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Sphagnum in peatlands of Australasia: Their distribution, utilisation and management

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Abstract

In comparison to the northern hemisphere, *Sphagnum* peatlands are an unusual and infrequent component of the Australasian landscape. Most peatlands in Australasia are primarily composed of either Restionaceous or Cyperaceous peats. *Sphagnum* peatlands in Australia and Papua New Guinea/Irian Jaya (now West Papua) are largely located in montane and alpine environments, but also occur down to sea level in New Zealand and as moss patches on some subantarctic islands. Fire is a major determinant of the characteristics of peatlands in Australasia. Peatland management in Australasia is hindered by the need for increased understanding of peatland processes to enable a sustainable balance of conservation of a small resource with localised utilisation. The management focus in Australasia has largely been on ensuring ecologically sustainable *Sphagnum* moss harvesting, with limited peat mining. We have found that general recovery of *Sphagnum* after moss harvesting can be enhanced by harvesting larger peatlands, and by leaving one-third of the acrotelm to regenerate. The largest upland peat swamp in mainland Australia, Wingecarribee Swamp, suffered a major collapse in 1998 following peat mining. Environmental and management consequences of this collapse have major ramifications for rehabilitation options. *Sphagnum* peatlands in Australasia are likely to be adversely affected by drainage, burning, grazing, trampling, global warming and peat mining.

Introduction

In comparison with peatlands in the northern hemisphere, Australasian peatlands dominated by *Sphagnum* are generally small in area, restricted in distribution, and have relatively few species. Most Australasian peatlands are instead dominated by Restionaceae, Cyperaceae, and Epacridaceae species, but *Sphagnum* is frequently an important component. There has been no comprehensive assessment of peatlands in Australia or New Zealand, but a general description of Australasian mires is provided in Campbell (1983). *Sphagnum* moss can also occur as a small but distinct component of other plant communities, such as in tropical mountains of New Guinea. *S. cristatum* is the most common species in both Australia and New Zealand, and is the main species harvested.

The most common resource from Australasian *Sphagnum* peatlands is *Sphagnum* moss harvested for the horticulture industry. At present all commercial *Sphagnum* moss harvesting is restricted to Australia and New Zealand and is from wild populations in natural peatlands. Small experimental trials of growing *S. cristatum* in tunnelhouse environments were initiated in New Zealand (Smale et al., 1995), but cancelled due to withdrawal of research funding.

Historically, many areas of *Sphagnum* peatland have been drained and fertilised for farmland or destroyed by peat mining, particularly in New Zealand, although a few extensive deposits up to several thousands of hectares still remain (Davoren, 1978). Current threats to the long-term survival of *Sphagnum* peatlands include draining for agriculture, frequent burning, peat mining and *Sphagnum* moss harvesting. A major threat to peatlands in Western Australia is groundwater abstraction (P. Horwitz, personal communication). In general, *Sphagnum* peatlands in Australasia have not been subjected to the same extent of broadscale mining operations reported in the northern hemisphere (e.g. Lappalainen, 1996; Rochefort, 2001).

Peatland management in Australasia is not unified but is mainly driven by the need to protect/reserve representative examples of the full range of natural biodiversity. For example, less than 10% of the original area of wetlands now remains throughout New Zealand (Newsome, 1987), making conservation of all remaining wetlands significant. In New Zealand, peatlands have an additional conservation value in that they have revealed, and still contain, many significant cultural artefacts from early Maori settlement. In both Australia and New Zealand, peatlands in lowland areas are particularly threatened, with most having been drained for farmland or subjected to frequent burning. These lowland peatlands are targeted for protection and restoration in New Zealand.

The aim of this paper is to present a brief overview of the currently known Australasian peatlands containing *Sphagnum*, specifically Australia, New Zealand, New Guinea, and some subantarctic islands. Descriptions of the current *Sphagnum* moss harvesting and peat mining industries are presented. Methods to manage harvesting impacts and issues encountered in peatland restoration are outlined. The major environmental problems and management issues that can be encountered as a result of peat collapse following mining are given in a case study of Wingecarribee swamp.

Sphagnum species distribution

In Tasmania 10 species of *Sphagnum* have been recorded in the literature (Dalton et al., 1991) but in a taxonomic revision (Seppelt, 2000) only 6 taxa (including one new species; Seppelt and Crum, 1999) are recognised (Table 1). Another species, formerly known as *Sphagnum leucobryoides*, has been transferred to a new monotypic Order, Family and Genus as *Ambuchanania* (Crum and Seppelt, 1999). Away from the eastern states on mainland Australia, only *Sphagnum novo-zelandicum* is represented in South Australia (Crocker and Eardly, 1939) and in a few localities in southwestern Western Australia (Smith, 1969; Figure 1). Under the provisions of the New South Wales Threatened Species Conservation Act one particular *Sphagnum* community (Ben Halls Gap National Park *Sphagnum* Moss Cool Temperate Rainforest) has been designated an Endangered Ecological Community. There are two communities with *Sphagnum* listed in Victoria under the Victorian Flora and Fauna Guarantee Act – Alpine Bog and Montane Swamp Complex.

Nine species of *Sphagnum* are recognised from New Zealand (Fife, 1996), five of which are common to Australia (Table 1). The diversity of *Sphagnum* species in the Chatham Islands and the Australasian subantarctic Islands (Auckland Islands, Campbell Island, Macquarie Island) is low. Only *S. falcatulum* is known from Macquarie Island, *S. australe* and *S. novo-zelandicum* from Campbell Island, *S. australe* and *S. falcatulum* from the Auckland Islands (Vitt, 1979), and *S. australe*, *S. cristatum* and *S. falcatulum* from the Chatham Islands (Table 1). In Australasia, only *S. falcatulum* and *S. fuscovinosum* appear to be specifically aquatic. There is less evidence of extensive patterned mires (Campbell, 1983; Kirkpatrick and Gibson, 1984; Whinam and Kirkpatrick, 1994; Mark et al., 1995) and of the hummock/hollow partitioning of *Sphagnum* species in Australasia (Millington, 1954; Ashton and Hargreaves, 1983) than reported in the northern hemisphere.

In the Malesian tropics approximately thirteen species have been described (Eddy, 1977, 1988; Table 1), and most are probably more widely distributed than currently documented as very few ecological surveys have been made. New Guinea is a tropical centre of diversity for *Sphagnum*, having twelve of these species, with only *S. luzonense* not occurring there. Endemic or near endemic species recorded from New Guinea include *S. antarense*, found at 2200 m in the Star Mountains and on mountains in Sulawesi, *S. efibrillosum*, from the Mt Albert Edward summit plateau at 3650 m and *S. novo-guineense* which occurs in central New Guinea and on adjacent islands. *S. sericeum* and *S. junghuhnianum* var *semiporosum* are known from stream edges and waterfall spray zones in grassland and montane forest near Lake Habbema in the Snow Mountains as well as Mt Dayman and Goodenough Island in eastern Papua. They occur in open mist forests at mid-altitudes along seepages

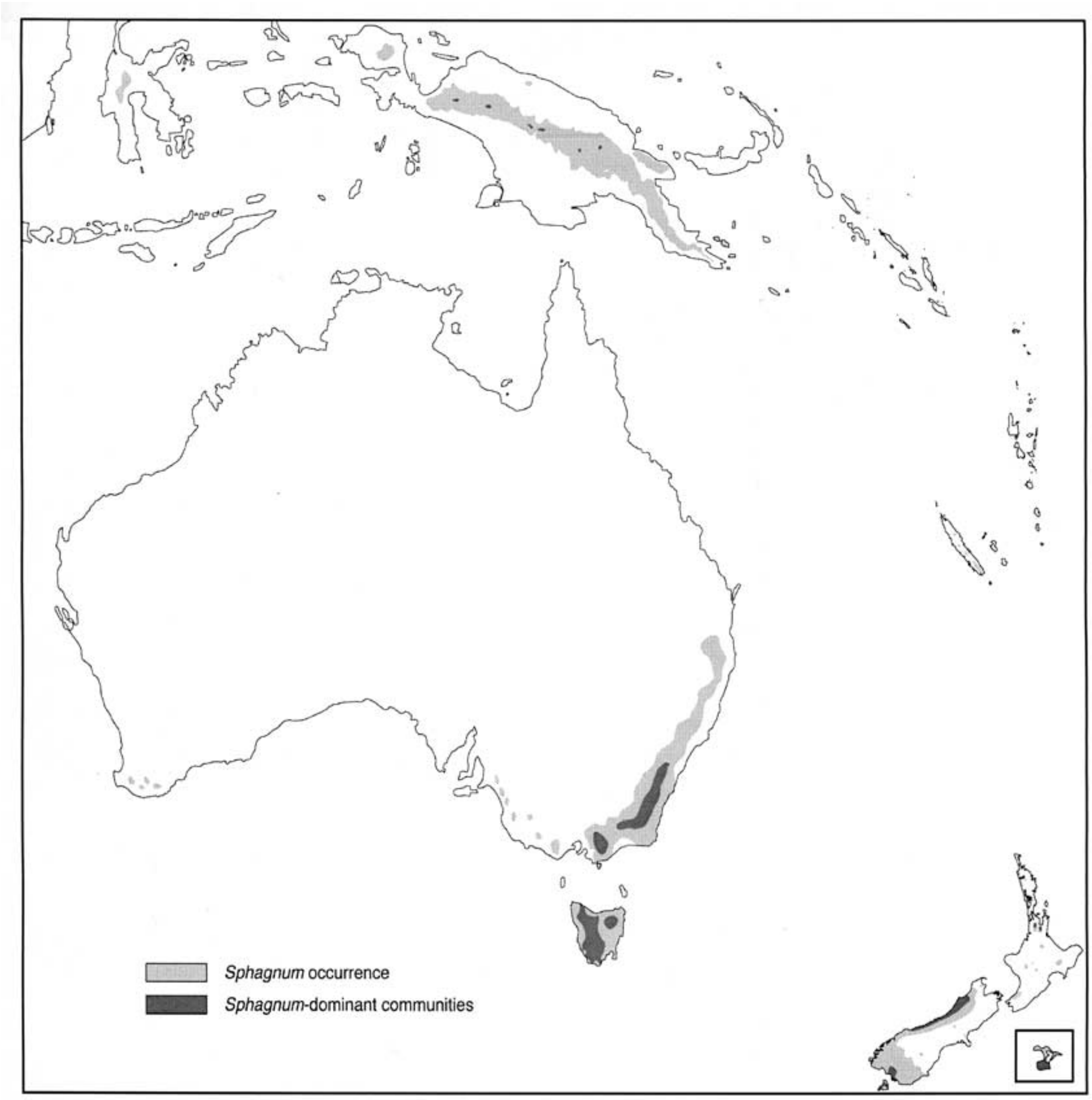

Figure 1. Sphagnum occurence and *Sphagnum*-dominated communities in Australasia. Chatham Island is enlarged as an inset.

(Bartram, 1942, 1957). Other Malesian or southern species in New Guinea are *S. perichaetiale* and *S. cuspidatum*, both occuring in the montane and subalpine zones above 2000 m, as well as the curious lax *S. cuspidatum* ssp. *subrecurvum,* which is found at low altitudes in Borneo, Malaya and Sumatra as well as New Guinea. *Sphagnum* species of mostly boreal distribution occur in the mountains of New Guinea – *S. subsecundum*, *S. cuspidatulum* and *S. compactum*. *S. compactum* is related to a species with an African – Malesian distribution, *S. strictum* ssp. *pappeanum* (Eddy, 1988).

In the Pacific, six *Sphagnum* species are restricted to the higher mountains (above 500 m). On New Caledonia *S. cristatum* also occurs in the austral temperate region and *S. cuspidatum* is also found in the Malesian tropics and boreal regions. *S. novo-caledoniae* is endemic to the high rainfall ultramafic area. Three endemic species occur further east; *S. palustre* on Viti Levu (Fiji) and Oahu (Hawaii), *S. seemannii* on Tavieuni (Fiji) and Samoa and *S. reichardtii* on Viti Levu.

Table 1. Distribution of *Sphagnum* species in Australasia. Australia (Aus, Mainland Australia; Tas, Tasmania), New Zealand (NZ, New Zealand; Chat, the Chatham Islands), Subantarctic Pacific islands (AI, Auckland; An, Antipodes; C, Campbell; M, Macquarie), Pacific (NG, New Guinea; VFJ, Viti Levu, Fiji; TaFJ, Tavieuni, Fiji; NCal, New Caledonia; HAW, Hawaii; Sam, Samoa), and Malesia (Sul, Sulawesi, Indonesia; BM, Borneo, Malaya; M, Malesia; WM, Western Malesia). Based on Streimann and Curnow (1989), Fife (1996), Seppelt (2000) and A. Touw (unpublished data).

Species	Australia	New Zealand	Subantarctic islands	Pacific	Malesia (other than New Guinea)
S. australe	Aus, Tas	NZ, Chat	AI, An, C		
S. antarense				NG	Sul
S. compactum		NZ		NG	M
S. cristatum	Aus, Tas	NZ, Chat		NCal	
S. cuspidatulum				NG	M
S. cuspidatum				NG, NCal	M
S. cuspidatum ssp. *subrecurvum*				NG.	BM
S. efibrillosum				NG	
S. falcatulum	Aus, Tas	NZ, Chat	AI, An, M		
S. fuscovinosum	Tas				
S. junghuhnianum var *semiporosum*				NG	
S. luzonense					WM
S. novo-caledoniae				NCal	
S. novo-guineense				NG	
S. novo-zelandicum	Aus, Tas	NZ	C		
S. palustre				VFJ, HAW	
S. perichaetiale (incl. *S. beccarii*)	Aus	NZ		NG	M
S. reichardtii				VFJ	
S. seemannii				TFJ, Sam	
S. sericeum				NG	M
S. simplex		NZ			
S. strictum ssp. *pappeanum*				NG	M
S. squarrosum		NZ			
S. subnitens		NZ			
S. subsecundum				NG	M

Distribution of *Sphagnum* peatlands

Australasia – generalities

Sphagnum peatlands, for the purposes of this paper, are defined as having *Sphagnum* species as the dominant peat forming vegetation and where the peatland area is greater than 1000 m^2 to form a distinct ecosystem. They occur in Australia most frequently between 600 to 1000 m altitude. In New Zealand they mostly occur from 1500 m down to sea level, with the proportion of *Sphagnum* in the vegetation generally increasing from north to south and with increasing altitude. They tend to be mostly minerotrophic in Australia and ombrotrophic in New Zealand. In New Zealand, *S. australe* commonly forms small bogs and moss beds under beech (*Nothofagus menziesii* and *N. solandri* var *cliffortioides*) forest canopies, yielding dominance to *S. cristatum* as light levels increase. *S. cristatum* covers extensive areas in wet heath and bog communities and may be regionally important as in eastern Fiordland (Burrows and Dobson, 1972; Mark et al., 1979) and south Westland (Dickinson and Mark, 1994). In New Guinea, *Sphagnum* occurs in wet hollows in montane forest, and along stream banks and lake edges above 3000 m, in minerotrophic and some ombrotrophic situations. Although a common element, *Sphagnum* is rarely dominant anywhere in Malesia, New Guinea or the Pacific (Hope, 1980).

The major geomorphic types of *Sphagnum* peatlands in Australasia include: kettle holes and moraine-dammed valleys of the depositional zone; glaciofluvial outwash or colluvial valley fill deposits; riparian or lacustrine environments; horizontally-bedded sandstone shelves; karst sinkholes (Whinam and Buxton, 1997).

The major floristic types include: snowpatch, subalpine coniferous; sedgelands; shrublands (including New Zealand pakihi wet heath; Mew, 1983); rainforest; grassy tussock and aquatic. Descriptions of *Sphagnum* communities in New Zealand are included in Wardle (1991) and for Tasmania in Whinam et al. (1989, 2001). On mainland Australia *Sphagnum* is most common as a component of shrub bogs dominated by epacrids and restionaceous species (Costin, 1954; Millington, 1954; Ashton and Hargreaves, 1983; Hope and Southern, 1983; Kershaw et al., 1997; Clarke and Martin, 1999). It occurs mainly on humic peats and deep accumulations of *Sphagnum* peat are unknown, suggesting that it is always a subsidiary taxon in Holocene mire communities.

Australia

Australia is predominantly arid or semiarid. Most of the continent is of low relief. Although there are very extensive wetlands in inland Australia, these are intermittent and the prolonged dry periods are not conducive to peat formation. The majority of permanent wetlands occur in the coastal zone, the Eastern Highlands and Tasmania (Australian Nature Conservation Agency, 1996). One of the major factors limiting the development of *Sphagnum* peatlands in Australia is moisture availability, in particular evapotranspiration in the driest month. While rainfall may be less important in peatlands that receive significant catchment runoff, the generally small size of the peatlands affects their sensitivity to hydrologic changes. In Tasmanian *Sphagnum* peatlands, the mean annual temperature ranges between 5.7 and 8.6 °C, the mean maximum temperature of the warmest month ranges from 16.2 to 19.5 °C. Mean annual precipitation varies at these Tasmanian sites between 1540 and 2020 mm and that of the driest month ranges between 70 and 100 mm. Despite topographic and climatic suitability, large *Sphagnum* peatlands do not occur on the siliceous substrate in south-western Tasmania. The Cyperaceous peatlands that dominate south-western Tasmania have lower values for total N, total P and percentage organic matter than those recorded for *Sphagnum* peatlands in Tasmania and the northern hemisphere (Whinam, 1990), suggesting that the combination of poor nutrient status and fire history have prevented the widespread growth of *Sphagnum* (Whinam et al., 1989). Similarly it is not prominent in the sandstone habitats of the Blue Mountains of New South Wales. This is in contrast with Northern Hemisphere and New Zealand data, which suggest that *Sphagnum* occupies nutrient-poor habitats (Clymo and Hayward, 1982), but reflects the lower nutrient status and fire history of south-western Tasmania (Bowman et al., 1986), which favours moorlands dominated by buttongrass (*Gymnoschoenus sphaerocephalus*). The total area of *Sphagnum* peatlands in Tasmania, estimated by using colour aerial photographs and vegetation mapping data for parts of the Tasmanian World Heritage Area (Parks and Wildlife Service, unpublished data) and ground confirmation, is approximately 1300 ha (J. Whinam, unpublished data).

In Victoria, peatlands are most extensive and hummocks better developed at altitudes above 900 m. At this altitude, the mean annual temperature ranges from 6.5 to 10.4 °C, the mean maximum temperature of the warmest month ranges from 19.0 to 23.1 °C and the mean annual precipitation ranges from 1570 to 1600 mm, with the mean annual precipitation of the driest month being around 75 mm (McKenzie, 1997).

Even in the high rainfall, well-vegetated regions, dry periods occur and bushfires are frequent. Fire can have serious impacts on peatlands (Kershaw and Bohte, 1997; Horwitz et al., 1998), causing substantial losses of substrate, although in many cases fire may burn surface vegetation without igniting the underlying peat (e.g. Clarkson, 1997). At a local scale *Sphagnum* may decline, even to local extinction, during drought periods. For example at a small hanging swamp on top of a seacliff in Sydney (Bridgman et al., 1995), small amounts of *Sphagnum* persisted until the late 1970s but disappeared during a drought in 1980–1981.

Extensively distributed, but normally shallow, peat deposits are occasionally found in the coastal lowlands, often in dune swales, both on the east coast and in the south-west of Western Australia (Horwitz et al., 1998). The vegetation on these sedgeland deposits is dominated mainly by Restionaceae species where rainfall exceeds 1000 mm yr^{-1} and Cyperaceae species elsewhere or wet heath, but forested wetlands (dominated by *Melaleuca* spp., *Eucalyptus* spp. and *Casuarina* spp.) also occur. Peat deposits are scattered across the sandstone plateaux around Sydney, New South Wales, along creek lines and in shallow depressions (e.g., Kodela and Dodson, 1989).

Peat swamps are found in the uplands and highlands of eastern Australia, for example in Victoria (Kershaw et al., 1997), the New South Wales

(N.S.W.)/Australian Capital Territory (A.C.T.) Alps (Hope and Southern, 1983), Barrington Tops (Dodson et al., 1986) and the New England region (Millington, 1954). *Sphagnum* may be a major component of the vegetation of some of these upland swamps. In some Australian states good data exist – for example, moorlands (Jarman et al., 1988) and *Sphagnum* peatlands (Whinam et al., 1989) in Tasmania and peatlands in Victoria (Kershaw et al., 1997). For other states coverage is still incomplete. Hancock (1998) provides an estimate of the peat resources in Australia, but his figures are misleading, as they over-estimate the resource considerably, by including extensive floodplain *Phragmites* swamps as peatlands.

New Zealand

The surface area for all peatlands in New Zealand (including farmland, forestry, etc.) is at least 2100 km^2 (derived from Newsome 1991). Much of the 270,000 ha of swamp (including bogs) and 97,000 ha of pakihi vegetation is peatlands (Hunter and Blaschke, 1986). Annual rainfall at *Sphagnum* sites in New Zealand, ranges from 1100 to >10,000 mm, with that of the driest month ranging between 60 and 190 mm. Mean annual temperature at these sites ranges from 3.5 to 13.4 °C, and mean maximum temperature ranges between 11.5 and 28.3 °C (Mark et al., 1995).

On the gley podzols of Westland, New Zealand, *Sphagnum* peatland communities have been favoured by activities associated with logging (e.g. tramways). Here, *Sphagnum* occupies a transitional phase to closed shrubland and forest that would ultimately reduce its abundance. Although forest clearance has led to *Sphagnum* abundance in the first instance, it is the disturbance associated with continued harvesting of *Sphagnum* moss (e.g. rise in water table caused by impeded drainage) that appears to be maintaining *Sphagnum* dominance. These cut-over forests are now some of the major sites of commercial *Sphagnum* harvesting on the South Island. On the North Island several *Sphagnum* bogs have similarly been induced or increased by forest logging, particularly in upland areas with high rainfall, e.g., Mamaku Ranges west of Rotorua. *Sphagnum* is also common along track margins and other disturbed areas (Mew, 1983).

Pacific

In the Pacific *Sphagnum* occurs in mountain areas on the windward slopes in shrub-rich peatlands, as these locations experience high orographic rainfall (Mueller-Dombois and Fosberg, 1998).

New Guinea and Malesia

In New Guinea and Malesia there are montane swamp forests which often have *Sphagnum* species around tree bases. Mires are common along the outer flanks of the main mountain cordillera that extends along the island, and also on outlying ranges and mountainous islands. Above 2700 m mosaics of subalpine grassland and sedge mires are common, and above 3400 m on most mountains' soils are peaty and mire taxa invade the grasslands to form cushion bogs. New Guinea is humid, with precipitation throughout the year in the mountains and rainfall totals from 2500 to >10,000 mm. Temperatures range from 20 °C at 1400 m to about 6 °C at the tree-line at 3900 m, and a snowline at 4620 m. Terrestrial mosses are particularly common in the mist zone forests and bogs between 2000–3500 m (Hope, 1996). Conditions are not as moist in south-east Asia but mountain plateaux and streamlines support sedge swamps. Large ombrotrophic peat swamp forests occur in the lowlands of Sumatera and Borneo (Reiley and Page, 1997).

In montane New Guinea, *Sphagnum* occurs in openings in forests that are beset by low-lying cloud for most days. The forest is often microphyll or nanophyll, with an open canopy formed by *Nothofagus, Elaeocarpus, Pittosporum, Rapanea* and *Syzygium* species. The ground is a tangle of scrambling orchids, with the trees draped in mosses and hepatics. *Sphagnum* grows in forest openings around wet hollows and is encouraged by forest clearing. At higher altitudes *Sphagnum* occurs around ponds and along stream banks in tree fern dominated riparian communities. Conifers such as *Phyllocladus hypophyllus* and *Dacrycarpus compactus* are common as remnant low forest. *Sphagnum* is rarely dominant but may form mats with hepatics around wet fens or tarns and occurs with cushions of *Astelia, Carpha, Oeobolus, Centrolepis, Rhododendron, Potentilla, Plantago, Eriocaulon* and other cushion mosses (Hope, 1980; Gibson and Hope, 1986). The western half of the island has less seasonality and less fertile substrates and seems richer in *Sphagnum* than the volcanic soils of most of the Papua New Guinea highlands. On the Tertiary sandstones and peats on the plateau around Lake Habbema (3240 m) in West Papua, *Sphagnum* seems to colonise wet areas caused by trampling, so is common along tracks through the blanket peats formed below cushion and grass bogs (Hope, 1980).

Subantarctic islands

On subantarctic Macquarie Island *Sphagnum* occurs in water-saturated conditions down to sea level, most commonly on old coastal terraces where drainage is impeded, or in old elephant seal (*Mirounga leonina*) wallows which have added nutrients and where the nutrient-favoured *Callitriche antarctica* occurs. On Macquarie Island plateau, *Sphagnum* often occurs in wet areas where skuas (*Catharacta lonnbergi*) add nutrients through washing themselves and their prey. However, *Sphagnum* does not form large peatlands on Macquarie Island, with a total area of less than 5 ha of *Sphagnum falcatulum*, although warmer temperatures over the past few years (Kininmonth, 1992), have coincided with an increase in *Sphagnum* moss (J. Whinam, unpublished data). *Sphagnum* is abundant on subantarctic Campbell Island on wet, deep, acid peats (Meurk et al., 1994), but mostly occurs either under or among other vegetation, or patchily along driplines, bases of erosional scars and footpaths or other disturbed areas.

The *Sphagnum* moss harvesting industry

The harvesting of *Sphagnum* moss is a major industry in both New Zealand and Australia. *Sphagnum* moss is harvested primarily for use in the horticultural industry, where species that have 'fat' moss strands able to hold a considerable amount of water are favoured (e.g. *S. cristatum* is favoured over *S. subnitens*). Harvesting is commonly done by hand, with the covering vegetation, usually rushes, cleared with a scrub cutter and rake. At some sites drains have been constructed around the edge of the peatland to allow easier extraction, but this practice appears to have long-term detrimental effects on recovery (Vasander, 1987). Harvested *Sphagnum* moss is put into nylon bales that weigh 100 to 120 kg when wet, therefore bale extraction has a high impact on the harvesting site. Extraction is carried out by various means – dragging bales by hand, using tramways, four-wheeled motorcycles, bulldozers, or, as has become more common in New Zealand, by helicopter.

Over the last three decades, the *Sphagnum* moss harvesting industry has expanded dramatically with exports leveling off in the early 1990s at about 1000 tonnes of dry moss in New Zealand and roughly 15 tonnes in Tasmania. A small amount of *Sphagnum* moss is harvested in Victoria. *Sphagnum* harvesting at Ginini Bog, in the Australian Capital Territory ceased in 1944, but has left damaged areas that are still apparent. In Australia, virtually all alpine and subalpine habitat is reserved in National Parks. Consequently there has been considerable pressure on unreserved peatlands. In New Zealand it is estimated that 20 to 30% of *Sphagnum* moss-producing land is in private ownership, the remainder being administered by two government agencies, Timberlands West Coast Ltd and the Department of Conservation, with a small portion reserved (c. 1800 ha in Westland National Park; Department of Lands and Survey, 1982; and 500 ha in formal Scenic Reserves; Wardle, 1980). Large parts of subalpine New Guinea are still remote and not accessible to harvesters, and a large subalpine reserve has been declared in West Papua. Traditional use is not affected by reserves but is not a threat in any area.

Sphagnum moss harvesting and management

Sphagnum regeneration on the bare peat surface left after complete moss harvesting in Australia and New Zealand is slow, or sometimes absent, leading to dominance by other species, notably Restionaceous and Cyperaceous graminoids.

Manipulation of the water table has been suggested, based on experimental trials in New Zealand, as a technique to promote moss, particularly *Sphagnum*, growth, and create conditions favouring the commercially more desirable *S. cristatum* (Stokes et al., 1999). Although one property owner exercises some control over water levels, no generally applicable protocols have been developed.

The rate of growth of *Sphagnum* will be an important determinant of ability to recover from disturbance. Several studies have been conducted on *Sphagnum* growth rates in Australasia. In general, growth rates decline with increasing altitude and latitude. Occasional moisture deficits limit growth. *Sphagnum* growth in montane situations in New Zealand and Australia is slow, ranging from 0.9 to 7.3 cm yr^{-1} (Whinam and Buxton, 1997).

Variation in height growth at lowland sites in New Zealand can be matched to temperature. Crank wires installed at permanent transects indicated that *S. cristatum* at Westport had a growth rate of 6.1 cm yr^{-1} (mean temperature 12.2 °C), Hokitika 5.4 cm yr^{-1}

(mean temperature 11.6 °C) and Kakapotahi 3.4 cm yr^{-1} (mean temperature 11.1 °C). These sites are all below 40 m above sea level with mean annual rainfall between 2200 and 3800 mm yr^{-1}.

Low winter temperatures limit *Sphagnum* growth in both lowland and montane situations, but in response to increased summer temperatures lowland sites appear capable of greater growth than montane sites (1.3 cm yr^{-1}). Buxton et al. (1995) found *Sphagnum* height growth is also enhanced by the presence of 20 to 60% rushes (*Juncus* and *Baumea*) and sedges (*Gahnia*).

The growth of *Sphagnum* was studied by Clark (1980) at Ginini Flats, a 75 ha subalpine bog at 1590 m in the Brindabella Mountains of the A.C.T. Up to 1.8 cm increase in height occurred in a growing season, but this was usually compressed by winter snow, so that the net annual growth varied from 9 to –2 mm, depending on the snow loading. Clark calculated the *Sphagnum* productivity at 1.7 tonne ha^{-1} dry weight, but thought that this might be an underestimate. By comparison, annual productivity in Westland, New Zealand, was estimated by Denne (1983) at 7.27 tonnes ha^{-1} dry weight.

The Delegate River floodplain at 900 m altitude near Bendoc, Victoria has an extensive epacridaceous *Sphagnum* bog overtopped by *Leptospermum* shrubland (Ladd, 1979). Gell et al. (1993) carried out high resolution analyses on short cores covering the historical period. They found that *Sphagnum* was suppressed and grass increased when the plain was burnt and used for cattle grazing. Reduction in fire frequency and clear felling of a high proportion of the eucalypt forest in the catchment has led to increased water supply and a recovery by *Sphagnum* and *Myriophyllum* over the last 50 years. *Sphagnum* may also be responding to increased nutrient provided by the inwash of sediment.

At sites in Tasmania and New Zealand, experimental harvesting has shown that reseeding (leaving 30% moss cover behind) resulted in faster recovery of the *Sphagnum* moss in terms of percentage cover than leaving a bare peat surface. In New Zealand, regrowth in reseeded 1 m^2 plots, either moderately or heavily harvested plots, resulted in approximately 90% cover of *Sphagnum* 36 months after harvesting compared with 50% in unseeded plots (R.P. Buxton unpublished data). Pressing of *Sphagnum* fragments into the water table to ensure good contact did not appear to substantially increase recovery rates (P.A. Alspach, unpublished data).

Reseeding and sensitive harvesting operations have enabled harvesting cycles as short as 2 to 3 years, with repeat harvesting of >15 cm *Sphagnum* fibers at some lowland sites in New Zealand, whereas in Tasmania, reseeding combined with hand-broadcasting of small amounts of slow release, recycled sewage pellets as fertiliser, has resulted in high-quality *Sphagnum* moss being harvested on a longer 10 year rotation (P. Binney, personal communication).

Like all plant growth, the rate of *Sphagnum* recovery after harvesting (when more or less 30% of the original acrotelm is not disturbed) is strongly influenced by climatic variables, with warmer, wetter sites recovering quicker than colder and drier sites.

On the basis of data collected to date (Whinam and Buxton 1997), *Sphagnum* moss harvesting is only likely to be sustainable in Australasia where the site

- is less than 600 m altitude;
- has 20% shade protection provided by other species;
- is large enough to allow harvesting rotation;
- is harvested while avoiding the use of heavy machinery;
- is left with an even surface with some meso-roughness to provide support for *Sphagnum* but keeping the moss close to the water table;
- an adequate period is provided between harvests, determined by growth rates and environmental conditions, to allow the moss to recover.
- has 30% moss *Sphagnum* cover left for reseeding.

Our observations in New Zealand and Tasmania suggest that the most damaging moss harvesting is done by poachers and harvesters operating on a once-off basis. Seeking short-term financial gain, they often over-pick a site leaving little for natural revegetation and take little care when extracting the moss. Poachers have become an increasing problem in both Tasmania and New Zealand (Yarwood, 1990). However, a system in New Zealand, which requires harvesters to be registered to avoid paying more tax at point of sale has deterred many poachers.

In places like Tasmania and Victoria, where observations suggest that *Sphagnum* moss can die due to desiccation in dry summers, *Sphagnum* peatlands may be near their climatic limits, in which case drier, warmer conditions associated with global warming are likely to be detrimental to their long-term survival. Moss harvesting activities add further pressures to this limited resource.

Conservation and management – peat mining

Most peat losses in Australia and New Zealand have been caused by agriculture, both through intentional drainage and through accidental fires and erosion. The valley mires (mostly *Carex* fen and grass bog) have gullied in many places with peat collapse, e.g. Jackson's Bog, New South Wales (Southern, 1982). Exposure of peat to drying (through peat mining, draining, etc.) has the potential to oxidise soils rich in iron (or other) sulphides, to produce sulphates which are hydrated to sulphuric acid, thereby posing a significant threat to the biota through reduced pH, with acidification an emerging issue in Western Australia (Sommer and Horwitz).

The scale of peat mining in Australasia is very small when compared to northern hemisphere operations. For example, a total of 5800 m^3 of peat is extracted from Tasmania annually. In South Australia, less than 6700 m^3 of peat yr^{-1} is mined from a deposit on the Woakwine Range near Lake Bonney. In Queensland, about 5–10,000 m^3 yr^{-1} is extracted from a 10 year old mining site on the Atherton Tableland. Currently, there is no mining in N.S.W., Victoria, or the A.C.T. Mining occurs in diatomous and restionaceous peats in W.A. (Meney and Pate, 1999; G. Hope, unpublished data). In New Zealand, a total of approximately 140,000 m^3 yr^{-1} of peat is extracted.

Sphagnum peat is preferred over restiad peat for horticultural purposes because it has better water holding ability, larger particles and is more freely draining. There is one small restiad mine in the Waikato region, harvesting about 3000 m^3 annually. However, the peat types can be mixed to conserve the resource. Australia is a net importer of peat, with supplies coming primarily from Canada, New Zealand, Germany and Ireland (in descending order of amount supplied). Approximately 67% of peat in Australia is used for mushroom cultivation, with a further 5% used for the production of grass turf (R. Wilkinson, personal communication).

The major impediments to expedite regeneration of peatland sites in Australasia are a lack of knowledge of restoration techniques appropriate to the environmental conditions and the absence of regeneration requirements in peat mining leases. However, data from *Sphagnum* moss harvesting regeneration combined with an understanding of bog succession can be used to provide some guidance for management and recolonisation of peat mining sites.

Before assessing the management and restoration options of peatlands subjected to mining, it is necessary to look at the context of the restoration goals. It is also necessary to evaluate the success of the restoration. One way to do this is to compare functional processes in the restored site with an adjacent unmodified peat bog ecosystem and to monitor whether peat accumulates. The re-establishment of *Sphagnum* communities is often the ultimate aim in restoration and is used as an indicator of peatland health. For example in the Snowy Mountain highlands of New South Wales, cattle grazing resulted in the destruction of *Sphagnum* peatlands in an important water catchment. Twenty years after the cessation of grazing, and many thousands of dollars later, the prevention of erosion and revegetation measures had led to the re-establishment of *Sphagnum* in these peatlands, which is interpreted as a sign of ecosystem recovery (Wimbush and Costin, 1979). Similarly, the combination of trampling by feral animals, and frequent fires has led to degradation of *Sphagnum* bogs and incision of water courses in the A.C.T. Removal of stock has allowed *Sphagnum* hummocks to regenerate and invade streamlines to re-establish wet conditions.

Of the six active *Sphagnum* peat mines in New Zealand (three in North Island, two in South Island) and Tasmania, only two – Gamman Mining and Yates-Watkins (New Zealand) are required to restore the peatland back to bog. This is because the other New Zealand mines were previously in pasture, not intact bogs, and there has not been a legislative requirement to restore the Tasmanian peatlands.

All three North Island mines work the Torehape peat bog in the Hauraki Plains. This 6000 year old bog originally covered more than 10,000 ha but now only about 700 ha of bog vegetation remains, mostly protected in reserve. Torehape has large deposits of *Sphagnum* peat, which is unusual because the main peat-forming species elsewhere in the Waikato/Hauraki Plains district are the restiads *Empodisma minus* and *Sporadanthus ferrugineus*. The current dominants in the nearby reserve, however, are *Empodisma* and *Sporadanthus* and there is also a surface layer 10 to 15 cm thick of restiad peat over the *Sphagnum* (Clarkson, 1994). It is thought that ring drainage in the early 1920s diverted water from surrounding hills out to sea, thus lowering water tables within the bog and causing a shift from *Sphagnum cristatum* to restiad species, which are better adapted to 'drier' conditions (Bates, 1973). The Torehape mining companies have a license to mine only the upper 1 m of peat (average thickness is 5 to 7 m) and then are required to restore the bared surface back to a functioning bog. Initial results of restoration trials involving combinations of fertiliser, plants, and water table have resulted in 100% vegetative cover being achieved with some treatments after two years (Schipper, in press). This first stage is based on restoring a restiad cover but stage two will involve encouraging growth of *Sphagnum*.

The high conservation values on the Chatham Islands of New Zealand (Wardle et al., 1986) have so far prevented any peat mining proposals from being successful there. There is no peat mining on the subantarctic islands.

In the central highlands of Tasmania, a large (10 ha) montane *Sphagnum* peatland is currently being mined. When the peat supply is exhausted, this will be the first attempt in Tasmania to restore a *Sphagnum* peatland after mining. At a nearby site that had *Sphagnum* moss harvested and drains constructed in preparation for mining, the drier margins have now converted to a restionaceous/cyperaceous peatland, dominated by *Empodisma minus* and *Gymnoschoenus sphaerocephalus*.

Peat mining is not carried out in a systematic way in the tropics but the forested peatlands are widely utilised for logging. The losses of peat due to illegal tree felling and clearance for agriculture, particularly in Kalimantan and Sumatra over 35 years, probably exceeds 10 million hectares, although estimates vary. Fox (2000) assesses the 1997–1998 El Niño fires in Indonesia at 9.75 million hectares, much of this in peatlands (Reiley and Page, 1997). The 1997 fires caused major damage to subalpine peatlands in Irian Jaya, many former mires being burnt and invaded by grasses and introduced composites. Considerable volumes of peat have also been removed as a result of alluvial mining for tin in Malaya, and in developing swamps for oil palm and sugar plantations in Indonesia and the Pacific.

Case study of bad peat mining management: Wingecarribee

The gently sloping Wingecarribee Swamp, a montane peatland located in the Southern Highlands of New South Wales (670 m), originally covered more than 650 ha and was the largest upland (restionaceous) peat deposit in mainland Australia. In 1974 the western half of the swamp was submerged by the Wingecarribee Reservoir, with small scale peat mining occurring in the remaining eastern swamp (307 ha). Extraction subsequently changed to a wet mining process, in which a lake was excavated within the swamp. Extracted peat was converted into a slurry on a floating pontoon and then pumped via a pipeline to a processing plant on dry land. Production increased from 3000 m^3 yr^{-1} to about 30,000 m^3 yr^{-1} by the mid 1990s. In 1997 the mining pond was 20 ha in extent and several metres deep, with a pronounced steep face of peat exposed at the upslope end, due to the general gradient of the swamp.

On the night of 8–9 August 1998 the swamp upstream from the mine pond collapsed following heavy, but not exceptional, rain. An estimated 6000 megalitres of peat and sediment and 6500 megalitres of runoff water moved into Wingecarribee Reservoir (Arachchi and Lambkin, 1999). The dredge on its pontoon was also swept into the reservoir, gouging a major channel through the swamp which immediately enlarged under the peak flows. A Mining Warden's Inquiry into a proposed renewal of the mining leases was held in 1997 during which the potential instability of the swamp was pointed out. However objections from government agencies and peatland expert witnesses were not accepted by the Warden (Bailey, 1997) and mining continued until it was halted by imposition of a Heritage Order in 1998.

Post collapse, about 70% of the swamp has sunk by 3 to 4 m and is fragmented by a network of deep fissures reaching to basal clays (illustrated in White, 2000). The former filtering capacity of the swamp has been lost which has serious implications for water quality in the reservoir. The peat in the reservoir also lowered the storage capacity (by 18%) and increased turbidity (Arachchi and Lambkin, 1999).

Changes to the swamp environment

What was once a continuous extensive swamp system has become fragmented, with large areas of exposed peat (both as vertical faces and flat plains). The long-term impacts of the collapse on the hydrology and ecological stability of these swamp margin habitats are currently unknown. Restoration of the original swamp system is not possible. About 140 ha consist of stranded blocks of fibrous peat up to 3 m in height, which are extremely vulnerable to fire. The major management priorities are to reduce the likelihood of fire and institute weed control. In the longer term attempts to disperse water and encourage swamp regeneration may be made. The swamp still provides habitat for a rich flora and fauna, including several endangered species, and stands of a range of fen communities. Conservation of these features remains a high priority, but specific action has been delayed by the lack of expertise. These bogs differ greatly from the extensive peatlands of the northern hemisphere, and current restoration knowledge is merely superficial. Patterns of recovery at Wingecarribee may provide some insight for future restoration of these Australasian communities.

Conclusions

While *Sphagnum* peatlands form a relatively small part of the Australasian landscape, they are distinct communities and can form their own ecosystem (>10 ha), be present in other peat forming ecosystems, or occur as small moss patches. There has been a significant loss of *Sphagnum* peatlands associated with draining, agriculture and fires. One of the major differences between resource use of *Sphagnum* peatlands in Australasia and the northern hemisphere is the importance of *Sphagnum* moss harvesting in Australia and New Zealand. Sustainable resource use and restoration techniques associated with *Sphagnum* moss harvesting are quite different to those associated with peat mining. With most of the subalpine and alpine *Sphagnum* peatlands in Australia and much of New Zealand's remaining peatlands in formal reserves, there are pressures from both moss harvesters and peat miners on remaining resources. Evidence to date suggests that it is easier to restore *Sphagnum* peatlands that have been subjected to drainage for moss harvesting and after peat mining to sedgeland peats dominated by Cyperaceae and Restionaceae than to *Sphagnum* moss. The limited knowledge about restoration after moss harvesting and even more limited understanding of ecosystem responses to mining indicate the need for further experimental trials. For peatlands near their climatic limits, global warming and an increased likelihood of fire pose significant threats.

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