, near Perisher, and Delaneys Bog and Boggy Plain, west of Adaminaby. Mire assessment has also been included in a continuing study to investigate the history of the peatlands. Stratigraphic coring has been carried out by the authors, with the help of staff and students from the Australian National University, at Blue Lake, Coree Flat, Dunns Flat, Micalong Swamp, Mosquito Creek, Pengillys Bog, Rennix Gap Bog, Snowgum Flat, Tarcutta Swamp, Tomneys Plain and Yaouk Swamp. Additional stratigraphic information was provided by Alec Costin, John Dodson, Tony Martin, Scott Mooney and Stuart Pearson.

Software

The digital map used in this report was constructed by using Esri ArcMap software, version 9.3. Site data were extracted and used to set up a database in Filemaker 10, which was used to classify peatlands, extract summaries and calculate peat volumes.

Impact of the 2003 bushfires on map accuracy

The majority of the orthophotos were captured following the bushfires of January 2003. Although some areas of the park were severely burned in these fires, other areas – sometimes nearby – were virtually unaffected. In some areas the fire appeared to have been more intense than in other areas, and in some orthophotos, but not in others, it was apparent that vegetation recovery had commenced.

The fire damage had both positive and negative impacts on the utility of the orthophotos in detecting peat:

- In some areas, the fire completely removed the vegetation, allowing unimpeded inspection of the colour and texture of the ground surface.
- Some peatland vegetation, especially Sphagnum, burned to a reasonably distinct yellow-orange, thus facilitating identification.
- Conversely, in other areas the fire had blackened areas into a uniform texture and colour, making identification of vegetation and accurate delineation of peat areas a difficult task.

Tussock grasses, for example, which are not usually an indicator for peat, sometimes burned to a very dark black, similar in appearance to bare peat soil.

Mosaiced 1:25 000 topographic maps

Paper and scanned 1:25 000 Land & Property Information topographic maps of all areas within the Kosciuszko National Park were used in naming the peat areas, as a ‘quick look’ tool to identify likely areas, and to locate known peat areas described in text from various sources.

In addition, the reverse sides of many of the topographic maps included an orthophoto matched to the topographic map. These photographs, captured in 1999 and 2001, were also useful in identifying areas of peat and assessing 2003 fire damage.

A note on the naming of peat areas

Almost all of the peat areas were delineated as far as possible into discrete polygons. Thus an area known generally as a ‘peat swamp’ may have been divided into multiple polygons. In some cases the separate polygons may have reflected the different vegetation in different parts of the peat area. In other cases, a small patch of rocks or high ground may have been excised. This was done in the interests of accuracy but has resulted in many peat areas being fragmented into numerous polygons.

Every polygon was assigned a catchment, an individual name and a position within or near the Kosciuszko National Park (north – KNPN, mid – KNPM, and south – KNPS). Catchments were allocated by overlaying a catchment map provided by OEH. Names for each polygon were derived from the maps by using available names (e.g. Finns Swamp) where possible, or the stream name for the majority of cases (e.g. Doubtful Creek 24).

Digital elevation model

A digital elevation model (DEM) provides averaged elevation values across a cell of a given size for the ground surface topography of a given area. The DEM used in this project was derived from 10-m and 20-m contour data contained in the pre-1995 NSW Topographic Map Archive, processed to produce a 25-m cell grid with vertical accuracy to within 0.5 of the source data interval. The DEM was used to determine the elevation, slope and area of the polygons that describe peat patches. In addition, the ArcMap software used the DEM to construct a nominal stream network (see below).

Mire parameters

Vegetation units

An attempt was made to allocate to each shape file a vegetation community that represented the dominant vegetation and ignores minor occurrences of other communities. The communities chosen are the first five categories in Table 2.

The five mapping units are:

1–3. *Sphagnum* shrub bogs divided into alpine, subalpine and mid-altitude communities

4. Restiad moorlands dominated by *Empodisma minus*, *Baloskion australe* and occasional grasses and shrubs. *Sphagnum* moss may be present but is minor.

5. *Carex gaudichaudiana* fens, including areas of *Phragmites* – *Typha* tall sedgeland at low altitudes.

Additionally, for selected larger mires the boundaries of simplified vegetation units on the mire and marginal tussock grasslands have been mapped. Vegetation cover could be allocated with confidence for inspected sites, but the allocation to remotely sensed sites is much more subjective. Alpine shrub bog, in particular, presents difficulties, as dryland heaths of *Epacris* species have a similar appearance to shrub bog and the alpine shrub bog is often a fine-scale mosaic of bog, fen and dryland heath on sand ridges or rocks. With images of severely burnt areas, sod tussock may be incorporated into fen or *Empodisma* moor. Vegetation is a dynamic characteristic of peatlands that can change via succession or under drying or wetting trends.

Elevation

In calculating the altitude of individual peat areas, the ‘spatial analyst’ extension in ArcMap calculated the *mean* elevation from all the elevation values for cells derived from the DEM. As some of the patches (polygons) of peat were smaller than the 25-m cells of the original DEM, the DEM was resampled to produce another with a 5-m cell size. The centroid of each of the 5-m cells occurring within each polygon was then averaged to provide the mean elevation for each patch of peatland.

Owing to the computationally unwieldy size of the 5-m DEM, it was not used for further terrain analysis and all other parameters were processed from the 25-m DEM dataset.

Slope

The spatial analyst extension in the ArcMap software calculates the slope of the individual areas of peat by determining the *maximum* change in elevation between each cell of the DEM image and its neighbouring cells. Where peat areas covered more than one 25 × 25 m cell, all slope values of all cells with centroids within the peat area were averaged.

Stream network

The 25 m DEM was also used to construct a stream network. The stream network was used to help allocate the ‘class’ of individual peatlands (see below). Using the spatial analyst extension of ArcMap, a stream network was calculated by examining each cell of the DEM and determining the number of up-slope cells that would deliver surface water to that cell. When the amount of surface water entering a cell from upslope reached a given threshold, a ‘stream’ is said to exist. In this project, the threshold at which a stream was said to exist was determined by overlaying the topographic map onto the DEM and varying the threshold until it most closely matched the streams delineated on the topographic map that reflect observable channels.

Hydrogeomorphic class

The slope, elevation and stream network datasets derived from the 25 m DEM were used to automatically allocate one of three ‘classes’ for each peat area (*sensu* Lawrence *et al.* 2009), namely **Hillside, Plateau and Ridge**, and **Valley Floor**. Peat patches with a mean slope greater than 5° were automatically allocated class Hillside. Peat areas on flatter ground without an intersecting stream were allocated to the Plateau and Ridge class, whereas areas that were intersected by a stream fell into class Valley Floor. As these class allocations were determined automatically by the ArcMap software on the basis of the parameters described above, a detailed visual inspection of the results was conducted.

Some peat areas were found to be classed as Hillside even though they appeared to be on relatively flat areas. The most common cause was found to be that although these areas usually fell on a moderate slope of a few degrees, they often included smaller areas of higher slope. In some cases this small area of steeper slope was assumed to have been enough to cause the *mean* slope value to ‘tip’ past 5°. Nevertheless, some adjustments were made to the membership of this class on the basis of visual inspection.

Visual inspection of the automatically-generated Valley Floor class of peat showed that many peat areas had fallen into this class by virtue of an intersecting stream. Although the term ‘valley’ is a subjective one (especially in a mountainous region such as the Kosciuszko National Park), it was considered that the set parameters had resulted in an overly generous view of what constitutes a valley. In consequence, many members of this class – particularly those from high elevations with small catchments – were re-classed as Plateau and Ridge. We did not assess the Valley Floor mires for the presence of major stream confluences that Lawrence *et al.* (2009) defined as a fourth class Tributary Junction peatlands, finding only one example in their study region.

Notes on the peat map

Most of the peat areas covered by this map have been examined at resolutions exceeding 1:3000 and have had their boundaries modified several times, reflecting improvement of data sources. However, even after several iterations, it is certain that many errors of commission and omission remain and that accuracy could always be improved. Even with expert help from people familiar with various areas in Kosciuszko National Park, it has not usually been possible to exactly map an area containing peat. Lower altitude mires along creek lines in forested areas such as Bago State Forest or the far south of Kosciuszko National Park may have been missed. The limited resolution of the aerial map, damage from fire, and the fragmented and variable nature of the peat all limit the final accuracy of the map.

The Kosciuszko region peatland map consists of GIS shape files that are congruent with the P&WG system. A version has been provided to P&WG in Queanbeyan, NSW. The GIS is currently maintained at the ANU Department of Archaeology and Natural History and will undergo further additions and corrections as an ongoing project. The map is owned by OEH, and requests for access should be directed to this department. It is summarised as Figures 3a to 3e, which show the mires by vegetation unit.

RESULTS OF MAPPING

Distribution of bogs and fens in southern NSW

Mire size

In the montane and subalpine regions of southern NSW and the ACT, mires total about 8000 ha, of which 6000 ha occurs in Kosciuszko National Park. The three *Sphagnum* shrub bog communities account for about two-thirds of the mires and half of this area. Table 3 and Figure 2 show that many of the mires, and especially the shrub bogs, are very small (though in many cases contributing to a larger mire complex), with over 70% being less than 0.5 ha (5000 m^2). Excluding the ACT, only nine shrub bogs are bigger than 20 ha, and the average size of those larger than 0.5 ha is 2.16 ha (median 1.10 ha).

Table 3. Peatland shapefiles and cumulative areas for all mires and for three types of *Sphagnum* shrub bog in the Snowy Mountains region, including the ACT and Brindabella Ranges. Figures from other states are not calculated on the same basis but should be comparable. Victorian figures (Lawrence *et al.* 2009) are mainly for subalpine shrub bog; Tasmanian data (J. Whinam, Tas. DPIPWE 2010, pers. comm.) include all *Sphagnum*-dominated communities, including herbfields, some of which are not found on the mainland.

Size (ha)	All peatlands			*Sphagnum* bogs	
	Number	Cumulative	Area (ha)	Number	Area (ha)
0.001–0.25	5058	55.5	510.2	3670	361.9
0.25–0.5	1516	72.1	536.9	1051	369.3
0.5–1	1058	83.7	744.8	708	494.8
1–5	1186	96.7	2477.4	709	1465.4
>5	303	100	3717.3	143	1437.0
All	9121		7986.7	6299	4130.8
Kosciuszko NP	7336		6037.0	5455	3655.6
ACT mountains	844		555.6	490	190.3
Victoria >1000 m	2377		2713		
Tasmania >800 m				757	2865

The total area of all peatlands in the Australian Alps above 1000 m, excluding *Carex* fens larger than 0.5 ha, is 8300 ha (ACT, NSW and Victoria combined). This is 60% more than the estimate of 5200 ha made for *Sphagnum* shrub bog by Alec Costin (1954) and Grover *et al.* (2005). This increase can largely be attributed to the detailed mapping and area calculation made possible by GIS techniques, and to the inclusion of *Empodisma* moor as a marginal mire type that occupies shallow peats.

The largest mires are montane and subalpine *Carex* fens, with 16 in the region exceeding 20 ha (average 43.9 ha). The most extensive fen is Mosquito Creek in northern Kosciuszko NP, at 160 ha (Figure 1m). However, the average size of those fens over 0.5 ha is nearly the same as for shrub bogs at 2.24 ha (median 0.73 ha), indicating that numerous small stands of fen also occur.

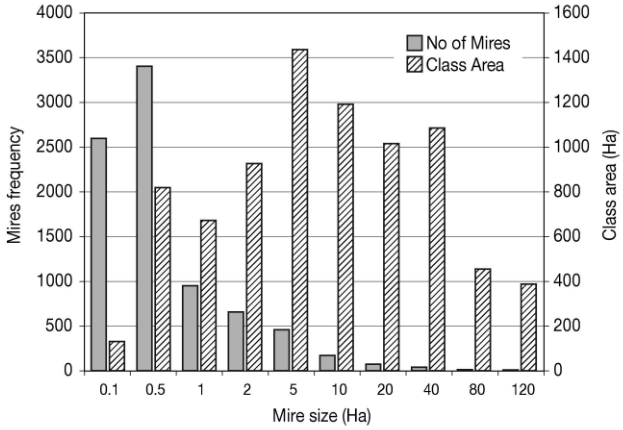

Figure 2. Number of mires and area in 10 size classes in the Snowy Mountains region, including the ACT

Although mires are found across the region, there is a concentration in higher rainfall areas (>1400 mm annually) with gentle topography, such as on the crests of the major ranges. Mires are also common at the break in slope at the bases of long slopes, where they occur along stream lines. By contrast, steep slopes such the western fall of the Main Range and the gorge of the Tumut River do not support mires. Similarly, mires are rare in rainshadow areas such as the Byadbo wilderness around the Snowy River (<800 mm). Peatlands on alluvial fills are replaced by sod tussock grasslands growing on organic-rich mineral soils.

Altitudinal distribution of mires

Mires form a larger proportion of the ground area with increasing altitude, accounting for only 0.035% in the montane below 1200 m, 1.35% in the subalpine from 1200 to 1600 m, and about 2.55% in the alpine above 1600 m. Mires larger than 0.4 ha have been categorised into the northern, central and southern regions of the Snowy Mountains (Table 4 and Figures 3a to 3e). The northernmost mires mapped include sedge fens east of Tumut, such as Couragago and Micalong, and the open plateau country at moderate altitudes ranging from Tomneys Plain and Tarcutta Swamp in the west to Yaouk in the east. Some subalpine area is included around Kiandra, on the Bogong Peaks (Jounama), and along the Brindabella Range in the Bimberi and Scabby NRs. The central region, from the Snowy Mountains Highway to the Thredbo River, has the greatest proportion of plateau-like wet high subalpine and alpine habitat that is subject to lengthy seasonal snow cover. It also includes some drier and lower country to the east of the range. The southern region is smaller and generally steep but has extensive subalpine habitat as well as montane valleys south of Jindabyne.

Table 4. Montane, subalpine and alpine mires greater than 0.4 ha (n = 2812) in northern, central (including the Main Range) and southern regions of the Snowy Mountains (ACT excluded)

Altitude zone (m)	Region					
	North		Central		South	
	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)
		501 100		298 087		116 722
600–1200	107	564.6	37	91.5	56	193.1
1201–1650	495	1749.2	1005	2206.0	223	387.9
>1650	5	4.8	772	1313.0	112	138.5
Total	607	2318.6	1814	3610.5	391	719.5
% Mire area		0.46		1.21		0.62

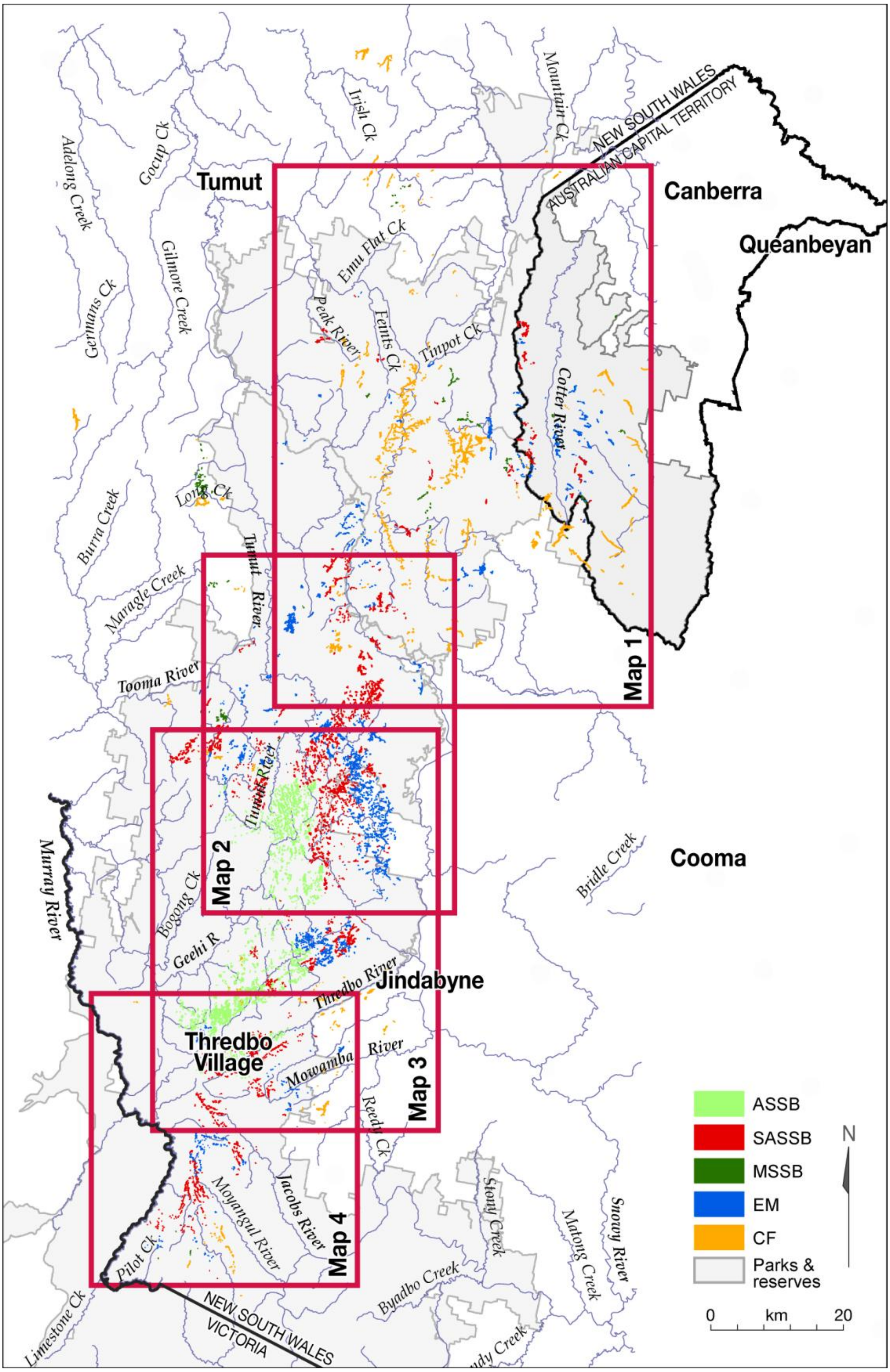

Figure 3a. Summary of mire distribution in the Snowy Mountains region. ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

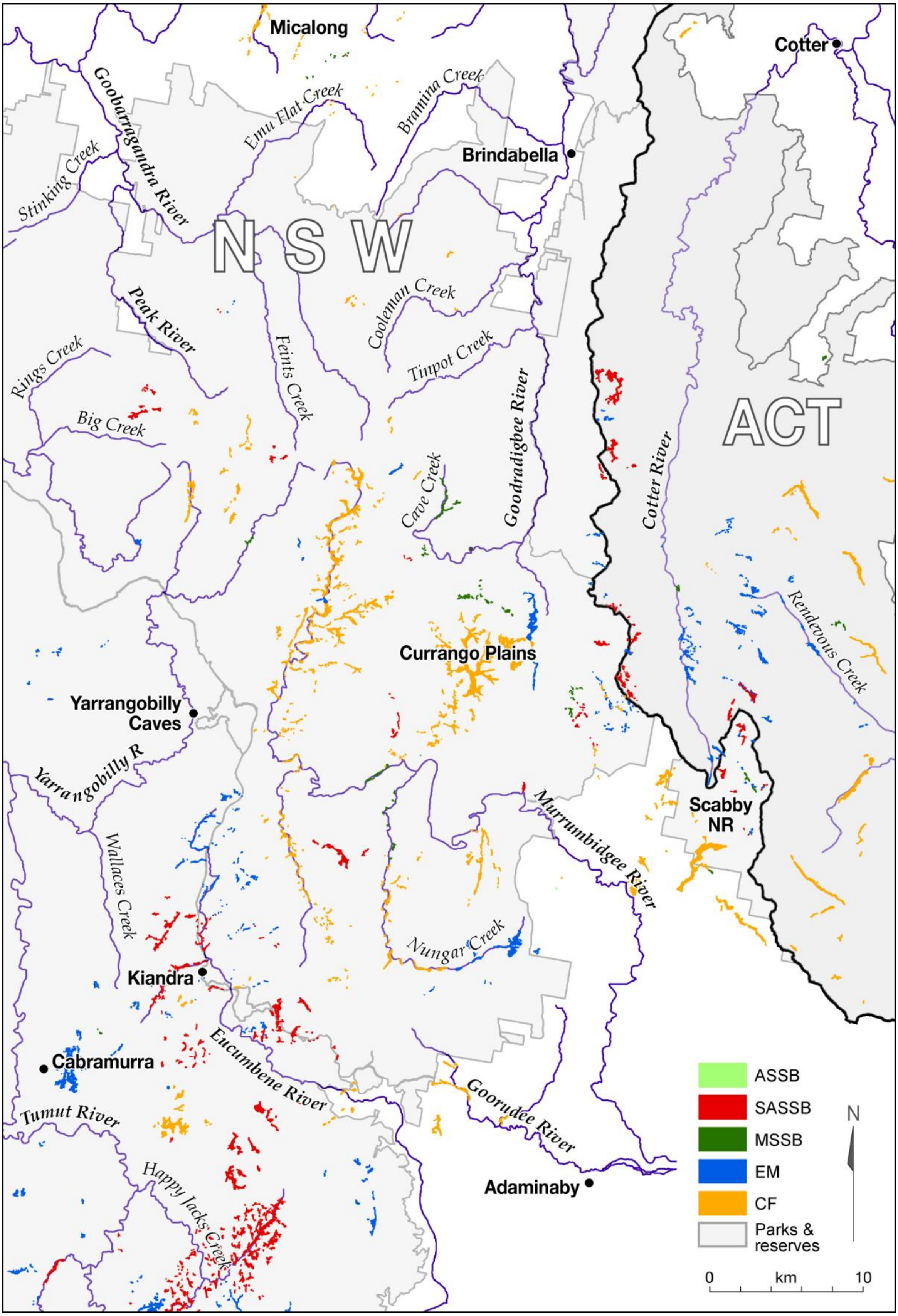

Figure 3b. Mire distribution in the northern Snowy Mountains. ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

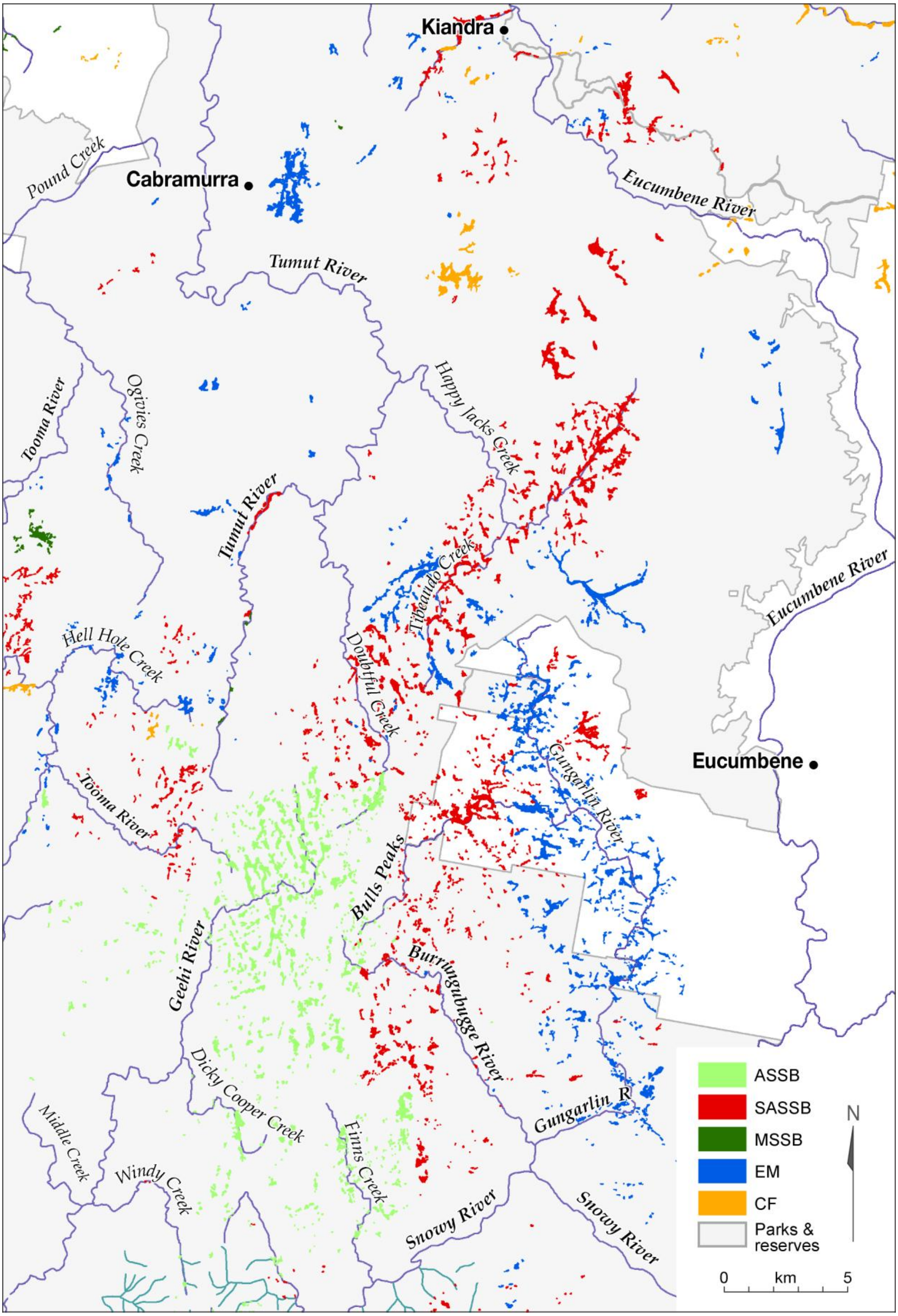

Figure 3c. Mire distribution in the central Snowy Mountains around Mt Jagungal. ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

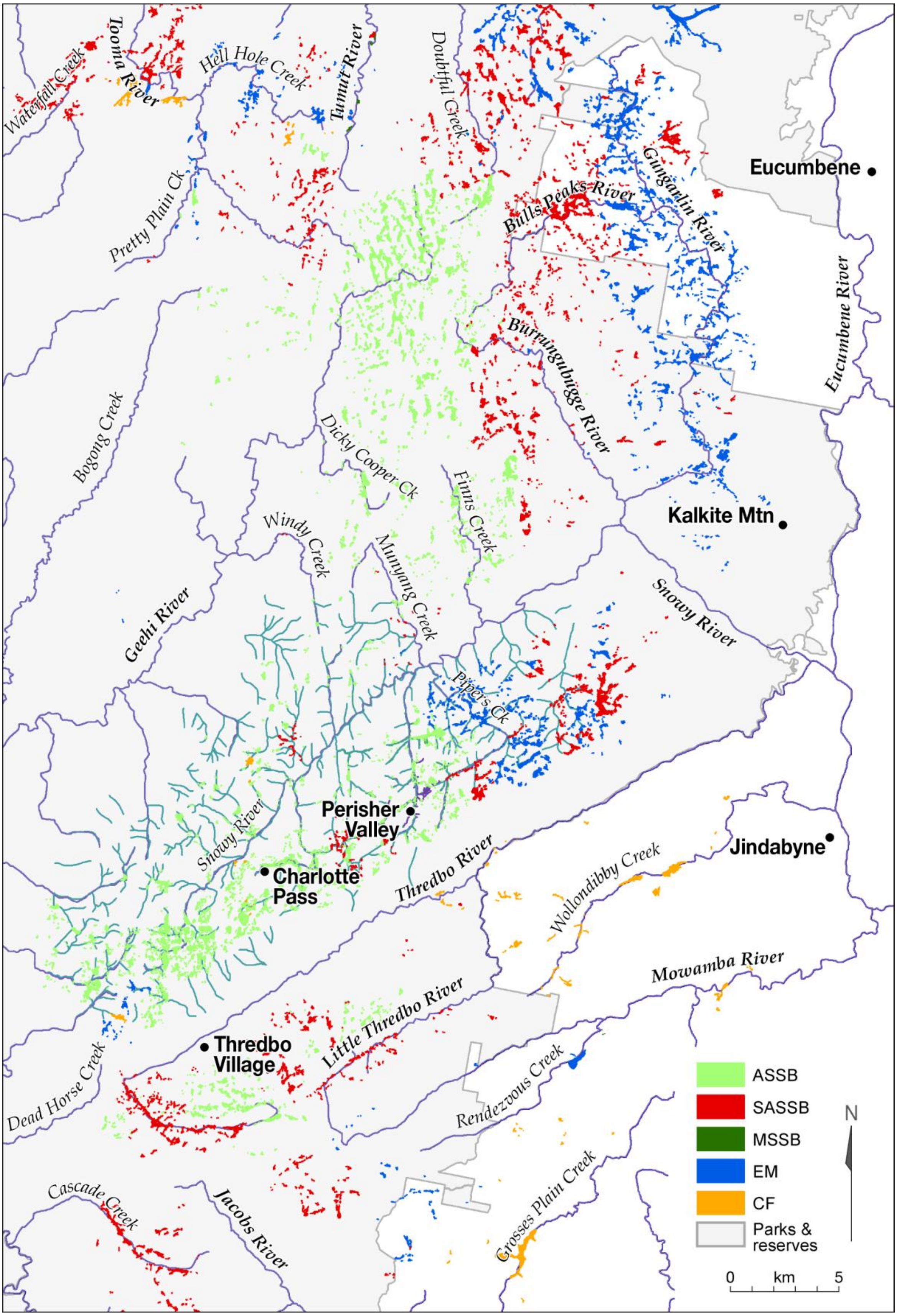

Figure 3d. Mires in the southern area and Main Range. ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

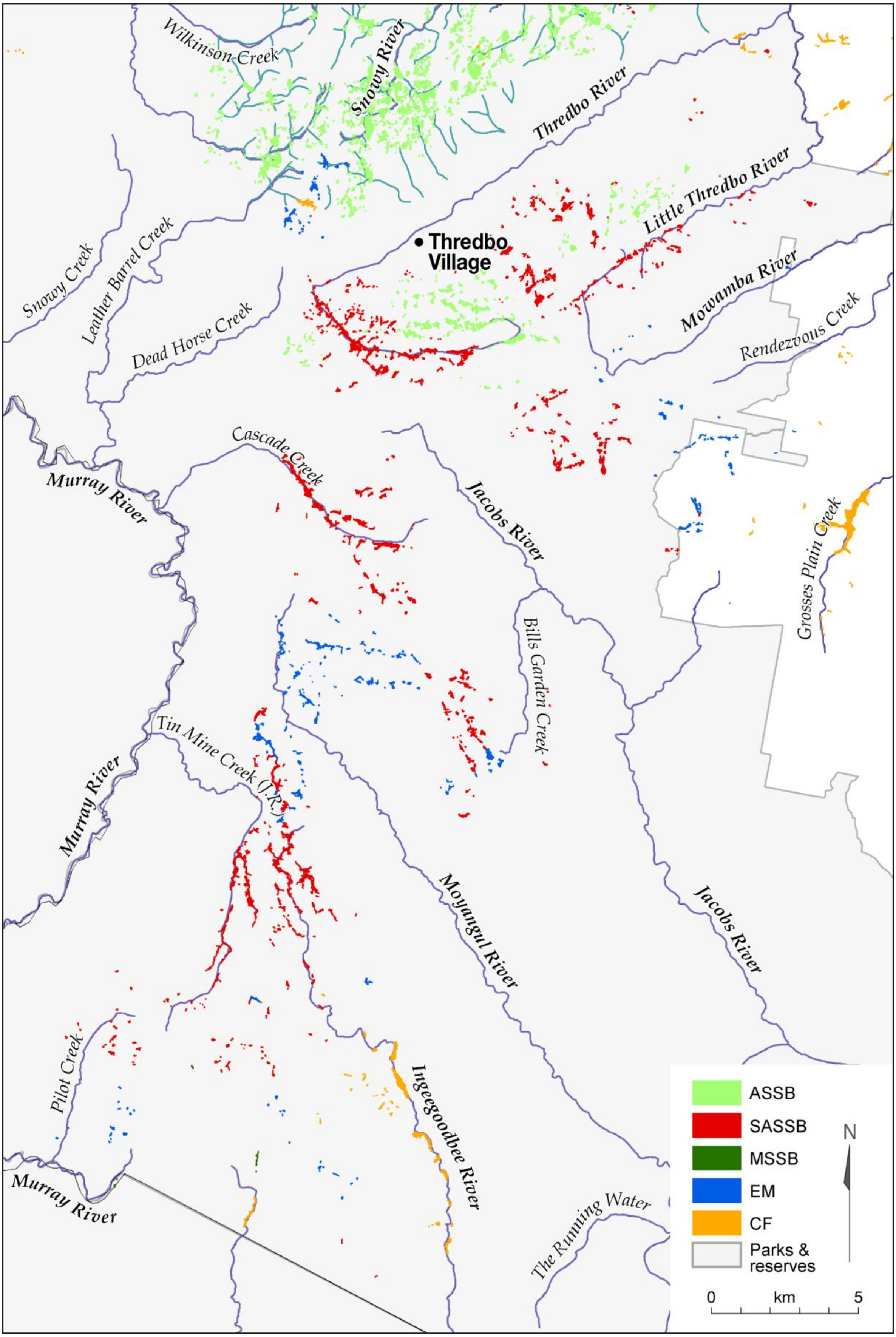

Figure 3e. Mires in Chimney and Charcoal ranges, southern Kosciuszko National Park. ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

Figure 4 shows that the frequency of mires increases with altitude, although the larger mires are found below about 1600 m. The northern region shows two peaks, one between 1100 and 1400 m and another, quite separate, occurrence around 700 to 800 m that includes some extensive fens at the northern and western limits of the mountains. The central region displays a large number of small mires in the alpine area above 1650 m; this reflects a high concentration, because the alpine area is relatively small. It also has the most extensive subalpine mires, centred at 1450 to 1700 m. This is a slightly higher altitude than those of the northern region. . The southern region has smaller mires that are not concentrated in any altitudinal band, although the larger mires occur at about 1100 to 1275 m.

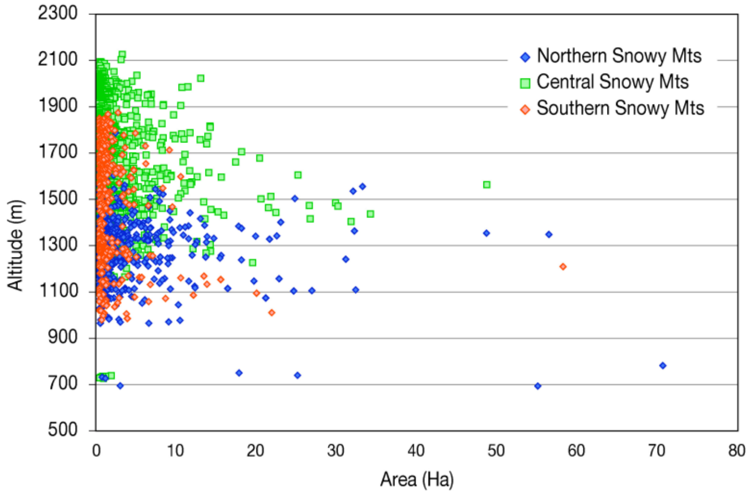

Figure 4. Plot of all mires greater than 0.4 ha (n = 2812) in the northern, central (including Main Range) and southern sub-regions of the Snowy Mountains. One large *Carex* fen (Mosquito Creek, 160.7 ha, 1230 m, northern Snowy Mountains) is omitted.

The same distribution is seen in Figure 5, which plots the 1000 largest mires. This shows that the southern region has relatively few such mires, with a near absence between 1325 and 1450 m, owing to the presence of steep slopes in this altitudinal zone.

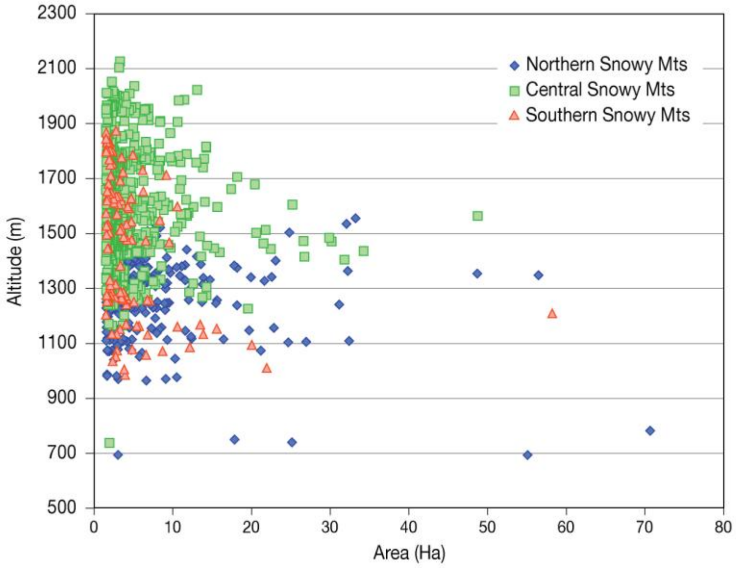

Figure 5. Plot of all mires greater than 1.5 ha (n = 967) in the northern range and southern regions of the Snowy Mountains. One large *Carex* fen (Mosquito Creek, 160.7 ha, 1230 m, northern Snowy Mountains) is omitted.

Above 1500 m in the central sub-region there is a near-linear reduction in the size of the largest mires with increasing altitude. This reflects the decrease in individual mire size as a mosaic of wet heaths, mires, herbfields and grassland that is partitioned by strong environmental gradients is established. Within mires, pools, fens, herbfield, moor and two types of shrub bog also occur on peat or organic soils in patches that become finer in scale with increasing altitude. Peat depth is greatly reduced at high altitudes, allowing minor changes in substrate to be expressed. Slow recovery from disturbances, such as through trampling and fire, also contributes to the heterogeneity.

The distribution largely reflects available habitat – for example the absence of high areas in northern Kosciuszko NP and the presence of extensive plateaus at 1500 to 1700 m south of Mt Jagungal. This confirms the conclusion of Lawrence *et al.* (2009) that 'the location of peatlands over 1000 m is strongly correlated with the location of elevated plateaus, rather than with elevation *per se*'. However, altitude is directly correlated with lower temperatures and increased precipitation and cloudiness. Hence it is not surprising that the raised plateaus south of Mt Jagungal down to the Rams Head Range support the best development of mires, including the most extensive areas of alpine *Sphagnum* shrub bog in mainland Australia.

Vegetation community distribution

Table 5 and Figure 6 show that the three *Sphagnum* shrub bog communities are altitudinally differentiated but show overlap that probably conceals greater diversity of community than can be covered here. Thus the presence of a diverse and emergent shrub cover that includes *Richea continentis* and several *Epacris* spp. distinguishes the subalpine shrub bogs from the more carpet-like alpine *Sphagnum* shrub bog and the more open and depauperate montane *Sphagnum* bogs. Although the misallocation of mire type in the case of individual mires that were not visited may contribute to possible errors, the overlaps seem to be real and to reflect topographic controls in some cases. The alpine mire is probably controlled by seasonal snow lie and wind exposure, as it is found on open areas, whereas the highest occurrences of subalpine *Sphagnum* shrub bog are found in protected valleys, often with shelter from adjacent snow gum stands. Small stands of montane *Sphagnum* bog extend to below 500 m in NSW but rarely dominate mires. The community is often shaded by slopes or overhanging trees but will grow in the open where water is abundant, for example along spring lines.

Table 5. Extents of five mire vegetation units in the Snowy Mountains region of NSW. (SSB = *Sphagnum* shrub bog)

Altitude zone (m)	Alpine SSB	Subalpine SSB	Montane SSB	*Empodisma* moor	All bogs and moor	*Carex* fen
	Area (ha)					
700–1000	0	0	0.9	1.3	2.2	225.7
1000–1300	0	173.2	139.1	202.1	514.7	1136.2
1300–1600	41.9	1590.3	15.9	1263.3	2911.4	493.0
1600–1900	981.5	597.2	0	166.2	1744.9	4.0
>1900	393.9	0	0	14.3	408.2	12.4
All	1417.6	2360.8	155.9	1620.2	5554.5	1871.3
KNP only	1417.6	2145.9	92.2	1265.7	4921.2	1109
ACT Mountains	0	156.6	11.3	160.6	350.9	203.7

The other two communities, *Carex* fen and *Empodisma* moor, occur at all altitudes, although fens are most common and extensive below 1400 m. A detailed floristic analysis would probably differentiate several fen communities, but all have a similar hydrological function, occupying drainage lines and acting to spread water and trap sediment while building up peat that forms level sheets across valleys. Kershaw *et al.* (1997) found that, in the south-eastern highlands of Victoria, raised bog dominates under higher rainfall, whereas in drier areas fen rather than bog is represented. There is a critical moisture threshold below which raised bog cannot form; at Caledonia Fen (1280 m) the rainfall of 1530 mm is around this threshold (Kershaw *et al.* 2007). Moisture variability is probably also a contributing factor to bog development as well as to maintenance of a continuum between aquatic communities and fen. Pollen analysis shows that such sedgelands have often been an early successional stage that has raised the watertable, allowing the invasion of bog plants. However, where the *Carex* fen is fed by a substantial catchment, its ability to spread this water across a broad valley section has created a stable and resilient ecosystem that has grown and persisted throughout the Holocene. These extensive fens include the largest mire complex in Kosciuszko National Park, the Sally Tree Creek – Mosquito Creek complex of 55 mires totalling 286.9 ha.

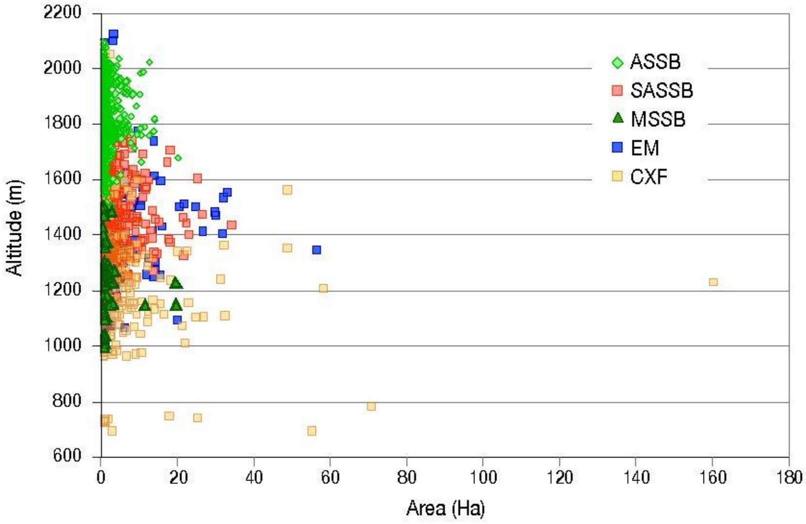

Figure 6. Plot of all mires greater than 0.4 ha (n = 2812) in the Snowy Mountains, by dominant vegetation type

Empodisma moor is common and extensive at all altitudes, particularly overlapping with subalpine *Sphagnum* shrub bog. On wet sites with gentle slopes and deep (>35 cm) peats it clearly is successional to *Sphagnum* shrub bog, with fire as a likely cause for its present extent. In a survey of a decline in *Sphagnum* shrub bog extent, Whinam and Chilcott (2002) found that *Empodisma* had colonised former moss hummocks in many areas. This has also been seen in the post-2003 fire monitoring at many sites, for example on Boggy Plain, where *Sphagnum* has persisted in only three of 10 former bog plots. However, the moor often forms a zone on steeper slopes on shallow peat, on which it is unlikely that *Sphagnum* shrub bog could develop. Here it may also be successional to a wet heath. In a study of an ACT mire, Hope and Clark (2008) have shown that the Restionaceae gradually increase and that *Sphagnum* shrub bog, though present over more than 8000 years, appears not to gain dominance. As is true of all mires in the region, the presence of charcoal shows that fire has always occurred at this site. As a tough and resilient form of vegetation, *Empodisma* moor is a valuable component of the mire systems in holding ground against dryland invasion and maintaining peat cover, even in the face of grazing (McDougall 2007).

Slope and mire hydrogeomorphic class

Slope influences water availability positively by run-on and groundwater discharge and negatively by drainage. Peatlands can form on steep slopes up to 22° but are usually on flatter ground. For all mires on slopes of 5° or greater the mean slope is 9.8° (n = 4979), and for mires greater than 0.4 ha the mean is 8.2° (n = 1327). We found that larger mires on slopes tend to occur on lower gradients.

Mires have been divided into three of the hydrogeomorphic classes of Lawrence *et al.* (2009): Hillside peatland, Valley Floor peatland, and Plateau and Ridge peatland. Hillside peatlands occur at breaks in slope or where drainage depressions join, but are defined by an average slope of > 5°. Valley Floor peatlands may infill valleys with pools and multiple small drainage lines, or have distinct sinuous channels that may be incised. Plateau and Ridge mires occur on level ground with only minor slopes around and do not have definite stream channels, but they often have ponds. Lawrence *et al.* (2009) also define Tributary Junction Peatland as a type of Valley Floor peatland that has at least one stream junction, but this proved impractical to map in our study. Table 6 summarises the distribution of peat classes by altitudinal bands.

Table 6. Summary of the extents of three hydrogeomorphic peatland classes in the Snowy Mountains region, excluding the ACT. Percentage values refer to the relative area of each peatland class within each altitudinal zone

Altitude zone (m)	Hillside peatland			Valley Floor peatland			Plateau and Ridge peatland		
	No.	Area (ha)	%	No.	Area (ha)	%	#	Area (ha)	%
700–1000	14	2.4	1.1	38	222.7	97.7	6	2.8	1.2
1000–1300	314	229.5	13.9	565	1304.9	79.0	200	116.4	7.1
1300–1600	1615	1047.1	31.0	866	1846.3	54.7	515	484	14.3
1600–1900	2354	900	51.3	438	548.8	31.3	429	306.3	17.5
>1900	681	256.8	61.1	81	89.1	21.2	163	74.7	17.8
All	4978	2435.9	32.8	1988	4011.9	54.0	1313	984.2	13.2
KNP only	4542	2221.5	36.8	1613	2970.5	49.2	1181	845.1	14.0
ACT	483	137.0	24.7	273	392.5	70.8	85	25.1	4.5
Vic. mountains above 1000 m	1044	1350	50.5	196	1190.2	44.5	137	132.3	5.0

It can be seen that Valley Floor peatlands form a smaller proportion of all peatland with increasing altitude. This probably reflects water relations in that, at lower and drier altitudes, the only sites with abundant water are at the bases of slopes and along stream lines. With increasing altitude mires become common on shallow and steep slopes. Plateau and Ridge peatlands are rarer than the others at all altitudes but become more common with increasing altitude. They are, however, much more common in the Snowy Mountains than in the Victorian highlands, reflecting both the presence of gentler slopes in NSW and the absence of recent cattle damage, which Lawrence *et al.* (2009) and McDougall and Walsh (2007) suggest have reduced Plateau and Ridge peatlands the most drastically in Victoria. In wetter or cooler climates the Plateau and Ridge mires would expand and form blanket bog.

Table 7 analyses the distribution of vegetation types in the three hydrogeomorphic classes. The alpine and subalpine *Sphagnum* shrub bogs and *Empodisma* moor contribute most to the Plateau and Ridge class. By contrast, *Carex* fen dominates the Valley Floor class, with relatively few, but very large, lower altitude mires. Montane *Sphagnum* shrub bog is also concentrated on valley floors, reflecting the relatively drier slopes in its altitude zone.

Table 7. Correlation of vegetation mapping unit with hydrogeomorphic class. Percentage values refer to the proportion of each vegetation unit in a particular hydrogeomorphic class.

Altitude zone (m)	Hillside peatland			Valley Floor peatland			Plateau and Ridge peatland		
	No.	Area (ha)	%	No.	Area (ha)	%	No.	Area (ha)	%
ASSB	2170	740.1	30.4	381	464.4	11.6	448	213.2	21.7
SASSB	1613	912.6	37.5	622	1113.5	27.8	362	334.5	34.0
MSSB	61	24.7	1.0	98	123.1	3.1	29	8.1	0.8
EM	907	526.4	21.7	404	761.5	19.0	326	332.4	33.8
CF	207	227.0	9.3	483	1549.4	38.6	144	95.0	9.7
Snowy Mountains All	4979	2435.9	100	1988	4011.9	100	1313	984.2	100

ASSB is alpine *Sphagnum* shrub bog, SASSB is subalpine *Sphagnum* shrub bog, MSSB is montane *Sphagnum* shrub bog, EM is *Empodisma* moor and CF is *Carex* fen.

Subalpine *Sphagnum* shrub bog is the most extensive mire type and is important in all three classes, dominating the hillslope peatlands, where it forms small patches at the head of creek lines.

Although Lawrence *et al.* (2009) make a case for classifying mires by hydrogeomorphic class, owing to the ability of GIS to distinguish these classes and their use in water yield modelling, the classes are a function of topography and are thus fixed. The vegetation units used by Hope *et al.* (2009) and in this report require field mapping, but they are dynamic and in our view are more useful for assessing changes in peatland condition.

CHARACTERISTICS OF THE MIRES

The mires preserve characteristic profiles of peat and organic-rich mineral sediment that reflect the types of source vegetation and history. Although the stratigraphy of the mires of the Snowy Mountains is quite variable, related sequences are found in similar mires, suggesting a common history of formation. Nine typical mires are described below, in terms of setting and stratigraphy, to provide examples of the wide range of mires in the region.

Alpine *Sphagnum* shrub bog on gravel fans

Swampy Plain River below Lake Cootapatamba: 9.1 ha; 36°29.044′S, 148°14.880′E; 1906 m; Hillside-Valley Floor (Figures 7a, 7b)

Figure 7a. Alpine bogs and fens below Cootapatamba hut, Swampy Plain River, February 2010. Photo: Geoff Hope

Figure 7b. Alpine *Sphagnum* shrub bog on gravel fans, Swampy Plain River. Photo: Genevieve Wright

In the high alpine zone to the west of Rams Head a mire complex has developed on a gravel fan and terraces along Swampy Plain creek. Gravel bars support an alpine heath with an alpine *Sphagnum* shrub bog in hollows and along stream lines. The bog is a flat shrub-herb mosaic of *Sphagnum*, with *Baeckea gunniana, Epacris glacialis* and *Richea continentis*, *Astelia alpina, Baloskion australe, Carex gaudichaudiana, Carpha nivicola, Celmisia* spp. *Diplaspis nivis, Empodisma minus*, *Erigeron paludicola* and *Oreobolus distichus.* Frequent pond areas are surrounded by *Carex gaudichaudiana* fen and support a *Myriophyllum* aquatic community. Peat depth varies from 10 cm along streams to 40 cm in ponds.

Depth (cm)	Sediment
0–15	*Astelia* cushion and brown sandy fibrous peat
15–65	Grey peaty coarse to medium sands
65– >90	Peaty silts with occasional sand bands and sapric peats

Although this site has not been dated, the layers above 65 cm probably reflect the widespread damage caused by grazing, which has led to removal of peat and burial by erosion from slopes. The modern peats are allowing mire vegetation to spread, but the extent of peat loss is hard to judge. Martin (1999) reports an age of 1485 ± 100 calibrated years before the present (cal a BP) (Gak 1402) for the lowest organic layer at 35 cm depth at 1990 m on Mt Stillwell. This may correlate with the buried organic layer at Swampy Plain River. Costin (1972) obtained modern dates (<150 cal a BP) for peats buried by sand and gravel at 2010 m on Mt Twynam. Six metres of sedge peat intercalated with silt bands has accumulated in a *Carex* fen on a terrace at 1955 m on the margin of Club Lake (Martin 1986a), a site that has abundant moisture and is more sheltered than Swampy Plain. Well-drained sites probably accumulated much less peat and peaty clays through the Holocene. Costin (1972) reports several examples of sites near Blue Lake where late Holocene peat was buried by gravels and the sites were then recolonised by peat; it is therefore likely that the high alpine area has not supported continuous peat growth at most sites. A current example is the loss of alpine humus soils and peat at Mt Tate after the fires of 2003 (Figure 20c). The fires burned and sterilised the top layers of organic soil, killing resprouters such as *Baeckea gunniana*. Plants found it difficult to recolonise for 5 years after the fire, during which time wind deflation and frost heave stripped away the organic layer, possibly representing soil capital of millennia Whereas Costin (1972) attributed the alternations of peat growth and slope erosion to direct climate influence, fire activity may have been responsible, although it also reflects climate periods of high temperature, summer drought and increased dry lightning episodes.

Alpine *Sphagnum* shrub bog and *Carex* fen

Upper Geehi River, southern slopes of Mt Jagungal: 2.5 ha; 36°09.677′S, 148°24.443′E; 1810 m; Valley Floor (Figure 8)

This site is a valley-floor mixed fen and alpine *Sphagnum* shrub bog on the southern slopes of Mt Jagungal, with a meandering stream incised about 50 cm into peat. Although the mire lies above the treeline it is lower and more sheltered than those on the Main Range. The alpine *Sphagnum* shrub bog is hummocky, and low shrubs are emergent in places.

Figure 8. Alpine shrub bog with *Astelia* cushions, Upper Geehi River, February 2010. Photo: Roger Good

Depth (cm)	Sediment
0–10	Dark brown fibrous peat with bands of charcoal, silt and sand
10–29	Dark brown sapric (humified) peat
29–35	Grey-brown humic clay with sand lenses
35–64	Grey coarse sand with root material
64–70	Brown clayey peat with sand
70 – >93	Grey medium-coarse sand with roots

The section also provides evidence for past burial by coarse sediment, as well as recent grazing impacts. Martin (1999) reports a basal age of 3640 ± 295 a BP (Lab Code: SUA 1617) from a similar stratigraphy from this area, so the lower sediments may have considerable antiquity. The plateau area south of Mt Jagungal historically experienced heavy grazing pressure, as access from nearby grazing properties to the east was relatively easy. The mires have numerous stone and gravel pavements, and streams have incised down to the gravel slope deposits of presumed Pleistocene age. At the coring site a small stream is continuing to incise headwards into silty peats but is also tending to flood out over the land because of blockage by recovering vegetation in some places. Before the areas of tussock grassland can revert to mire, the channel will have to infill (or be deliberately blocked) and spread (avulse) into multiple small channels.

Treeline alpine mire complex

Finns Swamp: 13 ha; 36°16.855′S, 148°25.817′E, 1810 m; Valley Floor (Figures 9a, 9b)

Figure 9a. Treeline alpine mire complex, Finns Swamp, Brassy Range, March 2007. Photo: Iona Flett

Figure 9b. Survey on alpine-subalpine shrub bog, Finns Swamp, Brassy Range. Photo: Geoff Hope

The valley of Finns Creek, south of the Brassy Mountains on the eastern side of Kosciuszko National Park, contains a broad, gently sloping section that contains a series of mires fed by streams and spring lines along the valley walls. A complex of old meander traces and stranded pools shows that the area of mire was formerly more extensive. However, the peats in the individual mire areas are deeper than those in the more crestal sites. An open woodland of snow gum occupies steep slopes above the mires. Cores were taken along and across one of the mires to provide profiles of peat types in order to estimate the volume of peat in the mire.

Depth (cm)	Sediment
0–10	Yellow-brown fresh *Sphagnum*
10–76	Brown fibrous peat
76–112	Brown sapric peat with scattered sand
112–122	Light brown clayey peat
122– >135	Grey sandy clay with roots, sandier with depth

The coring transect showed that the mire was developed on an uneven channelled sandy gravel substrate, probably an old alluvial fan. Peat depth averaged 95 cm except near the margins, with an organic content of around 60% to 70% of dry weight. Expansion of *Sphagnum* cover is evident and may reflect the removal of stock about 50 years ago.

Subalpine/alpine transition slope bog

Pengillys Bog 28.5 ha; 36°22.769′S, 148°24.781′E; 1685 m; Slope (Figures 10a, 10b)

Figure 10a. Subalpine-alpine transition slope shrub bog, Pengillys Bog, March 2009. Photo: Geoff Hope

Figure 10b. Permanent pool in alpine shrub bog, Pengillys Bog March 2009. Photo: Geoff Hope

This mire complex, 2 km north of Smiggin Holes, lies on an interfluve between Pipers Creek and Perisher Creek. It includes hillside and valley floor *Sphagnum* shrub bog communities of both carpet-like alpine and emergent shrub and large hummock subalpine types. Annual precipitation is probably similar to that at Perisher at 1750 mm, with areas of longer snow lie being associated with the alpine shrub bogs. A transect of cores found the deepest section to be on a south-facing hillslope where the bog surface forms a series of terraces or steps. The valley floor contained shallower peat under fen. Coring through the terrace gave a 160-cm section (see Figures 16b to 16e).

Depth (cm)	Sediment
0–2	Dark brown rot mat with charcoal from 2003 fire
2–18	Yellow-brown fresh *Sphagnum*-abundant woody roots
18–33	Very dark brown hemic peat with shrub wood, scattered sand and gravel
33–62	Black compacted sapric peat with fine rootlets
62–110	Dark brown fibrous peat
110–117	Brown to black humic peat with clay and sands below 114 cm
117–128	Yellow-brown peaty clayey silts with gravel, mica and rootlets
128–130	Light brown clayey hemic peat with scattered gravel
122– >155	Grey sandy clay with roots; paler and sandier with depth

The site appears to have supported *Sphagnum* for a lengthy period of time and is at least 4000 years old. The stratigraphy and setting are similar to those of Diggers Creek, which has a complete Holocene accumulation (Martin 1999), suggesting that 100 to 120 cm has been the maximum net peat accumulation over the last 8000 years or so in undisturbed subalpine bogs. Most of Pengillys Bog has about 60 cm of peat under variable thicknesses of recent *Sphagnum* moss. The layer below 18 cm may have been altered from fibrous to sapric peat by cattle trampling and contains elevated charcoal concentrations. The upper 18 cm of *Sphagnum* represents post-grazing recovery. Pine trees are invading the snowgum woodland, and seedlings have been found on the peatland. The endangered Perisher wallaby grass, *Rytidosperma vickeryae*, has been recorded from *Sphagnum* bogs nearby.

Subalpine *Sphagnum* shrub bog and *Carex* fen

Rennix Gap Bog: 11.3 ha; 36°22.0′S, 148°30.2′E; 1570 m; Valley Floor (Figures 11a, 11b)

Figure 11a. Subalpine *Sphagnum* shrub bog and *Carex* fen, Rennix Gap Bog, February 2010. Photo: Geoff Hope

Figure 11b. Subalpine *Sphagnum* shrub bog on the break of the slope, Rennix Gap Bog, October 2003. Photo: Roger Good

Rennix Gap Bog (also known as Boggy Plain) is one of the most easterly of the open grassed valleys on the undulating high plateau of Mt Kosciuszko. With an estimated annual precipitation of 1350 mm it is distinctly drier than Pengillys Bog. The swamp is crossed by the Jindabyne-Perisher road and has a steep slope along the western margin and a gentle slope to the east. It is a complex of *Sphagnum* shrub bog and *Carex* fen, with a fence line partly buried by peat showing that cattle were formerly grazed along the old Kosciuszko road, which passed along the eastern margin of the mire. The open area is surrounded by an inverted timberline of *Eucalyptus pauciflora* woodland, which attains its lower boundary with mountain gum (*Eucalyptus dalrympleana)* forest about 80 m lower down in Wilsons Valley. A stream traverses the bog, incised about 30 cm into the peat, gradually becoming more entrenched as it flows north and then east. Extensive stratigraphy has been carried out on the mire and shows that the deepest peat is on the edge of the steep slope and that it thins to the east under *Carex* fen and *Empodisma* moor to only 15 cm. A section on the western side under *B. gunnii – R. continentis* subalpine shrub bog had the following profile:

Depth (cm)	Sediment
0–105	Brown sapric peat, occasional charcoal
105–140	Grey peaty medium sand
140–185	Grey silty clay with sand bands
185–205	Grey sand with gravel and sedge remains

The section contains a complete Holocene sequence, the base of the peat being dated to about 11,000 cal a BP (Kemp 1993, Martin 1999). The sands and silty clay below the peat built up when there were alpine grasslands around the site, with abundant daisies and grass. The mire at that time was an open *Carex* fen on a sediment-choked aggrading fan. *Eucalyptus* increases around 10,000 cal a BP, marking the arrival of the treeline. The construction of the road channelled water into a culvert and dried out parts of the mire on the downhill side.

Large *Carex* fen with montane *Sphagnum* shrub bog

Sally Tree Creek Currango: 55.7 ha; 35°40.665′S, 148°40.784′E; 1240 m; Valley Floor (Figure 12)

Figure 12. Large Carex fen with montane Sphagnum shrub bog, Sally Tree Creek, Currango Plain, January 2009. Photo: Bren Weatherstone

The Currango plain north of the Murrumbidgee River was formerly a grazing lease of grasslands and snow gum woodland with gentle slopes and broad valleys. Above about 1150 m there are extensive *Carex gaudichaudiana* fens, which include Sally Tree Creek, where the fen is about 250 m wide and follows the valley for about 2 km. It consists of a uniform 40-cm-high sward of sedge, with very few minor herb species, that extends across the valley. Although this is classified as Valley Floor, any channels are broad and shallow, so that during rain periods water spreads across the mire. Sally Creek has one unusual feature: an area of about 2 ha where montane *Sphagnum* shrub bog has developed as a succession (Figure 1g). Coring in this bog produced the following section:

Depth (cm)	Sediment
0–35	*Sphagnum* and peaty *Sphagnum*
35–285	Brown fibrous sedge peat
285–385	Brown humic peat
385– >425	Black humic silty clay, becoming paler with depth

The stratigraphy indicates that the development of shrub bog may have occurred only in the past 100 to 200 years. Sally Tree Creek is a tributary of Mosquito Creek, where even more extensive fens occur at a slightly lower altitude. However, peat depth there is not as great at 150 to 200 cm, perhaps because the available water is dispersed over a greater area. Similar *Carex* fens at Yaouk and in Namadgi National Park typically have around 300 cm of sedge peat over 200 to 300 cm of organic-rich silty clays, with basal dates of 10000 to 14 000 cal a BP (Hope *et al.* 2009). The major development of fibrous peat started around 3500 years ago.

The invasion of the fen at Sally Creek by a *Sphagnum* bog is all the more remarkable because the area has a long history of grazing and currently supports large numbers of feral horses, which often graze in the fens and leave a dense network of tracks. Horses have broadened stream lines and almost completely removed a former subalpine *Sphagnum* shrub bog at Dunns Creek, 5 km to the east (Figure 21m). The secret of the resilience of the *Carex* fens may lie in the absence of discrete channels, where bank collapse by trampling causes bog drainage and oxidation.

Montane *Sphagnum* shrub bog

Tomneys Plain: 11.6 ha; 35°44.821′′S, 148°15.409′E; 1146 m; Plateau, Valley Floor (Figure 13)

Figure 13. Montane *Sphagnum* shrub bog, Tomneys Plain, April 2010. Photo: Margaret Ning

There is a complex of montane *Sphagnum* bogs in the Bago State Forest area to the west of Kosciuszko National Park. These were the best examples of montane *Sphagnum* shrub bog found during the survey by Hope and Southern (1983): they contained undisturbed peatlands with large *Sphagnum* hummocks largely hidden below myrtaceous shrubs. Unfortunately, the Crown land on which most are found has been leased for cattle grazing and these mires have been seriously affected, with areas of cover disappearing, invasion by blackberry and other weeds, stream bank collapse and compaction and oxidation. Tomneys Plain is an extensive grassland with a swampy drainage area on the northern side that supports degraded montane shrub bog with scattered *Sphagnum* under 1-m-high shrubs of *Baeckea utilis*, *Epacris paludosa* and *E. brevifolia*. The 1980 stratigraphy had altered when the bog was re-cored in 2010.

Depth (cm)	Sediment in 1980	Depth (cm)	Sediment in 2010
0–10	Litter and rootmat	0–10	Litter and *Empodisma* rootmat
10–35	Brown clayey fibrous peat	10–45	Black-brown hemic peat
35–160	Brown fibrous peat	45–120	Dark brown clayey sapric peat
160–230	Dark brown humic peat	120–140	Humic clay
230–310	Black peaty sand		
310–330	Coarse sand and gravel		

Sphagnum hummocks have been replaced by *Poa* tussock grassland and *Empodisma* moor, and the creek line is incised. Some peat on shallower sites has been replaced by humic clays and silts (Figure 21d). The oxidation of fibrous peat to clayey sapric peat represents a loss of 50% or more of the organic matter and is irreversible. The process has been studied by Grover (2006) and Grover and Baldock (2010), who concluded that cattle grazing had caused widespread peat loss in the Victorian alps through a similar process. Current attempts are being made by the lessee, supported by the Murrumbidgee Catchment Management Authority to block the drainage lines and re-wet a small area of the mires in the area. Removal of grazing by straying cattle and feral horses is part of this rehabilitation (B. Cooper, Leapfrog 2010, pers. comm.).

Close to Tomneys Plain, MacPhersons Plains preserve two endemic terrestrial Leek Orchid species, *Prasophyllum bagoensis* and *Prasophyllum innubum* (McDougall and Walsh 2007). The area is a former habitat of the blue-tongued greenhood, *Pterostylis oreophil*. About 12 km north-west of Tomneys Plain, Paddys River Bog is a montane *Sphagnum* bog remaining in excellent condition (Figure 1h). The continuous carpet of moss is overtopped by *Baeckea utilis* and *Epacris paludosa*, with a relatively low diversity of other species. Unfortunately feral horse numbers throughout the State Forest lands have risen dramatically, and these may adversely affect the bogs in the region (Figure 21o).

Large *Carex* fen

Micalong Swamp: 34.1 ha; 35°18.960′S, 148°31.431′E; 980 m; Valley Floor (Figure 14)

Within the Snowy Mountains region, *Carex* fens continue down to 700 m and include some of the deepest peat deposits in south-eastern Australia. Micalong Swamp, near the northern boundary but outside Kosciuszko National Park, is the best developed of a number of fens in the region. It has a robust growth of *C. gaudichaudiana* to 50 cm, with cane grass, *Phragmites australis,* forming a seasonal cover over part of the surface. A poorly defined channel meanders down the fen, except where trampling from illegal cattle grazing has cleared and incised it (Figure 21h). The presence of old fence lines crossing the fen show that it was formerly grazed, but it is now a gazetted flora reserve.

Dating of a peat section (Kemp 1993) shows that the mire invaded the stream line in the late Pleistocene and has grown continuously since then. The layers of silty clay are associated with charcoal and represent times when erosion of the catchment has occurred, presumably after fire. In a tributary of the swamp there is an area of montane *Sphagnum* shrub bog on shallow peat that has been invaded by blackberries. The original *Eucalyptus camphora* – *Eucalyptus dalrympleana* forest has largely been replaced by pine forest around the swamp. Interestingly, very little eroded soil seems to have reached the swamp from these forestry operations. However, blackberry forms impenetrable thickets in the pine forest and on the edge of other mires in the area.

Figure 14. Large *Carex* fen: Micalong Swamp, November 2006. Photo: Geoff Hope

Relict *Carex* fen with sinuous channel

Snowgum Flat, Ingeegoodbee River: 3 ha; 36°46.078′S, 148°18.034′E; 1055 m; Valley Floor (Figures 15a, 15b)

This small mire occurs as a riparian flat at low altitude in the southern Kosciuszko National Park. It is one of a remarkable series of valley floor fens along the river from 1125 to 965 m that together total 35 ha and display a highly sinuous channel with numerous scroll traces. The river flats are separated by narrow sections with rock bars. Small areas of montane *Sphagnum* shrub bog are surrounded by peaty clay soils supporting *Carex* fens and a grassland-herbland complex. There are scattered mounds of degraded dead *Sphagnum* covered by *Empodisma* representing former hummocks, surrounded by grasses. *Eucalyptus pauciflora* woodland surrounds the site, and the slopes have an open forest of mountain gum.

Figure 15a. The sinuous channel and oxbows of the Ingeegoodbee River, Snowgum Flat. Photo: Google Earth 2010

Figure 15b. Relict *Carex* fen with sinuous channel, Snowgum Flat. The exposed bank is formed from sedge peat. April 2010. Photo: Geoff Hope

The banks of the stream consist of humic sandy peat above sedge peat over an undulating former surface of sands and gravels at 80 cm. Probing suggests that peat is widespread but of very variable thickness.

Depth (cm)	Sediment
0–15	Humic peaty sands and occasional gravel
15–25	Brown humic peat, occasional mica
25–65	Brown fibrous sedge peat with sand and mica
65– >80	Coarse sand and gravel

The area was formerly grazed and burned but is now undisturbed by cattle. However, grazing by kangaroos and feral horses is heavy, and a pasture is maintained across the flats. It is clear that the Ingeegoodbee flats were formerly a significant *Carex* fen with patches of montane *Sphagnum* shrub bog. There must have always been a significant stream through the mires, given the catchment of 5700 ha, and the mica and quartz grains in the peat show that overbank flooding was frequent. Nevertheless, the channel has become incised and degraded, presumably as a result of grazing, but possibly from some deliberate drainage and burning. A considerable depth of peat may have been lost.

PEAT AND ORGANIC-RICH SEDIMENTS

Only a limited range of peat types and organic-rich silts, clays and sands are encountered in the region. These are listed in Table 8 and illustrated in Figures 16a to 16h.

Table 8. Sediments of the Snowy Mountains peatlands

Sediment	Peat grade (Boelter 1969)	Colour range	pH range
Rootmat trapping litter and sediment		Dark grey, dark brown, brown	4.5–7
Fresh dead *Sphagnum*		Pale yellow, light brown	3.5–5
Fresh fibrous peat –fibrous plant material >0.15mm	Fibric	Dark brown, brown, reddish brown	3.5–5.5
Humified peat with 33%–67% fibre remaining	Hemic	Dark brown, brown, light brown	4–5.5
Fully humified peat with less than 33% fibre	Sapric	Dark brown, brown	4–5.5
Clayey peats	Sapric/hemic	Very dark grey, light brown	4.5–6.5
Peaty clay and silts		Dark grey, grey, pale grey, blue, green	5–6.5
Peaty fine to medium sands		Grey, pale grey, yellow	5–6.5

Fibric peat, and often hemic peat, contains enough plant material so that the source vegetation can be assessed. Peat derived from *Sphagnum* can be distinguished from the more coarsely fibrous *Carex* peat. Woody stems are often present in peat derived from shrub bogs, even when the matrix is well humified. Silt and clay layers often reveal vertical traces of well-preserved *Carex* leaves, indicating that the sediment was washing into a sparse sedgeland. Pollen analysis can check these identifications and determine the source of other fine-grained organic matter, including organic muds from lakes, which can be hard to distinguish from sapric peat.

Peat volumes

An estimate of peat volumes can be made by using available stratigraphic data to derive a simplified standard stratigraphy for each mire type by altitude zone. The mean thickness of each layer is multiplied by the mapped area and summed to calculate volume. Table 8 shows the mean depths used to calculate peat volumes by vegetation type and altitude zone. These depths are chosen conservatively to allow for shallow peats around the margins of small mires. However, mires larger than 1 ha were examined individually and mean depths increased where stratigraphic information suggested that this provided a truer picture. For example, in the large *Carex* fens the sedge peat layer is usually consistent across the mire and may be up to 400 cm in depth, as at Micalong Swamp. A value of 220 cm was used as the average depth of fibric sedge peat for this mire.

Figure 16a. Shallow peat over gravels, upper Geehi River. Photo: Rachel Nanson

Figure 16b to 16e (top to bottom). *Sphagnum* over burnt layers and hemic *Sphagnum* peat over clay, Pengillys Bog. Photo: Geoff Hope

Figure 16f. Fibrous sedge peat, 200–250 cm, Bogong Creek ACT. Photo: Matiu Prebble

Figure 16g. Peaty silts under hemic sedge peat, Micalong Swamp. Photo: Geoff Hope

Figure 16h. Peaty silts under a gravel band, Boboyan Fen, ACT. Photo: Ben Keaney

Table 9. Estimated mean thicknesses and volumes of fibric/hemic and sapric peat and organic rich clays in the Snowy Mountains region of NSW. Comparative values for the ACT have been recalculated and are less than those shown by Hope *et al.* (2009). SSB = *Sphagnum* shrub bog

Altitude zone (m)	Alpine SSB			Subalpine SSB			Montane SSB		
	Fibric (cm)	Sapric (cm)	Humic clay (cm)	Fibric (cm)	Sapric (cm)	Humic clay (cm)	Fibric (cm)	Sapric (cm)	Humic clay (cm)
700–1000							30	25	20
1000–1300				30	25	20	40	30	20
1300–1600	30	25	20	35	30	25	35	30	25
1600–1900	30	15	15	30	35	15			
>1900	10	10	10						
Snowy Mountains ($m^3 \times 10^3$)	**3485**	**1971**	**1950**	**7877**	**7294**	**5318.0**	**616**	**468**	**1089**
KNP ($m^3 \times 10^3$)	3485.2	1971.1	1950.1	7134.1	6641.2	4698.2	363.1	276.6	190.0
ACT mountains ($m^3 \times 10^3$)				509.4	378.3	258.3	45.3	34.0	22.7

Altitude zone (m)	*Empodisma* moor			*Carex* fen		
	Fibric (cm)	Sapric (cm)	Humic clay (cm)	Fibric (cm)	Sapric (cm)	Humic clay (cm)
700–1000	10	10	15	40	20	60
1000–1300	15	10	20	75	20	80
1300–1600	20	15	20	45	15	30
1600–1900	20	15	15	40	10	20
>1900	10	5	5	15	10	10
Snowy Mountains ($m^3 \times 10^3$)	**3123**	**2314**	**3135.3**	**17015**	**4854**	**12098**
KNP ($m^3 \times 10^3$)	2426.4	1794.2	2427.3	8337.9	2514.4	6303.7
ACT mountains ($m^3 \times 10^3$)	295.8	212.6	318.3	3943.5	603.9	2573.2

Table 9 shows that the bogs and fens of the Snowy Mountains region of NSW contain 49 million cubic metres of peat. *Carex* fens contribute an estimated 21.9 million cubic metres, compared with 15.2 million cubic metres in the subalpine Sphagnum shrub bogs. Although *Carex* fens cover less than half the area (1870 to 3935 ha), the estimated peat volume is equal to all the peat under the three types of *Sphagnum* shrub bog (21.7 m^3). *Carex* fen peat is even more significant in the ACT, which lacks very extensive wet subalpine areas but has large montane mires, which contain 74.1% of the peat. Comparative figures are not available from the Victorian Highlands, as no large *Carex* fens are mentioned by Lawrence *et al.* (2009). Morass Creek, 5 km east of Lake Omeo at 700 m, appears to be an example of a large sedge fen, but it lies below the area that they surveyed. Only 49.9% of the peat volume in *Carex* mires surveyed in the NSW Snowy Mountains lies within Kosciuszko National Park, compared with 92.9% of the peat underlying the *Sphagnum* shrub bogs.

Carbon storage and sequestration

Mire peat and other histosols (soils containing significant organic matter) represent major stores of carbon and it is important to appreciate the size of the store and the best management to encourage sequestration against loss to the atmosphere and streams. Although peat volume is the key measure for calculating the amount of carbon stored in peatlands, the water content, organic content and dry bulk density are needed to convert peat volume to elemental carbon in tonnes per hectare. As with volume, a comprehensive data set of water content, dry bulk density and factors for converting organic matter to elemental carbon is not available for the Snowy Mountains region – or indeed for montane south-eastern Australia. However, in this study some values were collected from individual mires from a range of altitudes, thus allowing the carbon content of the different peat types to be estimated. The following methods were used:

Water content

Samples of 10 mL of peat or sediment were gently packed into an open syringe to estimate volume, weighed, and then dried at 90°C for 64 hours and reweighed. Water content is represented by the weight lost, and the dry weight provides the dry bulk density (converted to kg/m^3).

Organic content

The dried samples are ignited in a muffle furnace at 550°C for 4 hours, in accordance with the technique of Heiri *et al.* (2001). Loss on ignition (LOI) provides an estimate of the organic content of a sample but can be affected by loss of pore water or other inorganic components, such as CO from carbonates. Acid peats have no carbonate, but increasing inorganic content may affect the results, making estimation of organic content of peaty silts and clays less reliable.

Carbon content

LOI is often assumed to be proportional to carbon content, but a wide range of conversions has been found to apply to peats from different settings and states of preservation. One cause is the different organic makeup of fresh peat compared with humified peats. The former have a lower carbon content per gram dry weight owing to the presence of components, such as sugars and proteins, with less carbon in their molecules. Humification, including microbial digestion, preferentially removes these or converts them to phenols (Freeman *et al.* 2004), and concentrates less oxidisable components such as partially combusted plant material (carbonised particles). Direct elemental analysis (EA) was undertaken on samples from subalpine and alpine *Sphagnum* shrub bogs by using C-N-H infrared gas chromatography. Duplicates (2 mL) of the LOI samples were milled, subsampled and analysed using a Carlo Erba EA-1110 CHN-O Elemental Analyser to directly determine C content per unit mass of dry peat soil. This provided a range of values that were used to determine the relationship of LOI to EA carbon, which can be used regionally. The results can be compared with values from a Victorian subalpine shrub bog (Grover *et al.* 2005).

The test set includes 178 LOI measurements and 90 C-N-H determinations. LOI and carbon percentages are graphed by peat type in Figure 17.

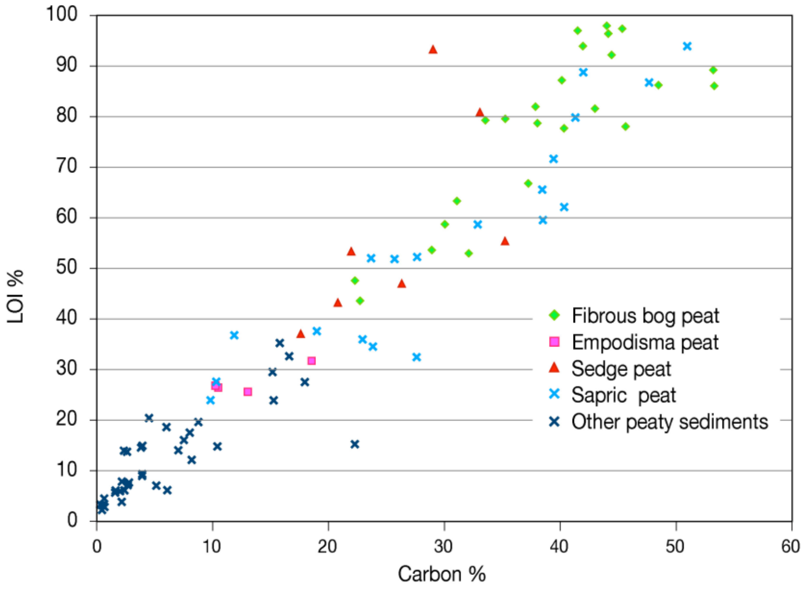

Figure 17. Organic content vs elemental carbon for five mire sediment types

The graph shows a reasonably robust relationship between LOI and carbon content for all types of peat and peaty sediments, but there are significant outliers and a considerable spread of up to15% of the carbon values for similar LOI results. LOI has been shown to vary with experimental conditions (Heiri *et al.* 2001), and additional water loss from oven-dried peats may have been a factor contributing to weight loss on ignition in some cases.

The fibrous peats and sapric peat provide the highest carbon values, whereas hemic peat from *Empodisma* moor is significantly lower in carbon, suggesting that it is partially humified or even mineralised. The samples tested came from a site on the margin of an *Empodisma* moor in the ACT and were subject to slope wash. Sapric peat tended to record higher carbon contents in relation to LOI than the fibrous peats. Grover *et al.* (2005) recorded the same phenomenon and attributed it to greater carbon density in sapric peat, suggesting that carbon bulk density increases down profile.

In Table 10 characteristic values are given for water content, LOI and elemental carbon for different types of sediment. Carbon values (in kg per cubic metre) are derived by multiplying mean carbon percentages by dry bulk density. Accuracy could have been improved by drying at higher temperatures over a longer period.

Grover *et al.* (2005) recorded mean C values of 41.5% for fresh *Sphagnum* peat (fibric), 43.0% for hemic and 41.3% for sapric peat from a 230-cm section in subalpine *Sphagnum* shrub bog at Wellington Plain, Victoria. Their figures are higher than the mean values shown above, particularly for sapric peat, but some individual values at Kosciuszko match and exceed theirs. The standard deviations of 20% to 50% show that a wide range of values for all components can occur and that many more measurements using standardised techniques will be required to improve accuracy.

When the C values are converted to carbon concentrations per unit volume, the low-density, high-water-content fibrous peats have lower values of carbon per unit volume than the more compressed hemic and sapric peats. Hemic *Carex* peats have slightly lower C content than fibric-hemic shrub bog peats.

Table 10. Averaged measurements of water, LOI and carbon are used to derive values for the carbon content of different peat and sediment types. Values for Wellington Plains Victoria (Grover *et al*. 2005) are included in Moss, Fibric-hemic and Sapric. P-C is peaty clay; C-S is clayey sand; n is the number of samples used in each determination. Standard deviations (SD) do not include measurement errors.

Vegetation type	Peat type	Water content kg/m^3	Organics LOI (%)	SD	n	Carbon (%)	SD	n	Carbon kg/m^3
ASSB	Moss	878.3	74.41	17.12	6	34.03	7.27	6	41.61
ALL	**Moss**	**889.9**	**79.67**	**13.20**	**13**	**35.97**	**6.50**	**9**	**45.30**
ASSB	Fibric-hemic	832.5	86.09	8.31	8	43.44	3.50	8	73.52
SSSB	Fibric-hemic	853.3	66.55	17.74	7	37.61	12.27	7	55.3
ALL	**Fibric-hemic**	**832.5**	**76.97**	**18.52**	**15**	**40.72**	**8.93**	**15**	**65.02**
EM	Hemic	650	27.67	30.20	4	13.08	3.85	4	45.79
CF	Fibric sedge	827.4	60.45	19.10	25	26.28	6.55	7	58.87
ASSB	Sapric	812.3	58.57	21.78	14	32.98	11.56	14	61.23
CF	Sapric	716.9	32.65	14.50	8	16.13	7.58	5	65.06
ALL	**Sapric**	**807.1**	**55.37**	**19.39**	**35**	**30.20**	**12.41**	**16**	**63.26**
ASSB	P-C	761.7	22.72	8.39	6	12.85	4.24	6	28.11
CF	P-C	493.5	16.09	8.56	17	10.25	6.16	4	26.21
ALL	**P-C**	**565.7**	**17.13**	**8.49**	**6**	**11.81**	**4.94**		**27.22**
ASSB	C-S	438.3	10.05	5.32	6	10.05	2.95	6	17.7
CF	C-S	284.6	5.78	4.46	25	3.34	1.47	10	18.16
ALL	**C-S**	**287.7**	**5.80**	**4.65**	**50**	**3.59**	**2.07**	**17**	**17.23**
CF	Sand	188.2	3.31	0.93	4	0.47	0.14	4	3.62

ASSB is alpine *Sphagnum* shrub bog, **SASS**B is subalpine *Sphagnum* shrub bog, **MSSB** is montane *Sphagnum* shrub bog, **EM** is *Empodisma* moor and **CF** is *Carex* fen.

Table 11 uses the values for carbon concentration and peat volume derived above to provide a first approximation of the possible carbon store held in mires in the Snowy Mountains region. We emphasise that the values in Table 11 have very large errors that probably exceed 50%.

Because conservative values were used to calculate peat volume, it is likely that the carbon stock estimates are minimum values. The average carbon store in *Sphagnum* bogs in the subalpine and alpine areas is 200 t C/ha; for montane and subalpine *Carex* fen it is about 750 t C/ha. However, individual mires may preserve much higher stores. The 4-m peat column at Micalong Swamp represents around 2600 t C/ha, whereas a 1.5-m hemic-sapric profile in the subalpine area represents 950 C t/ha. Thus some peatlands approach the 2844 C t/ha store held in *Eucalyptus regnans* forests, claimed to be the most carbon-dense ecosystem in the world (Keith *et al.* 2009). Living matter provides only a small part of the carbon store in peatlands but is 64% of the forest. Peatlands are thus a less labile store that is more easily preserved when compared with living carbon stores.

Table 11. Estimated peat volumes (m^3) and carbon weight (kt) in the Snowy Mountains mires

	Mire area (ha)	*Sphagnum* peat (m^3)	*Empodisma* peat (m^3)	*Carex* peat (m^3)	Sapric peat (m^3)	Organic clays (m^3)
Alpine	1528	3 518 234	139 139	40 979	2 454 229	2 085 770
Subalpine	4026	7 380 306	2 680 262	2 227 157	9 298 939	9 016 966
Montane	1879	1 079 895	304 386	14 746 799	5 148 084	11 618 401
Total peat	**7432**	**11 978 436**	**3 123 888**	**17 014 936**	**16 901 329**	**22 721 238**

Carbon	kt	kt	kt	kt	kt	kt
Alpine		258.7	6.4	2.4	150.3	58.6
Subalpine		408.1	122.7	131.1	588.3	245.4
Montane		59.7	13.9	868.1	334.9	304.5
Total C	**3553.3**	**726.5**	**143.0**	**1001.7**	**1073.5**	**608.6**

Carbon sequestration rates

Two quite separate approaches can be used to determine the role of mires in fixing atmospheric CO_2. Direct measurement of a small area of a peatland can determine whether the carbon balance is positive or negative over the period of measurement. Alternatively, the long-term sequestration rate can be calculated if the length of time taken to accumulate organic sediment is known. Both methods are valuable to determine the current sequestration or loss rate under contemporary conditions and to measure the actual performance as a carbon store and assess the potential for long-term sequestration.

Direct measurement

Detecting whether a given peatland has a positive or negative carbon balancer requires measurement of carbon flows. The net CO2 respiration of a peatland ecosystem is measured to detect the balance between photosynthesis and respiration. Complex flow models are then applied to estimate carbon flux and balance. Methane emissions from breakdown are also measured and added to the total of carbon compounds, leaving the profile in water flows to obtain a carbon budget. Such experiments are difficult to maintain over several years and involve disturbing the system being measured (Limpens *et al*. 2008). Typically, CO_2 net balance requires an instrumented 8-m tower that measures vertical and horizontal air velocities while simultaneously sending air to an infrared gas analyser to be measured for CO_2 (Roulet *et al*. 2007). Methane production is obtained by installing a series of fixed collars that are temporarily covered several times per week to allow an air sample to be taken (Bubier *et al*. 2005). Continuous stream gauging and automated sampling for dissolved organic carbon is also required. Typically, such measurements need to be set up semi-permanently and the mire needs to be protected with access board walks because of the frequent visits required. The necessary resources for such a project have not yet been found in Australia, although short-term measurements have been carried out in *Sphagnum* shrub peatlands in Victoria (Grover 2006). In a lowland bog dominated by *Empodisma minus* near Hamilton, New Zealand, the annual carbon sequestration was 1.85 t C/ha in 1999 and 2.10 t C/ha in 2000. Areas of the bog drained and used for dairying showed a net annual loss of carbon of 48 kg C/ha and continued lowering of the surface (Nieveen and Schipper 2005).

Overseas studies such as that of Roulet *et al*. (2007) in Canada found large fluctuations in the carbon balance that were related to seasonal variations in the climate. Dry periods led to a reduction in the rate of peat growth and a rise in methane production. It seems likely that, for the marginal peatlands of the Australian Alps, dry warm phases – particularly hot summers – probably cause most peatlands to record negative growth and become carbon sources. Freeman, Evans *et al.* (2001) and Freeman, Ostle *et al*. (2001) have suggested that peat is preserved in waterlogged conditions by an inhibitor that prevents phenols from being metabolised by phenol oxidase, an enzyme produced by bacteria. Drying episodes depress the levels of inhibitor, allowing peat to be metabolised. Grover and Baldock (2010) found that although fresh peat was readily oxidised and lost its structure, this process slowed as the more resistant components such as waxes, phenols, cuticles and carbonised material made up a larger proportion of the peat. Hence the peatlands of the Snowy Mountains can be resilient even under such negative growth conditions, because the bulk of the deposit has already lost readily oxidisable components.

Long-term accumulation rates

Dated peat sections provide a model for long-term sequestration rates. The peat component of a mire will build up only if plant material production exceeds losses due to decay and removal. Whinam and Hope (2005) suggest that Australian montane peat deposits reflect a very slight positive balance, giving rise to long-term accumulation rates in the order of 0.01 to 1.0 mm/year (commonly expressed as 0.1 to 10 cm per century). Clark (1980) has reviewed growth rates for *Sphagnum* bogs and made observations of surface levels against fixed pins on Ginini Bog (ACT) over several seasons. She found that although the moss surface might increase by 30 cm in a good growing season, all this height can be lost in a single winter because of compression by snow or animal trampling, and that the current net growth in the bog is almost nil or perhaps negative.

Calculation of long-term sequestration rates in bogs and fens are possible using late Holocene net accumulation rates of carbon for bogs and fens. The appearance of pollen from European introductions, particularly pine, also provides a marker that allows the late Holocene and post-grazing sequestration rates to be compared. Additionally, by comparing results from both damaged and undamaged mires, the overall carbon losses caused by widespread humification associated with grazing can be broadly assessed. However, the additional losses that converted many mires to tussock grasslands are not yet quantifiable.

For Ginini Bog (ACT), which was not damaged by grazing, the long-term net accumulation rate of hemic *Sphagnum* peat is a maximum of 3.2 cm per century over 3000 years (Hope *et al.* 2009). This can be compared to the relatively protected Diggers Creek Bog, near Smiggin Holes, where the deepest hemic-sapric peats built up at 0.85 cm per century from 4880 to 2000 cal a BP, then averaged 2.31 cm per century for the next 1900 years (Martin 1999). Rennix Gap Bog, which is drier and was heavily grazed, preserves sapric peat with a mean accumulation rate of 1.11 cm per century between 8000 and 1000 years ago (Martin 1999). Montane *Sphagnum*-restiad mires such as Bega Swamp, at 1080 m east of Nimmitabel, built up sapric peats at mean rates of 2.17 cm per century from 3500 to 1000 years ago (Donders *et al.* 2007). The only estimate for *Empodisma* moor suggests a long-term rate of only 0.8 cm per century, but complications in the dating make this estimate very unreliable (Hope and Clark 2008.

Historical damage to bogs by grazing, ditching and fire has created significant gaps in many records where many centuries of peat accumulation may have been lost (Figures 20, 21). At its most extreme, nearly all the peat record is removed, as at Yaouk Swamp, where the top of a sapric sedge peat is about 8000 years old and is buried by post-European clays; it may represent a completely humified former peatland that has been ditched and burned repeatedly (Ben Keaney, ANU 2004, pers. comm.). This has also been the fate of extensive areas of *Sphagnum* shrub bog such as that around the Valentine River and the upper Geehi, where 10 to 20 cm of *Sphagnum* and peaty silts is perched on peaty gravels. In some cases the recovery by *Sphagnum* since the cessation of grazing has been impressive, with up to 70 cm of compressed *Sphagnum* accumulating in about 100 years at Snowy Flats (ACT) since cattle were removed to protect water supply catchments (Hope *et al.* 2009). Martin (1999) found that depths of 32, 20 and 18 cm of

Sphagnum moss peat had built up at Wilsons Valley, Rennix Gap Bog and Diggers Creek, respectively, presumably over about 60 years. On the alpine Swampy Plain we noted 10 to 15 cm of litter and peat in wet areas; these materials had built up on gravel fans that were probably caused by erosion following grazing. These accumulation rates provide a guide to potential short-term (decadal) carbon sequestration rates. However, even under good conditions for preservation, these values will considerably overstate the longer term (millennial) net sequestration rate.

Under extremely good conditions, *Carex* fens can accumulate peat at 6 to 9 cm per century, and many seem to have been in a growth phase for the past 3500 to 2700 years. For example, Micalong Swamp built up dense fibrous sedge peat at 3.77 cm per century from 7740 to 3600 cal a BP (Kemp 1993). After that the average rate was 3.66 cm per century of less dense peat. The highest rates found are for fibrous sedge peat in Boboyan and Bogong Creek swamps in the ACT, where the averages over the past 2500 years are 8.4 and 9.2 cm per century, respectively (Hope 2009, 2011; Hope *et al.* 2009). About 2 m of humic clays under the *Carex* peats in these sites built up between 9000 and 2700 cal a BP, giving net accumulation rates of 3.3 to 3.7 cm per century.

Applying these rates to the carbon density values derived in Table 11 allows an estimation of the possible rate of sequestration of mires over the historical period and the actual average rates for 2 to 3 millennia before that time (Table 12).

Table 12. Estimates of long-term carbon sequestration rates in the Snowy Mountains mires. PAR is peat accumulation rate, SR is sequestration rate. Average carbon density is taken from Table 10.

	Fresh *Sphagnum* peat	**Hemic *Sphagnum* peat**	**Hemic *Empodisma* peat**	**Fibric-hemic *Carex* peat**	**Sapric peat**	**Organic clays**
Max PAR (cm/100 years)	35	3.2	?0.9	9.2	1.5	3.3
Min PAR (cm/100 years)	12	1.5	0.7	3.6	0.9	0.8
Carbon (g/mL)	0.04530	0.06502	0.04579	0.05887	0.06326	0.02722
Max SR (kg/ha/year)	1585.5	208.1	41.2	541.6	94.9	89.8
Min SR (kg/ha/year)	543.6	97.5	32.1	211.9	56.9	21.8
Area (ha)	3934	3934	1620	1871	7426	7426
Max annual SR (t/year)	6238	819	67	1014	705	667
Min annual SR (t//year)	2139	384	52	397	423	162
Annual SR (t/year)	**3564**	**601**	**59**	**705**	**564**	**414**

The historical annual mean sequestration rate is 4953 ± 2360 t/year, being the sum of the three fresh peat categories, *Sphagnum, Empodisma* and *Carex*. The range of 0.55 to 1.5 t/ha/year for fresh *Sphagnum* peat is comparable to the New Zealand eddy carbon flux values of 1.8 to 2.1 t/ha/year noted above for restiad peat. The estimate of a historical sequestration rate of about 5000 t/year can be compared to the long-term rate of 2344 ± 925 t/year, a reduction of 53%. It is assumed that the bulk of this difference is due to compression and loss of easily degraded components. However, the long-term rates also reflect the impact of drought and fire events that may have led to periods of negative sequestration. High and low accumulation rates are given, and these reflect both the range of productivity in different mires and the conditions of storage of peat once formed. The low range may thus reflect the damage done by a few decades of intentional burning and cattle grazing to thousands of years of peat 'capital', converting fibric and hemic peat to sapric peat and organic clays. The values given above indicate that this conversion from hemic peat to sapric peat involves a loss of around 50% and to organic rich clays 60% to 80% of the carbon. In addition, at least part of the area of *Empodisma* moor that may once have supported shrub bog, and the area of sod tussock that formerly supported mires, has not been quantified.

The estimate for historic sequestration rates of around 5000 t C/year for the 70 km^2 of peatland is, of course, only a small fraction of the carbon fixed each year by the mires but subsequently lost to respiration, decay and solution. Nevertheless, the mires are the most carbon-dense ecosystem in the region, with a carbon store of 3.5 million tonnes. The balance between positive and negative sequestration is clearly precarious, and it was firmly tipped to the negative by the grazing era. Monitoring of the current carbon budget of some representative mires is necessary to understand whether climate change and current management have caused the system to recover towards being a store or whether it is an increasing sink.

Hydrology

Raw peat consists of up to 92% water, and peatlands are very efficient at intercepting rainwater and surface flow. Using water loss values from moist peat samples (Table 10), the water held in peatlands is estimated in Table 13.

Table 13. Water content (in kilotonnes) held in mires in the Snowy Mountains

	Mire area (ha)	*Sphagnum* ('000s of tonnes)	*Empodisma* ('000s of tonnes)	*Carex* ('000s of tonnes)	Sapric ('000s of tonnes)	Organic clays ('000s of tonnes)
Alpine	1528	3090.2	90.4	33.9	1993.6	1179.9
Subalpine	4026	6297.9	1742.2	1842.6	7505.4	5100.7
Montane	1879	961.0	197.9	12200.8	3690.5	5733.3
Total	7432	10349	2030	14077	13190	12014

Much of the 52 million tonnes of water is retained as pore water, even under drought conditions, and hence acts as a significant buffer for mire vegetation against drought and a protection against damage to the peat from fire. Although bogs may store excess water, they release it fairly quickly and are probably not major water stores over weeks or months. Experiments at Prussian Creek at Smiggin Holes in a small hillside shrub bog on a steep slope showed only temporary retention of water (Wimbush 1970). Western *et al*. (2009) studied the hydrology of several high-altitude bogs in Victoria for which daily stream gauging information was available and concluded that the strong baseflows of peat catchment streams that are maintained into summer reflect storage in the underlying regolith of the whole catchment, not releases from the peatland. They demonstrated a diurnal cycle in which summer flows decreased during the day because of water use by the mire vegetation. This has also been demonstrated by flow measurements in large peatlands on Barrington Tops, NSW (Nanson 2010). Western *et al*. (2009) point out that increasing or decreasing the area and condition of the peatland would have little effect on water yield from large catchments, because mires form only a small proportion of the area. This contradicts a commonly held view in Victoria that removing cattle from the subalpine areas would cause mires to soak up water, reducing water availability for agriculture.

Peatlands are important in the subalpine catchments because they moderate runoff to some extent and, being thermally insulating, retain warmer ground water than would otherwise be the case. Snow also lies earlier and lasts longer on peat surfaces. Water moves through peatlands as ground water, across the surface in wide shallow channels floored by depressions or in narrow deep channels. However, the oxidised sapric peat at depth has extremely low hydraulic conductivity (Grover 2006); the water in the mires is therefore often 'perched' or disconnected from the general watertable. This was demonstrated several times through the 1999 to 2009 drought by piezometer measurements in granite catchments. The measurements showed that the clayey sands underlying bogs and moor became dry even though the peatland remained damp and retained water in pools (Whinam *et al.* 2010). The surface vegetation filters out mineral sediment and releases clear water, although it also uses up water in transpiration. The fibrous surface vegetation and top sediment layer are tough and resistant to erosion, which is often not very active on the flats and gentle slopes (Wimbush and Costin 1983).

The deep fibric-hemic peats of *Carex* fens behave differently from the shallower shrub bogs. The upper 1 to 3 m of uncompacted fibrous sedge peat may have high hydraulic conductivity, but it is similarly ‘sealed’ by the organic rich clays below. In four fens examined in the ACT there is a resistant sedge root mat at the surface and 15 to 30 cm of clay-rich peat that provides a resistant and tough surface layer (Hope 2006, 2009). The clays have probably been derived from catchment disturbance by grazing, as they have built up through European times. This sediment was not found at Micalong Swamp. Water may cause the surface to rise or fall significantly, and the hydraulic pressure may cause the fibrous peats to separate (or float) from impervious layers below. This effect was the underlying cause of the 1998 Wingeecarribee peat burst, in which 6 million cubic metres of peat flowed down the valley after heavy rain following destabilisation of the peat face by peat mining (Adam 2005).

The retention of moist vegetation and water sources through dry periods means that the mires at all altitudes are critical to the maintenance of biodiversity. They are an important resource for wildlife each summer and may prevent population extinctions across drought cycles.

Mire histories

Macro remains of the swamp vegetation are the basic components of peat, and their variation through a deposit provides a good record of any changes at the site. Other stratigraphic evidence for change comes from changes in the proportions of clay, silt and sand, or from more sophisticated chemistry, including analyses of stable isotopes such as ^{13}C. Among biological proxies, fossil pollen and spores derived from both local and regional sources are well preserved in peat media and may indicate regional environmental changes. Good results have also been obtained from using the remains of insects such as beetles and cladocerans. Charcoal from fires on swamps or washed in from catchments can provide an indication of fire frequency. Gravel or sand layers associated with charcoal are evidence of erosion following catchment fires (Worthy 2006). Preliminary analyses are available from cores and sections from several dated sites in the Snowy Mountains region, and these data provide a general indication of the formation of the mires and their subsequent growth.

Age of peatlands

Current research suggests that the peatlands in subalpine NSW post-date the last period of glaciation, which occurred from 26 000 to 16 000 years ago (Barrows *et al*. 2002), and that they owe their origin to the post-glacial amelioration of climatic conditions. At the end of the Pleistocene, about 14 000 years ago, the Snowy Mountains lay above the treeline and montane streams were infilled by sands and gravels from active screes and bare slopes. Increasing temperature and precipitation stabilised the catchments, allowing the establishment of tussock grasses and swamp plants on the river flats. Plant cover blocked streams and built up a layer of litter. Where conditions were wet enough, organic breakdown slowed and peat accumulation followed. Table 14 gives basal dates from mires in the region, the results being shown in Figure 18.

Table 14. Earliest dates for the initiation of sedimentation in Kosciuszko NP and nearby sites. Carbon dates have been calibrated by CalPal (www.calpal-online.de).

Site name	Locality	Altitude (m)	Depth (cm)	Date (cal a BP)	Lab. no.	Material	Source
NSW sites							
Giandarra Bog	Kiandra	1390	82	700 ± 100	ANU 6957	Organic clay	Thomas 1991
Brooks Ridge	Eucumbene	1450	46.5	4125 ± 395	β-81387	Humic peat	Mooney *et al.* (1997)
Wilsons Valley	Jindabyne	1460	55	1505 ± 90	Gak 3923	Humic peat	Martin 1999
Rennix Gap	Kosciuszko	1575	150	12 470 ± 220	ANU 2177	Humic peat	Kemp 1993
Smiggin Holes	Kosciuszko	1675	NA	8250 ± 125	Gak 1193	Humic peat	Martin 1999
Diggers Creek	Kosciuszko	1690	131	11 810 ± 250	Gak 3929	Humic peat	Martin 1999
Perisher Valley	Kosciuszko	1675	NA	9005 ± 315	W 769	Fen peat	Costin 1972
Upper Geehi	Jagungal	1740	NA	3640 ± 295	SUA 1617	Humic peat	Martin 1999
Charlotte Pass	Kosciuszko	1825	NA	7740 ± 140	Gak 2787	Humic peat	Martin 1999
Upper Snowy	Kosciuszko	1830	NA	18 195 ± 375	NZ 399	Sedge peat	Costin 1972
Wrights Creek	Kosciuszko	1835		8265 ± 100	SUA 2821	Humic peat	Martin 1999
Club Lake fen	Kosciuszko	1955	265	11 140 ± 245	SUA-1259	Peaty silts	Martin 1986a
Pound Creek	Twynam	1960	162	17 010 ± 450	SUA 272	Muds	Martin 1986a
Twynham NE Cirque	Twynam	1980		9717 ± 235	NZ 400	Fen peat	Costin 1972
Mt Stillwell	Kosciuszko	1990	32	1485 ± 100	Gak 1402	Peaty silts	Martin 1999
Twynam SW	Twynam	1950		2323 ± 146	ANU 432	Peat	Costin 1972
Carruthers Creek	Carruthers Peak	1950		17 575 ± 330	NZ 401	Peat	Costin 1972
Carruthers Creek	Carruthers Peak	1980		2560 ± 140	NZ 402	Peat	Costin 1972
Twynam SW Cirque	Twynam	2010		10 355 ± 193	ANU 431	Peat	Costin 1972

Table 14. ***continued***

Site name	Locality	Altitude (m)	Depth (cm)	Date (cal a BP)	Lab. no.	Material	Source
***Carex* sedge fens**							
Tarcutta Swamp	18 km S of Batlow	780	522.5	10 745 ± 220	ANU 4384	Peaty clay	Williams 1985
Mulloon Swamp	25 km W of Braidwood	799	345	3710 ± 115	ANU 10753	Peaty clay	Hope unpubl.
Micalong Swamp	35 km E Tumut	980	390	14 550 ± 495	ANU 3342	Sedge peat	Kemp 1993
Yaouk Swamp	Scabby Nature Reserve	1115	195	10 415 ± 80	ANU 11439H	Peaty clay	Keaney and Hope 2006.
ACT sites							
Blundells Flat	Condor Creek	762	190	2430 ± 70	Wk17023	Charcoal	Hope *et al.* 2009
Bogong Creek Swamp	Gudgenby River	1000	577	11 005 ± 145	SSAMS-ANU	Peaty sand	Hope *et al.* 2009
Tom Gregory Bog	Upper Cotter	1024	240	13 455 ± 255	ANU 12023	Peat	Hope 2006.
Nursery Swamp	40 km SW Canberra	1092	298	14 470 ± 375	OZI 144	Peaty clay	Hope *et al.* 2009
Boboyan Swamp	Upper Naas River	1154	535	10 515 ± 65	SSAMS-ANU	Peaty silts	Hope *et al.* 2009
Rotten Swamp	North-east of Mt Kelly	1445	60	6300 ± 90	ANU 9484	Peaty sand	Hope and Clark 2008
Ginini Flat	Mt Ginini	1592	110	3520 ± 80 3305 ± 50	GRN 249l Wk18654	*Sphagnum* peat	Costin (1972) Hope *et al.* 2009
Cotter Source Bog	Mt Scabby	1720	115	10 150 ± 125	ANU 10194	Peaty sand	Hope and Clark 2008

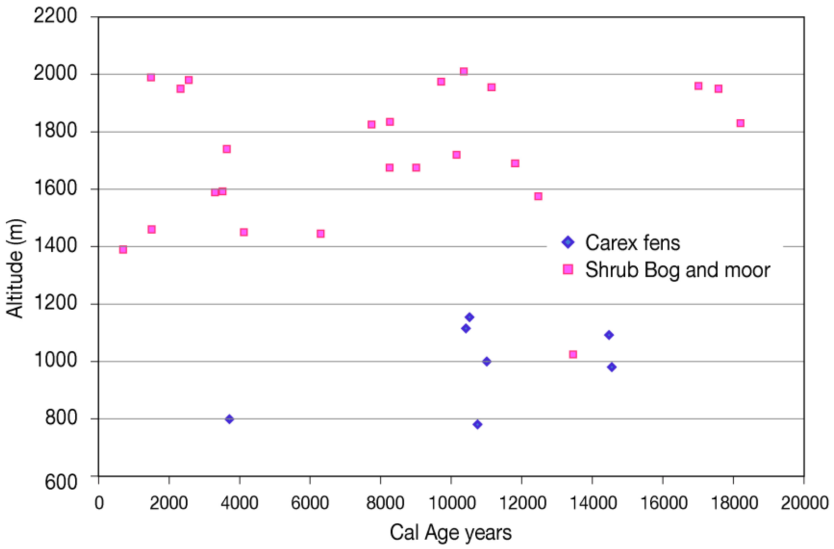

Figure 18. Basal ages of bogs and fens, by altitude

There is no clear correlation between the timing of the onset of peat formation and altitude in the Snowy Mountains region, confirming the observations of Kershaw and Strickland (1989). The oldest date of ca. 18 000 cal a BP comes from high on Mt Twynham and provides a minimum age for deglaciation but does not mark the start of peat growth (Costin 1972). However, basal peats had formed in the upper cirques of Carruthers Peak and the Snowy River by 17 000 cal a BP, reflecting the relatively wet conditions at the crest of the Main Range. Other early sites at 15 000 to 14 000 cal a BP occur at all altitudes in the region and must reflect topographically favourable settings for early peat build-up. Because most deposits are floored by gravels, sands or clays, it is likely that peat-forming vegetation moved onto old slope and alluvial fan deposits when these ceased to form. By 12 000 to 8500 cal a BP, peat formation had begun at a wide range of sites, so we can conclude that the slopes had become increasingly stabilised between 14 000 and 10 000 years ago. These dates are matched by the transition at 1280 m at Caledonia Fen, Victoria, where organic clays at 137 cm depth become peats at 12 001 ± 483 cal a BP (Kershaw *et al.* 2007). At Bega Swamp, near Nimmitabel, NSW, at 1080 m, this transition occurs at 15 500 ± 350 cal a BP at the base of a 270-cm peat section.

Dated pollen sequences from the Mt Kosciuszko area show that forest vegetation developed in the region after 12 800 cal a BP, whereas in alpine sites at about 2000 m the original feldmark (open alpine heath) had been replaced by closed alpine herbfields or heaths by about 10 800 cal a BP (Martin 1986b). Martin (1999) also showed that a stable subalpine vegetation was maintained over 10 000 years at Diggers Creek. At Bega Swamp the main early Holocene forest expansion occurs at around 13 200 cal a BP, with increased *Eucalyptus*, *Casuarina*, *Pomaderris* and *Cyathea* replacing subalpine snow gum woodland (Donders *et al*. 2007). A mid-Holocene wet phase, characterised by the expansion of *Pomaderris*, wet heath and ferns, started at about 8300 cal a BP, followed by eucalypt expansion and drier conditions after 3500 cal a BP. Short centennial alternations between wet and dry taxa can be observed in the record. After 1620 cal a BP, assemblages remained relatively stable until, in about 1850 AD (100 cal a BP), forest cover declined slightly because of grazing of European animals and deforestation. Martin (1999) and Costin (1972) both consider that fluctuating climate has affected peat growth, in some cases burying peat under gravels during cold and possibly frostier phases.

There is good reason for presuming that climatic conditions and well-developed vegetation generally resembled present-day environments by 12 000 to 9 000 cal a BP. This broad conclusion needs a great deal of further research on a geographical range of sites to obtain details of the processes of environmental change. The reasons for the variation in ages for the initiation of peat are not yet understood. Possibly the early sites are those in the most humid regions, and increasing rainfall probably played a part. The development of a seal under some mires, which perches the watertable and allows peat growth, may be a lengthy process in some settings. However, instability and loss of early deposits also seems to have been a factor, even in the wettest areas.

Mid-late Holocene peatlands. Two trends are apparent in the age data for regional mires shown in Table 14. Whereas some mires have accumulated peat throughout the Holocene, some high-altitude and drier-region mires contain only much younger sequences. Given the generally suitable conditions through the Holocene for peat accumulation, the initiation of peat growth 1500 years ago at Mt Stillwell and the Valentine River on the one hand, compared with the initiation 1500 to 4000 years ago at Mt Twynham, Brookes Ridge, Wilson Valley, Ginini Flat (ACT) and the Mulloon Swamp on the other, require an explanation. It seems likely that some of these sites may have lost possible earlier Holocene fills. The peatlands rest on gravelly slope deposits of probable late Pleistocene age. The dated *Carex* fens in the ACT, such as at Nursery and Bogong Swamps, have preserved humic clays with bands of peaty silts during the early-mid Holocene (10 000 to 3500 years BP). This phase is sometimes capped by lenses of sand, suggesting catchment instability. The fens then entered a phase of expansion of the peatland and rapid growth of fibrous peats over the last 3500 to 2700 years. After this time, peat accumulation becomes widespread and is in close agreement with the initiation of *Sphagnum* bog expansion at Ginini Flat.

To the east of Canberra, Mulloon Creek (790 m) has similar Late Pleistocene alluvial fills, with any early Holocene sediments having been removed before peat formation began; this has built up 350 cm of sedge peat over the past 3800 years (Johnston and Brierly 2006). The peat growth was relatively aggressive, as demonstrated by the fact that it covers stumps of *Eucalyptus* sp. Cohen and Nanson (2007) demonstrate that this pattern of an early Holocene ‘gap’ in alluvial deposits followed by a post-3500 a BP build-up of terraces is common in the highlands of south-eastern Australia. They tentatively ascribe the period in the alluvial record with few or no dated alluvial deposits to an increase in water discharge but a decline in sediment yield (hence there was a marked increase in transport capacity accompanying scant alluvial deposition). The absence of sediment supply would have resulted from good vegetation cover in the catchments. Such conditions of increased rainfall and decreased evaporation should, however, accord with peat formation in the mires. The lack of much preserved peat and the late initiation at some sites suggests that periods of drought and fire limited peat bogs in the early Holocene and may have eroded or oxidized deposits at times. However, there is little sign of this in mires that preserve a complete record.

Fire histories

Evidence for past fire in the mires is obtained from charcoal fragments preserved in the peat. All records contain some charcoal, which may have come from catchments or the burning of mire vegetation. Peat cores from *Sphagnum* bogs are of particular interest because they do not generally accumulate washed-in charcoal, so that each record is a measure of strictly local fires.

In general, the available records show that fire has been present throughout the history of the regional peatlands, so it is not surprising that these peatlands are resilient to burning, provided that the underlying peat is moist. At Rennix Gap, an early phase of alpine herbfield and grasses when the site was above the treeline also preserves abundant fine charcoal (Kemp 1993).

Worthy (2006) used OSL (optically stimulated luminescence) dating to determine the ages of sand layers from Coronet Creek and the upper Cotter in the ACT. He interprets the sands and gravels within peat or fine alluvium as resulting from catchment erosion following fire events. He found significant build-up at one or both sites at 440 to 410, 1100, 3800, 5400 and around 6500 years ago. These reflect significant 2003-scale fire events. However, the erosional response to the 2003 fires was very patchy, and hence the sedimentary records are not a complete set of possible significant fires.

Zylstra (2006) compared the 1000-year high resolution charcoal record prepared by Dodson *et al.* (1994) from Club Lake on Mt Kosciuszko to climatic fluctuations. He suggests that there is a strong climate control on fire in that the cooler times of the Little Ice Age (300 to 100 a BP) were marked by a lower influx of microcharcoal. The warm periods saw higher charcoal influxes, although fire suppression over the past 60 years has reduced this peak. In the Snowy Mountains, fire is more likely to reflect the degree of variation in climate, which is thought to have fluctuated through time. For example, the frequency and magnitude of El Niño events may have been less than at present from 7600 to 5400 cal a BP and more extreme and prolonged between 2500 and 1700 cal a BP (Gagan *et al*. 2004).

A feature of the last few centuries at Club Lake and at sites in the ACT is a rise in charcoal influx that coincides with the appearance of weed pollen, indicating European arrival (Hope *et al.* 2009). These peaks then decline to historically low values in the 1920s after exotic pine pollen becomes significant. The records thus seem to reflect widespread deliberate ignition associated with grazing practices of the late 19th century, followed by fire suppression in the catchments in the 20th century. Zylstra (2006) finds a similar result based on tree ring records of fire scars from Mt Ginini. One interesting correlation is for reduced *Sphagnum* spore incidence associated with the charcoal peaks and increased *Sphagnum* spore levels at low fire frequencies, seen in several ACT records (Hope *et al.* 2009). This suggests that *Sphagnum* produces spores at times of lower stress and depends on vegetative spread at other times. However, *Sphagnum* was observed sporulating at Pengillys Bog 2 years after the 2003 fires, a possible response to stress.

Knowledge gaps

Mapping

Although the areal extent and location of peat-forming mires in the Snowy Mountains is now reasonably well established, we believe that refinements of the mapping are essential. Accuracy can be improved and numerous sites need to be checked on the ground to improve reliability. We currently have mainly anecdotal evidence for historical changes to the extent of mires. The mapping of the mires and their vegetation boundaries to 2003 as a reference year is the first stage in understanding the dynamics of these systems. Mapping against older air photo sources, maps and former peatland extent established by analysis of sediments could be used to establish the pre-European extent and historical changes in the dominant vegetation of the peatlands. Future mapping against the 2003 boundaries will allow management progress in maintaining or expanding mire area to be quantitatively measured. Climate parameters for the mires based on existing climate stations and extrapolations such as the bioclimatic analysis and prediction system BIOCLIM (Houlder *et al.* 2000) will allow better explanations of the pattern of mire distribution. There is potential for further modelling research to assess the environmental controls on mire formation and persistence. This could include studies of the microclimate of the mires and their catchments.

Extension of the mapping is also needed. The mire mapping in the Victorian subalpine is held as a GIS data set at the Arthur Rylah Institute for Environmental Research, Victorian Department of Sustainability and Environment. It was assembled from vegetation mapping and so could be augmented to match the NSW and ACT data and ideally extended to include the 700- to 1000-m altitude zone. An integrated peatland database for the Australian Alps as a whole would be valuable, as it would allow peat condition and sequestration calculations and would help with peatland management. There is also no natural break at 700 m, and extension of the survey to include peatlands at lower altitudes is needed. Other montane peatlands elsewhere in south-eastern Australia should be mapped to provide some idea of the extent and vulnerability of the regional peatlands. Some mapping is already held by state and commonwealth agencies, for example by the Office of Environment and Heritage (NSW) and the Commonwealth Department of Sustainability, the Environment, Water, Population and Communities.

Peat stratigraphy and characteristics

We have only a preliminary idea of the stratigraphy and peat characteristics of a very small proportion of the mires. A more standardised classification of the peats is needed – one that can be tied to physical, chemical and biological characteristics. As an example, the assessment of apparent hemic *Sphagnum* peat under some *Empodisma* moor areas could be checked for indicator fossils and dated to establish the former extent of shrub bog. This would then provide a target for rehabilitating the mire to its former extent.

We do not know whether the mires are currently carbon sinks or sources, although the historical data suggest that under present management the bogs, and especially the fens, have good potential to act as sinks. The estimates provided in this report are no more than indicative of the carbon budget in the short and long terms. More precise historical data are needed of peat type, bulk density, water and carbon content, supported by detailed chronology. The mires are appropriate as study sites for carbon balance studies, as they are likely to be very sensitive to climate variability. Refinements of the carbon balance estimates need to be combined with improved estimates of the carbon held in the mires and long-term sequestration rates. High-resolution accelerator mass spectrometry dating and detailed peat stratigraphy involving large numbers of precise bulk density and C-N-H determinations are needed to significantly improve data on peat and carbon accumulation rates to contribute to a total carbon budget for the Australian Alps. This work should be supported by setting up carbon flux facilities to measure the carbon budgets of characteristic mire types – at a minimum the budgets of a sedge fen and a subalpine shrub bog. Such monitoring stations would provide a sensitive indicator of climate change.

Similarly, the pioneering work of Grover (2006) on peatland chemistry should be extended to the full range of mire types. A current program to measure silver accumulation in a range of peatlands in relation to cloud-seeding programs (Colin de Paget, Helisurveys 2009, pers. comm.) could also yield useful data on peat chemistry and the role of aerosols and dust if it were extended. Much more work is needed on the carbon cycle to clarify the conditions most helpful in retaining the carbon store and peatland functions.

Hydrology

Instrumentation of some mires with weirs and piezometers recording to data loggers would allow the water balances to be assessed in relation to vegetation development and climate change. Detailed daily meteorological records from a range of sites and stream-gauging data held by various water authorities in NSW, the ACT and Victoria are available; these would provide valuable modelling inputs if they could be made available publicly. Hydrological measurements could provide a measure of the effects of mire rehabilitation works. Modelling of the behaviour of streams in peatland in the Snowy Mountains has not yet been attempted. Nanson (2010) and Nanson *et al.* (2010) have shown that sinuous channels in peatlands on Barrington Tops are stable and pre-date European use of the area. Similar work is needed in the Alps region, the Ingeegoodbee peatlands being an obvious case needing research that could aid rehabilitation. Quantification of the impacts of grazing on channel form and function and mire retention should also be studied. Dissolved organic carbon studies should form part of a hydrology program, and these could be focused on peatlands under different types of disturbance such as drying or fire (Fenner *et al*. 2001).

Ecology

We have used a very simplified scheme for classifying mire vegetation, and we acknowledge that short-and long-term studies of the biology of the mires across their range are badly needed. Lawrence *et al.* (2009) wonder why it is that *Sphagnum* shrub bogs have received the bulk of research attention and that fens, restiad moor and aquatic communities have been ignored. It may be because *Sphagnum*-dominated communities are ecologically more diverse and are recognised as natural assets. Work on vegetation dynamics and studies of all aspects of keystone species are needed to substantiate the anecdotal observations in this report.

Notably, this report, together with those of Lawrence *et al.* (2009) and Hope *et al.* (2009), completely ignores mire vertebrate and invertebrate fauna. The important role of freshwater crustaceans in Tasmanian mires suggests that the ecology of this group may be particularly important (Dreissen 2006). The burrowing spiny crayfish, *Euastacus rieki* (Figure 19a), moves sands and gravels onto bog surfaces, and its burrows are utilised by the alpine water skink

Eulamprus kosciuskoi (Lintermans and Osborne 2002). Whereas some amphibians such as the corroboree frog have received a lot of attention (e.g. Hunter *et al.* 2009), other faunal groups, including rodents such as the broad-toothed rat, and birds and reptiles, are part of the ecology and may affect peatland function in a variety of ways. Peatland streams and ponds also provide aquatic habitats that require more study.

Figure 19a. Spiny crayfish, *Euastacus rieki*, probably caught by a fox. 1815 m, Three Rocks Creek, Mt Anderson, February 2010. Photo: Genevieve Wright

Long-term monitoring of plant ecology at a limited number (100) of quadrats at three *Sphagnum* shrub bog mire sites in Kosciuszko National Park has begun (Whinam *et al.* 2010). This program should be extended and possibly expanded to non-*Sphagnum* mires (Figure 19b). Further testing and monitoring of rehabilitation methods is desirable, together with ongoing assessment of the rehabilitation works already carried out in 1983 and 2003 to 2008. The impacts of the 2003 fires have been better recorded than any previous events (e.g. Carey 2005, Carey *et al.* 2003, Growcock and Wright 2006) (Figures 19b and 19c).

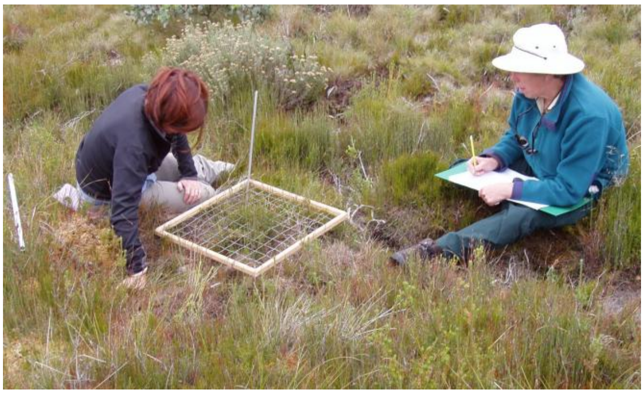

Figure 19b. Monitoring of a former *Sphagnum* shrub bog by Jennie Whinam and Trish MacDonald after the 2003 fires. Boggy Plain, Tantangara area, March 2007. Photo: Geoffrey Hope

POST-FIRE REHABILITATION AREA

This Sphagnum Bog is being rehabilitated as part of the post-fire catchment rehabilitation program for the Snowy Mountains and Brindabella Ranges.

The rehabilitation work is being undertaken by the National Parks and Wildlife Service, with assistance from Prof. Geoff Hope (Australian National University) and Dr Jennie Whinam (Nature Conservation Branch, Tasmania).

This sensitive area is habitat for threatened native species. Special habitat restoration will be undertaken in this bog.

Your assistance in protecting these areas from further disturbance would be appreciated.

Figure 19c. Signage to conserve long-term shade trials and recovery monitoring at Pengillys Bog. Photo: Jennie Whinam

History

Work to date, mainly using low resolution pollen and microcharcoal analysis, is a start but is far from comprehensive and is uneven in application. New proxies include insect remains, cladocerans, phytoliths, and macrofossils such as seeds and wood charcoal, along with chemical and isotope analyses. If supported by detailed accelerator mass spectrometry dating of individual components, these methods, plus improved pollen analyses, can provide much more information about individual mire dynamics and regional patterns. Analysing the resting spores of testate amoebae through time can provide a sensitive measure of the history of the wetness of a mire (Booth 2007, Wilmshurst *et al.* 2003). The mires have been shown to contain testate amoebae, but sampling of a range of modern mire surfaces is needed to provide data for a transfer function (Seamer 2007).

New statistical techniques are being applied to high-resolution measurements of a larger size range of charcoal (125 to 300 µm). These can be interrogated to show fire recurrence intervals through time (Conedara *et al.* 2009). These records can help with management and can also be aligned with ecology, archaeology and climate (Mooney *et al.* 2001).

Although looking at the entire history of a mire is of great scientific interest, it requires a lot of resources and expertise. A great deal of effort is also going into looking at shorter time scales, such as the last 1000 or 300 years (e.g. Lynch *et al.* 2007), as it is easier to find a network of suitable sites and the number of analyses is reduced. Such work focuses on the questions of changing land management and climate change impacts. Hence it can provide useful inputs into management choices and help to assess system resilience and identify risks.

Fire and organic soils

There is a role for targeted fire science research into the behaviour of fire in mires and its impact on biota, peat chemistry and regeneration. The 2003 fires provided a wealth of observation on the effects of fire on the range of mires and the extent to which peatlands have been destroyed or reduced in area (Figures 20a to 20d). Methods for fire control on various types of mire also need to be researched. Peat fires, in which the substrate is consumed by subterranean fire, were fortunately uncommon and seemed to occur where ditching or stream incision had allowed peat to dry out.

Figure 20a. The January 2003 fire killed *Sphagnum* hummocks at Brumby Flats, Brindabella National Park. Photo taken in April 2003. Photo: Ben Keaney

Figure 20b. Fire-killed *Sphagnum* along a drainage line, Cup and Saucer area, January 2004. Photo: Geoff Hope

Figure 20c. Burnt and wind-eroded alpine humus soils with no vegetation recovery after 1 year, indicating a peat fire. Mt Tate, 1900 m, January 2004. Photo: Geoff Hope

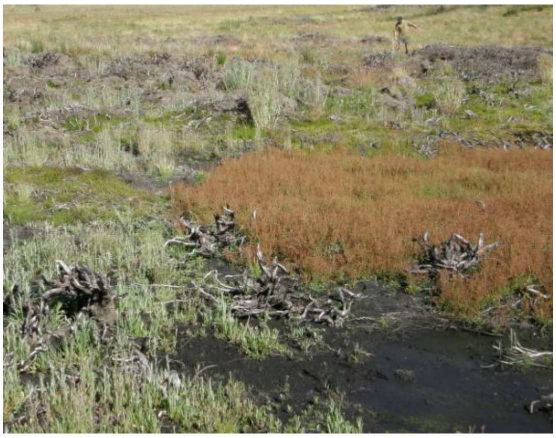

Figure 20d. Burnt peat 5 years after the 2003 fires, invaded by *Acetosella vulgaris*. Currango Plain, January 2010. Photo: Matiu Prebble

Mire management and rehabilitation

Applied research focusing on the stability of mires and the effects of passive or active management is needed. Good *et al.* (2010b) outline the use of various techniques, such as water spreading using straw bales and gabions (baskets filled with stones). They recommend catchment protection and removal of large grazers. Limited trials to see if succession can be accelerated with fertiliser, shade or transplants have also been started. All of these techniques require more long-term research to determine their long-term effectiveness.

The possible effects of climate change in cold-dependent habitats (DECCW 2009, 2010; Pickering *et al.* 2004) can be studied in mires, as these are likely to be sensitive to increased temperatures and drought.

MANAGEMENT CONSIDERATIONS

The long-term goal of management is to maintain the biodiversity and geomorphological stability of the catchment in order to maximise the resilience of the ecosystems. Although the peat-forming mires cover only 0.89% of the Snowy Mountains region (2.0% of the 360 012 ha of KNP above 1200 m), they have received substantial management attention and expenditure because of their critical role in biodiversity maintenance and perceived fragility in the face of disturbance, fire and climate warming. As indicated by the survey, a healthy mire is one that is growing actively with a substantial proportion of the peat column made up of fibric or fibric-hemic peat. Such a system creates and maintains its local watertable and is resistant to periods of drought. As it obstructs slope or stream drainage it creates pools and ever more complex surface structures that maximise ecological gradients. Maximising the extent of such mires by allowing damaged or immature peatlands to recover or progress provides the basis for management. Mire status (increase, maintenance or decline) is thus a measure of the effectiveness of management in the face of the environmental variation caused by both natural and human processes.

Threats

Short growing seasons and low nutrient supply mean that subalpine and especially alpine peat bogs are very slow to regenerate, once stripped of vegetation. The peat growth figures in the previous section show that deep peats take thousands of years to accumulate and cannot be replaced within human life times once lost or mineralised. The mires are unusual in retaining their own history of gradual accumulation since the last event that exceeded their capacity to resist destruction. The historical studies show that this covers at least 2000 to 10 000 years in many cases. The first priority for positive management is therefore the prevention of damage to the peat deposit, stream lines or mire vegetation. Physical threats to mires are those that result in entrenchment of water, removal of surface peat or sapping by sub-peat erosion (Hope *et al.* 2009). Common causes are trampling, ditching and unusual rainfall events, often reinforced by fire damage to the mire or the catchment.

In large areas in the coldest or driest zones of the Snowy Mountains, mires are reoccupying sites that were wrecked by grazing that eroded or buried the peats and entrenched the watercourses (Figures 21a to 21e). In some cases, active drainage of the mires by trenching and deliberate burning was practised (Figure 21f). Worboys and Pickering (2002) outline the history of disturbance in the highest areas and describe the particularly difficult campaign to discontinue seasonal grazing. Although large-scale grazing had nearly ceased by the late 1950s, horses, deer and pigs remain as real threats in some areas and a potential problem throughout the region. McDougall and Walsh (2007) note:

> The chief threatening process for peat communities in the Australian Alps is physical damage by trampling leading to loss of cover and alteration of local hydrology which leads to channelling of waterflow through the bog. This alteration of drainage patterns within and immediately outside the bog reduces its water- holding capacity, which in turn accelerates the degradation process. Damaged bogs are often identified by deeply channelled streams. Pristine bogs typically have little or no free running water. Although most alpine areas in the Australian Alps are now protected from grazing, human foot traffic remains a significant damaging process in many areas. Trampling by feral horses is an increasing threat in the Nunniong- Cobberas areas in Victoria and the Tantangara and upper Thredbo valley areas in NSW. Significant areas of bog have been lost through the creation of lakes or dams for hydroelectricity production.

Horse numbers have continued to rise since the above was written in 2006. Populations are high in both southern and northern areas of Kosciusko National Park, having been only slightly reduced by a costly program of trapping and removal. Until large grazers are removed, rehabilitation is pointless. Grazing has not, unfortunately, been prevented on many mires outside the park, and cattle still cause damage at Tomneys and MacPhersons plains and occasionally at Micalong Swamp (Figures 21g to 21o).

Figure 21a. Formerly heavily grazed valley floor with peatland reduced to small area. Valentine River near Big Bend, January 2006. Photo: Iona Flett

Figure 21b. Recovering alpine shrub bog with very shallow peat over gravels. 1825 m, Upper Valentine River, January 2006. Photo: Geoff Hope

Figure 21c. Incision and desiccation due to former grazing at upper Geehi River, February 2010. Photo: Rachel Nanson

Figure 21d. Incision and peat humification at Tomneys Plain following recent high grazing pressure, April 2010. Photo: Geoff Hope

Figure 21e. The dark humic profile and eroded banks suggest that peatland was extensive on Nungar Plain before extensive grazing and stream incision. October 2008. Photo: Bren Weatherstone

Figure 21f. Ditching of Swampy Creek near Eucumbene to drain a former *Carex* fen and montane shrub bog. January 2009. Photo: Geoff Hope

Horse riding is permitted in parts of Kosciuszko National Park, and these activities cause some damage to the mires (see Figure 22 h).

Human trampling of mires can have similar effects to trampling by other large mammals but is readily avoided by track routing, education, and (in particular cases) by installing raised metal or wood walkways. Vehicles can cause even greater damage but are well controlled in the National Park areas.

Figure 21g. Cattle in subalpine shrub bog on a lease adjoining Kosciuszko National Park, Grey Mare Fire Trail, April 2009. Photo: Bren Weatherstone

Figure 21h. Three hundred cattle being driven onto Micalong Nature Reserve in November 2006. Photo: Geoff Hope

Figure 21i. Cattle damage to stream line in the peatland, Micalong Swamp, November 2006. Photo: Rachel Nanson

Figure 21j. Feral horses on the margin of a subalpine shrub bog, Chimney Range, February 2010. Photo: Geoff Hope

Figure 21k. Horse droppings at 1930 m on Swampy Plain, Kosciuszko Main Range, February 2010. Photo: Geoff Hope

Figure 21l. Horse trampling of stream banks, Carters Hut, Ingeegoodbee, April 2010. Photo: Peter Jones

Figure 21m. A former subalpine shrub bog completely removed by trampling and increased drainage, Dunns Flat, near Murray Pass, January 2009. Photo: Bren Weatherstone

Figure 21n. Wild horses and incised gully on a former sedge fen, Mosquito Creek, Currango Plain, January 2009. Photo: Geoff Hope

Fire in itself is not usually a threat to the biodiversity of peatlands, provided the peat is moist (Whinam *et al.* 2010). Williams *et al.* (2008) noted recovery of fauna after the 2003 fires and concluded that the fauna is adapted to a cycle of small and occasional landscape-scale fire events. This is borne out by the previously discussed records of fires in all sites throughout the Holocene. It is extreme events or combinations of events, such as severe and repeated fire, extreme drought, and 100-year precipitation events that cause major landscape change. The best defence against these are balanced, diverse and fully functioning ecosystems that provide cover, seed or germination stores for recovery.

Weed invasion was predicted to be severe after the 2003 fires, but monitoring found that most appearances were ephemeral and not a threat to the mire vegetation as it re-grew (Whinam *et al.* 2010). Several introduced plant taxa are now established in mires, including *Hypochaeris radicata*, *Trifolium* spp., *Acetosella vulgaris* and *Holcus lanatus*. Localised problems have been experienced with willow (*Salix cinerea* and other *Salix* spp.), *Cytisus* spp. (broom), *Juncus effusus* (spike rush) and *Anthoxanthum odoratum* (sweet vernal-grass) (DEWHA 2009), all of which tolerate low pH. Pines have also been invading peatland margins. Monitoring for weeds, and their removal, is essential (Figure 22a). Careful attention to washdowns for vehicles and clean-up of equipment that will be used in peatlands is also recommended. Horses, deer and pigs play a part in facilitating weed establishment by disturbing vegetation and enriching areas with dung (see Figure 21k).

Figure 21o. Wild horse at Paddys River Bog, cutting paths through *Sphagnum* mounds, February 2011. Photo: Geoff Hope

Rehabilitation

All of the alpine national parks authorities have made attempts to trial rehabilitation methods for mires affected by the 2003 fires, which burned almost all the peatlands. Observation after the fires suggested that prevention of erosion was the most critical concern, together with re-wetting areas of peatland that appeared to be drying out. Kosciuszko National Park and Namadgi trialled the use of steam-sterilised straw bales to block stream ways and spread water onto the peatland at several *Sphagnum* shrub bog sites, notably Guthries and Pengillys bogs and sites south of Jagungal (Good 2006a, Good *et al.* 2010b, Hope *et al.* 2009). Coir 'logs' were later introduced, as they lasted better and could be tailored to fit variable gaps. Victoria trialled woodchips wrapped in shadecloth but concluded that using plastic was not appropriate after fires in 2006 reburned areas of rehabilitated mire on Mt Buffalo. These barriers are intended to emulate the growth of peat to impede drainage, a process that might take decades or centuries (Figures 22b to 22d). They also may prevent instability that would see headward erosion and the loss of sediments from a catchment. Materials used are intended to gradually degrade and be overgrown by the mire. Steam-sterilised straw bales have been more successful in allowing peat accumulation across small drainage lines but have failed in larger channels subject to high flow. Other countries have installed permanent barriers using rock gabions or wooden dams to block channels and spread water across the mire (Steiner 2005). These will trap sediment and re-wet the mire and can be justified for large areas such as the million-hectare drained peatland in central Borneo.

Figure 22a. Ranger Rob Gibbs removing a willow, Tinmine Creek, March 2010

Figure 22c. Sterilised straw bale impeding drainage, Valentine River, February 2010. Photo: Genevieve Wright

Figure 22b. Amanda Carey and Roger Good examining a straw bale barrier placed in a ditch, April 2005. Photo: Trish MacDonald

Figure 22d. Guthries Bog, formerly incised following grazing, has been reflooded by placing large numbers of straw bales in channels, October 2004. Photo: Geoff Hope

Persistence of peatland ponds with seasonally variable water levels is critical to providing nesting sites for corroboree frogs and suitable protected water for tadpoles. Hunter *et al.* (2009) raise the concern that pond rehabilitation may fix water levels and prevent nest flooding and drying cycles. They point out that the processes of peatland pool formation are poorly understood and suggest that interference with natural regeneration should occur only in well-designed and -monitored situations. Works carried out in the ACT and at Kosciuszko are designed to 'leak' to provide natural seasonal fluctuations while trapping sediment and retaining water longer than would be the case if the channels were left unblocked. Monitoring by using photo plots, together with condition assessment, has been part of the works (Good *et al.* 2010b, Growcock and Wright 2006). Ponds are more complex and frequent in the least-damaged mires and can be expected to develop as the grazing-damaged mires recover.

More experimental has been the post-fire temporary use of 70% shadecloth to cover burnt *Sphagnum* shrub bog (Figures 22e, 22f). The cloth can be removed once shade plants have regenerated, usually after 2 or 3 years. Trials were undertaken after the 2003 fires at Pengillys Bog and in some ACT mires. The effectiveness of this technique is still being assessed (Whinam *et al.* 2010), but a comparison of adjacent treated and untreated areas has shown enhanced moss regeneration and regrowth of shrub and restiad cover. A major effect seems to be the maintenance of a humid layer under the cloth, limiting bleaching of the moss in summer and enhancing growth rates. Remeasurement of study plots will show whether this effect has long-term benefit in accelerating regeneration. A long-term program of monitoring is in place to assess the various techniques used.

Figure 22e. Roger Good and Jennie Whinam monitoring shade experiments at Pengillys Bog, October 2004. Photo: Geoff Hope

Figure 22f. Shadecloth removed after 3 years at Pengillys Bog, showing significant regeneration, March 2003. Photo: Geoff Hope

In addition to shade, the effect of moderate fertiliser application is being tested at some of the permanent plots set up in 2003. A light application of low-phosphorus fertiliser has not given a statistically significant response, perhaps because of the extreme heterogeneity of the test plots. It is likely to be most useful on lightly burned sites for enhancing *Sphagnum* growth, but it does not help on severely burned plots.

Sphagnum is readily killed by fire and has retreated from former areas across south-eastern Australia over the past 50 years (Whinam and Chilcott 2002). As its recolonisation is extremely slow, the possible role of transplants has been investigated (Whinam *et al.* 2010). Slabs of *Sphagnum* bog, 25 cm square and spade-depth, were taken from live bog and inserted in holes in burnt bog (Figure 22g). Variable results have been achieved, but the most successful have been in minor streamways, in hollows in burnt bog that are shaded or given litter shading. The transplants have also allowed the included shrubs and restiads to develop. Dry burnt peat areas, such as organic soils on Mt Tate, have proven resistant to transplanted sedges and grasses, probably because of the hydrophobic properties of the peat and the capture of water by underlying gravels.

Use of advanced peat tube stock may be necessary to allow the plant to reach the watertable, now below the peat layer.

Transplanting holds some promise in returning bogs to their known former extent. However, transplants should have local provenance, and some bog areas may not have remaining healthy mire to provide materials. The occurrence of delayed natural regeneration of *Sphagnum* up to 3 years after the fire suggests that transplanting may be left until the long-term loss of shrub bog is apparent. As such programs would be carried out at the individual bog scale, good mapping of former *Sphagnum* boundaries is essential.

Figure 22g. A *Sphagnum* transplant at Pengillys Bog after 6 years. March 2009. Photo: Geoff Hope

Human trampling has been addressed at Kosciuszko National Park by re-routing tracks and in some cases raising them above peatlands in the alpine zone (Worboys and Pickering 2002). However, horse trails in the northern part of the park cross mires and affect stream lines (Figure 22h). Structures associated with the ski field development also need to protect mires. For example, at Perisher the main valley mire has been incised and then covered for car parks, some of which are proposed to be extended (Figures 22i and 22j). Mires are routinely ditched where roads cross stream lines. Damage can be minimised by careful routing and by providing under-road drainage to maintain natural flows.

Figure 22h. Trail-riding group crossing a subalpine shrub bog at upper Boggy Plain, April 2007. Photo: Geoff Hope

Figure 22i. Perisher ski resort is built adjacent to extensive subalpine shrub bogs and has placed structures, car parks and drainage works on some areas of mire. April 2004. Photo: Geoff Hope

Figure 22j. The main car park at Perisher lies on infilled shrub bog. April 2010. Photo: Geoff Hope

Figure 22k. Ski facilities at Smiggin Holes lie on former shrub bog, which is now mown. April 2010. Photo: Bren Weatherstone

Fire protection

It is hard to see how the mires can be directly protected from fire during large events such as the fires of January 2003. However, they could be made a target for individual fire suppression efforts if conditions are suitable. Unlike in some forest areas, fire on peatlands tends to proceed slowly and to take a long time to consume the vegetation. A team may therefore be able to put out spot fires and break fire fronts using local water sources, with the aim of achieving a mosaic burn. Protection of ‘islands’ of intact bog will enhance overall mire recovery after the fire. Sections of riparian vegetation might also be protected to maintain stream integrity. The occasional use of fire retardant on bog margins should not have long-term effects (Jenny Whinam, Tas. DPIPWE 2009, pers. comm.) and might be used to hinder fire entry to bogs. By contrast, fens do not need special measures unless they are very dry. Accordingly, fire plans are needed for selected individual mires to assess the most valuable elements and best means for protecting them, together with assets such as stream barriers and resources such as stream ponds. The possibility of modifying (e.g. by slashing) marginal vegetation to act as a buffer zone might be considered, but this raises ecological questions for fauna, such as the corroboree frog, that utilises the mires. Monitoring of mire condition is needed to keep the strategies up to date and identify risks such as drying of surface peats. The best overall protection for the mires is the retention of available moisture. This may require the installation of temporary artificial barriers in streams and the growing of mire vegetation across drainage lines. Feral animal control is an essential aspect for achieving mire resilience to fire.

Education and training

Education of the public about the mires and their unusual historical archives has begun with information boards and displays as at Rennix Gap Bog (Figure 22l). There may also be scope for boardwalks and on-site interpretation in both fens and bogs. For example, Micalong Swamp Flora Reserve is traversed by the Hume and Hovell walking track, but few walkers are informed about this remarkable fen. Further educational material, including web-based information and access to databases, is needed. Engaging the public and commercial operators is the best way to protect mires from unnecessary damage. Groups such as the National Parks Association, Friends of Grassland or other more recreational groups could be involved in some aspects of monitoring, rehabilitation or research, thus spreading enthusiasm and skills more widely.

Rennix Walk

12km return

This track skirts the edge of a montane forest and winds through subalpine meadows, snowgum woodlands and open plains. It provides views of alpine ash forests, and glimpses of the Snowy River and Lake Jindabyne.

Rennix Walk starts in a 10,000 year old bog. Aboriginal stone tools have been found in this area.

About 1.6km along the track a gap in the treeline provides views of the Main Range. About 1km further on you can see Mt Blue Cow with the Main Range in the background.

A trig station on a prominent group of boulders near the Snowy Hydro radio reflector marks the end of the track. From here you can see the site of the Island Bend township and the airstrip used during the construction of nearby dams, tunnels and power stations in the 1950s.

Rennix Gap is named after the engineer in charge of the construction of the Kosciuszko Road from 1906 to 1909. He died of pneumonia after being caught in a blizzard there.

Weather in the Alps can change quickly any time of the year. Be prepared for all weather conditions.

In the subalpine area, many small mammals are adapted to life in and under the snow. Above the snow you may see lizards, insects and birds such as little ravens.

The walk provides views of alpine ash forests

You are in a 10,000 year old bog. Sphagnum moss, t hummocky mounds in bogs, takes in water du snowmelt and slowly releases it into streams.

Acting like giant sponges, they absorb then releas clear water into the mountain streams that Snowy River.

Please stay on the track, especially through these wet

KOSCIUSZKO NATIONAL PARK

Figure 22l. Signage at Rennix Gap Bog acknowledges mire studies. Photo: Geoff Hope

Training of national parks personnel and workshops and field days to share practical management skills have been occurring for several years. However, although the program is Alps-wide, it could be more comprehensive (Figure 22m). A training manual that includes advice on mire repair has also been a valuable resource but could be expanded (Good 2006b). We hope that this report, supplemented by those for adjacent parts of the Alps (Hope *et al.* 2009 and Lawrence *et al.* 2009), will contribute to this process by showing the extent and complexity of the mires. There is an urgent need to inform the land-management practices of non-Park managers and private landholders in the Snowy Mountains region of NSW.

Figure 22m. Roger Good and Andy Spate explaining bog drainage rehabilitation to a group of Parks personnel from Victoria, ACT and NSW. June 2004. Photo: Geoff Hope

CONCLUSIONS

The 8000 ha of montane and subalpine mire in the Snowy Mountains is the most extensive in the region and includes the only high alpine mire examples in Australia. Although most people think of the *Sphagnum* moss-and shrub-dominated bogs as the typical mire, this survey shows that there are very significant *Carex* sedge fens in all areas of Kosciuszko National Park and outside the park boundaries. These contain significant stores of peat, amounting to almost 50 million cubic metres, made up of water and organic matter. This substrate retains moisture through dry periods, thus maintaining a mosaic of biodiversity and habitat that is important to the fauna of both the wetlands and the surrounding plant communities. The mires are shown to resist fire damage and provide refuge and rapid post-fire resprouting, which enhances resilience in the fauna and flora as a whole.

The peatlands have been badly damaged by the historical period of summer grazing, and an unknown volume of peat has been removed. Recovery is proceeding, with bogs expanding into former sites and peat starting to slowly accumulate again. Preliminary data suggest that the bogs and fens now have positive carbon budgets and can play some part in the sequestration of atmospheric CO_2. This role can be enhanced by retention of water in the bogs and by repairing damage to stream lines. On the other hand, the mires may revert to being carbon sources if significant increases occur in summer temperatures and drought frequencies.

Given that the Australian Alps must be managed to maintain natural values, active management of mires aims to reinforce natural processes of vegetation succession and enhance the retention of sediment stores. Control of access, control of feral animals and weeds, and fire suppression, are already considered in plans of management for the Kosciuszko National Park and in consultation with relevant land managers in NSW, Victoria and the ACT. However, horse control in particular is becoming critical to the preservation of mires in many areas. Detailed bog-recovery plans are needed as part of catchment rehabilitation.

There is much more to learn about the peatlands of the Australian Alps and their role in hydrology and ecology and as geomorphological systems. The negative perception of mires as ‘wasteland’ should be replaced by a new appreciation of the fascinating processes, environmental services and aesthetic highlights of these natural treasures of the Snowy Mountains.

APPENDIX: PRIORITY SITES FOR PROTECTION

The following list is of suggested mires that have particularly high scientific and landscape values. Sites have been selected for one or more of the following criteria:

- They are representative of a class of mires, or best expression in the region.
- They represent outliers, often with unique features.
- They have been used for scientific research and have archive value.
- They are amongst the largest mires in a sub-region.

Because we have not been able to work on all mires, the list is likely to be incomplete and subject to revision and additions.

Code: A, high conservation value; B, high scientific value, threatened; C, significant mire in damaged condition

Tenure: Ex ANNP, lies outside a conservation area. BNP, Brindabella National Park. SRNR, Scabby Range Nature Reserve. KNPN, KNPM, KNMS: Kosciuszko National Park north, middle or southern sections

Vegetation: Dominant vegetation is alpine (A), subalpine (S) or montane (M) *Sphagnum* shrub bog (SSB), *Empodisma* moor (EM) or *Carex* fen (CF)

Code	Mire	Catchment	Tenure	Area (ha)	Altitude (m)	Veget-ation	Comment
Alpine *Sphagnum* shrub bogs							
A	Big Bend, Geehi	Murray R	KNPM	4.23	1762	ASSB	High-altitude recovering bogs
A	Blue Lake Ck	Snowy R	KNPM	5.13	1854	ASSB	Fen and bog subject to high snow lie
A	Blue Lake Twynam	Snowy R	KNPM	1.49	1974	ASSB	Only Ramsar site; study site, aquatic communities
B	Club Lake Margin	Snowy R	KNPM	6.75	1951	ASSB	Study site and alpine fen-bog
B	Doubtful Ck	Murrumbidgee R	KNPM	33.09	1679	ASSB	Large sedge fen
A	Finns Swamp	Snowy R	KNPM	7.90	1696	ASSB	Recovering alpine bog complex
A	Geehi R Bulls Peaks	Murray R	KNPM	18.79	1789	ASSB	Extensive high-altitude recovering bogs
A	Geehi R Dicky Cooper Ck	Murray R	KNPM	6.25	2000	ASSB	High-altitude recovering bogs
A	Geehi R Duck Ck	Murray R	KNPM	5.94	1778	ASSB	High-altitude bog
C	Geehi River North	Murray R	KNPM	59.47	1782	ASSB	High altitude bog/fen/herbfield complex
A	Geehi S 51	Murray R	KNPM	8.38	1765	ASSB	High altitude recovering bogs
A	Geehi S Valentine Ck	Murray R	KNPM	25.89	1913	ASSB	Alpine fen bog mosaic
B	Guthrie Bog	Snowy R	KNPM	12.63	1732	ASSB	Rehabilitation site, alpine bog
B	Lake Cootapatamba	Murray R	KNPM	1.23	2023	ASSB	Aquatic communities and small marginal fens

Code	Mire	Catchment	Tenure	Area (ha)	Altitude (m)	Veget-ation	Comment
Alpine *Sphagnum* shrub bogs *continued*							
A	Merritts Ck	Snowy R	KNPM	6.88	1926	ASSB	High altitude bog
B	Pengillys Bog	Snowy R	KNPM	6.94	1617	ASSB SASSB	Extensive bog, study site. Type locality of southern corroboree frog site
A	Pipers Ck Rock Ck 10	Snowy R	KNPM	6.67	1807	ASSB	High altitude bog
B	Pounds Ck	Snowy R	KNPM	1.78	1906	ASSB	High altitude bog, study site
A	Spencers Ck	Snowy R	KNPM	4.98	1743	ASSB	Rehabilitation study sites
A	Swampy Plain High	Murray R	KNPM	25.88	1906	ASSB	Alpine Bog-fen complex
A	Thredbo Slopes	Snowy R	KNPM	22.22	1987	ASSB	Scattered but extensive *Richea* shrub
A	Wilkinsons Ck	Murray R	KNPM	8.15	1884	ASSB	High altitude bog
A	Wrights Ck 56	Snowy R	KNPM	13.09	2022	ASSB	Highest site, feldmark-mire complex
Subalpine shrub bogs							
B	Bald Mountain Ck	Snowy R	Ex AANP	21.51	1464	SASSB	Large bog-fen mosaic
A	Big Plain Ck	Murrumbidgee R	KNPN	9.67	1357	SASSB	Isolated subalpine in northern KNP
A	Blanket Plain	Murrumbidgee R	KNPN	18.16	1375	SASSB	Extensive bog complex
C	Boggy Plain	Murrumbidgee R	KNPN	23.05	1401	SASSB	Degraded bog and fen, study site
B	Brooks Ridge fen	Snowy R	Ex	6.39	1441	SASSB	Marginal bog, study site
A	Brumby Flats	Murrumbidgee R	BNP	4.80	1787	SASSB	High-altitude outlier, slope bog
A	Bulls Peaks Ck	Snowy R	Ex AANP	34.24	1437	SASSB	Extensive lower altitude bogs and fens. Recovering
A	Cascade Ck	Murray R	KNPS	18.50	1468	SASSB	Extensive lower altitude bogs and fens. Damage occurring
C	Dead Horse Ck	Snowy R	KNPM	5.94	1732	SASSB	Higher altitude shrub-rich bog
B	Delaneys Ck	Snowy R	KNPN	3.90	1358	SASSB	Study site, valley floor
C	Dunns Ck	Murrumbidgee R	KNPN	9.21	1450	SASSB	Former extensive peatland
B	Happy Jacks Ck complex	Murrumbidgee R	KNPM	55.32	1456	SASSB	Range of damaged bogs and fens
A	Ingeegoodbee Carters Hut	Snowy R	KNPS	6.75	1258	SASSB	Low altitude *Richea* and *Astelia* SSB

Code	Mire	Catchment	Tenure	Area (ha)	Altitude (m)	Veget-ation	Comment
Subalpine shrub bogs *continued*							
B	Pinch R Paradise Hill 1	Snowy R	KNPS	4.73	1543	SASSB	Plateau bogs
A	Prussian Ck	Snowy R	KNPM	1.21	1697	SASSB	Study site, steep slope
A	Rennix Boggy Plain Ck	Snowy R	KNPM	14.72	1575	SASSB	Deep peat area, study and teaching site. Recovering
B	Sams Ck	Murrumbidgee R	SRNR	7.95	1527	SASSB	Outlier mires recovering from fire
A	Temperance Ck 2	Murrumbidgee R	KNPM	25.19	1605	SASSB	Extensive bog area
B	Tooma Bogong Swamp 63	Murray R	KNPM	8.02	1603	SASSB	Extensive mire complex
Montane shrub bogs							
C	Coree Bog	Murrumbidgee R	BNP	2.51	1040	MSSB	Northernmost bog, corroboree frog site
A	Paddys River Bog	Murray R	Ex AANP	31.28	1185	MSSB	Best and largest MSSB found
A	Tomneys Plain	Murrumbidgee R	Ex AANP	11.58	1146	MSSB	Recovering bog, rehabilitation site
***Empodisma* moor**							
C	Botherum Plain	Snowy R	KNPM	14.27	1305	EM	Drier area, marginal mire
A	Diggers Ck	Murrumbidgee R	KNPM	30.17	1471	EM	Old gold area, recovering moor
A	Gungarlin R 113	Snowy R	KNPM	46.34	1318	EM	May recover to bog
B	Happy Jacks McKeahnies Ck 6	Murrumbidgee R	KNPM	29.86	1485	EM	Post-fire extensive moor
B	Jounama Ck	Murrumbidgee R	KNPN	6.09	1066	EM	Northern example
C	McPhersons Plain	Murrumbidgee R	Ex AANP	8.28	1151	EM MSSB	Endemic orchids and recovering mires
C	Peppercorn Ck 1	Murrumbidgee R	KNPN	6.34	1324	EM MSSB	Outliers in Fiery Range
B	Pipers Ck Thompsons Plain 38	Snowy R	KNPM	13.83	1740	EM MSSB	Extensive moor following fire
C	Plains of Heaven	Snowy R	KNPM	2.22	1713	EM	Extensive moor following fire
A	Rams Head Bogong Ck	Snowy R	KNPM	9.12	2126	EM	Highest altitude moor
C	Snowy Plains	Snowy R	Ex	57.51	1416	EM	Extensive moor and sod tussock

Code	Mire	Catchment	Tenure	Area (ha)	Altitude (m)	Veget-ation	Comment
Empodisma* moor *continued							
B	Tooma Cool Plain 35	Murrumbidgee R	KNPM	10.99	1571	EM	Extensive moor
***Carex* fen**							
C	Bradleys Ck	Murrumbidgee R	Ex AANP	12.37	1118	CF	Large sedge fen
B	Camerons Ck	Murrumbidgee R	Ex AANP	13.47	1168	CF	Large sedge fen
C	Couragago Swamp	Murrumbidgee R	Ex AANP	42.97	740	CF	Northernmost sedge fen
C	Gurrangorambla Ck 1	Murrumbidgee R	KNPN	17.29	1247	CF	Montane *Epacris* bog
A	Ingeegoodbee Snowgum Flat	Snowy R	KNPS	6.59	1058	CF	Large damaged fen-bog complex, southernmost mire in KNP
C	Lake Eucumbene Swamp Ck	Snowy R	KNPM	1.85	1171	CF	Damaged former montane bog and fen
B	Long Plain	Murrumbidgee R	KNPN	84.94	1364	CF	Isolated riparian fens and former bogs
A	Micalong Swamp	Murrumbidgee R	Ex AANP	17.10	965	CF	Best developed sedge fen in Flora Reserve
B	Modder Ck	Murray R	Ex AANP	22.83	1157	CF MSSB	Fen-bog complex
B	Mosquito Ck	Murrumbidgee R	KNPN	160.07	1230	CF	Largest sedge fen in region
C	Mowamba R Grosses Plain	Snowy R	Ex AANP	58.22	1209	CF	Large fen on south-east area of mountains
B	Pugilistic Ck	Murray R	KNPM	6.09	1594	CF	Higher altitude fen
A	Sally Tree	Murrumbidgee R	KNPN	33.62	1239	CF, MSSB	Large fen and montane bog in good condition
C	Swampy Plain	Murray R	KNPM	9.87	1316	CF,	Swampy stream flats
C	Tarcutta Swamp	Murrumbidgee R	Ex AANP	70.66	782	CF	Westernmost large sedge fen, study site. Degraded
C	Tumorrama Swamp 1	Murrumbidgee R	Ex AANP	55.08	694	CF	Northern degraded sedge fen
A	Twynam NE Pounds Ck	Snowy R	KNPM	6.42	1950	CF	Alpine fen, study site
A	Yaouk 1	Murrumbidgee R	Ex AANP	121.61	1104	CF	Study site, recovering mire

Code: A, high conservation value; B, high scientific value, threatened; C, significant mire in damaged condition

Tenure: Ex ANNP, lies outside a conservation area; BNP, Brindabella National Park; SRNR, Scabby Range Nature Reserve. KNPN, KNPM, KNMS: =Kosciuszko National Park north, middle or southern sections

Vegetation: Dominant vegetation is alpine (A), subalpine (S) or montane (M) *Sphagnum* shrub bog (SSB), *Empodisma* moor (EM) or *Carex* fen (CF)

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