Sphagnum moss: an indicator of climate change in the sub-Antarctic

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ABSTRACT. *Sphagnum* moss has been used globally as an indicator of climate change. Since continuous meteorological recording started in the late 1940s, there has been a marked change in the climates of Southern Ocean islands. The distribution of *Sphagnum* on Macquarie Island appeared to be expanding through the 1980s. All patches of *Sphagnum* were mapped in the 1992/93 austral summer, with 112 *Sphagnum* moss patches ($<3\,m^2$) and 12 larger ($\geq 3\,m^2$) patches recorded. The vast majority of sites recorded were lowland coastal, with a few sites around plateau lakes. The area of moss beds ranges from $0.03\,m^2$ to $32.4\,m^2$. A total of 23 sites were pegged and tagged by 1996, but only 14 of these sites still had *Sphagnum* moss present by 2004. It is considered that the climatic conditions (higher than average temperatures and wind speeds and lower than average humidity and precipitation) that occurred between April 1999 and May 2000 would have resulted in a period of desiccation that accounts for the destruction of the smaller and/or shallower *Sphagnum* beds on the island. It is highly likely that both the spatial distribution and size of *Sphagnum* moss beds on Macquarie Island will continue to decline with predicted changes in sub-Antarctic climate.

Contents

Introduction

Sphagnum is one of the most widespread of moss genera, extending in latitude from the Arctic through to sub-Antarctic Macquarie Island (Moore and Bellamy 1974; Gore 1983). It is a genus that has attracted a considerable amount of research, which in recent years has included its potential to be used as an indicator of climate change (for example, Intergovernmental Panel on Climate Change 2001; Dorrepaal and others 2004). However, the use of *Sphagnum* in this way in the Northern Hemisphere has been complicated by the impact that atmospheric acid rain has in restricting growth response (Gorham and others 1987; Lee and others 1987). While *Sphagnum* occurs from northern New South Wales on mainland Australia south to sub-Antarctic Macquarie Island, most of the *Sphagnum* deposits in Australia are found in Tasmania (Whinam and others 2001, 2003).

Climatic conditions on Macquarie Island are generally cool, cloudy, moist, and windy. Its oceanic location means there is an equable climate with relatively little variation in daily or annual temperatures (De Lisle 1965; Selkirk and others 1990). However there has been a marked change in the climates of Southern Ocean islands since continuous meteorological recording started in the late 1940s. This trend is especially clear at Marion, Kerguelen, and Macquarie islands (Bergstrom and Chown 1999). Mean daily temperatures have increased on Macquarie Island by approximately 1°C since record keeping began in 1949, a rate of 0.026°C per year (Selkirk 1992). There has also been a decline in mean annual precipitation on sub-Antarctic islands by as much as 500 mm (Begstrom and Chown 1999). Mean wind speed on Macquarie Island is $9.3\,m\,sec^{-1}$, which is greater than on Heard, Marion, or South Georgia (Selkirk 1992).

Sphagnum falcatulum is the sole *Sphagnum* species found on Macquarie Island and is the dominant species of one of three bog alliances described (Taylor 1955). *Sphagnum* was first recorded on Macquarie Island by Harold Hamilton in 1912, from 'near West Point' (Handspike Point area) (Hamilton 1912–13). *Sphagnum falcatulum* also occurs on mainland Australia, Tasmania, New Zealand, the Chatham Islands, and sub-Antarctic Auckland Island and Antipodes Island (Seppelt 2000). The general vegetation of Macquarie Island is described in Selkirk and others (1990). A vegetation map has been produced at a scale of 1:25,000, but this does not delineate *Sphagnum* mossbeds (Selkirk and Adamson 1998). Earlier work mapped the distribution of *Sphagnum* on Macquarie Island on a one square kilometre grid (Seppelt 1980). *Sphagnum falcatulum* is described as having an altitudinal range of 201–250 m on Macquarie Island (Selkirk and others 1987) and is found in boggy mire habitats (Seppelt 1980). Seppelt (1980) suggested that *Sphagnum* had probably been introduced by birds to Macquarie Island from the New Zealand region.

The authors' personal observations and those of other long-term Macquarie Island researchers were that the distribution of *Sphagnum* on Macquarie Island was extending, through the 1980s, with new patches appearing (the late D.A. Adamson, personal communication; Patricia Selkirk, personal communication; Rod Seppelt 1980, personal communication). It seems that mapping the distribution of *Sphagnum* on Macquarie Island and

monitoring changes in areal extent may provide some data that might be tested for correlation with climatic data.

Methods

All patches of *Sphagnum* were mapped in the 1992/93 austral summer by systematically searching the entire island, using the 1-km^2 map grid system established by Skira in 1974. By 1994/95, the authors' observations indicated that the moss beds were expanding and markers at the longest and widest points of 23 sites were installed to give a rough estimate of moss area. The sites were randomly distributed across the geographic range, habitats, and size classes that were observed and were possible to re-measure during the annual Australian Antarctic Division re-supply voyage of between four and six days on the island. It became clear by 1996 that more detailed measurements were necessary to determine the areal extent of each moss patch. At 19 sites, a tape measure was run out along the long axis and a second tape measure was run transversely across this tape and measurements recorded.

Five cranked wires (Clymo 1970) were installed in a number of moss beds in 1996 to measure *Sphagnum* growth. Photographs using a medium format camera were taken from several fixed points for comparison with earlier and later photographs (Copson, unpublished data). Australian Bureau of Meteorology climatic data for the period 1988 to 2004 were analysed. Annual and monthly mean data of humidity, precipitation, temperature, and wind speed, during the 16-year 1988–2003 period and eight-year periods, 1988–95 and 1996–2003, were compared.

Results

The distribution of *Sphagnum* moss on Macquarie Island (Fig. 1) shows a tendency for geographic clumping of sites. A total of 112 small *Sphagnum* moss patches (<3 m^2) and 12 larger (≥ 3 m^2) were recorded. The vast majority of sites recorded were lowland coastal, with notable exceptions around Skua, Scoble, Square, and Tulloch lakes. *Sphagnum* was most commonly found in poorly drained valley floors, abandoned elephant seal (*Mirounga leonina*) wallows on the raised beach terraces, and along shallow drainage lines with only slow-moving water-flow. No sporophytes on the *Sphagnum* moss have been recorded in more than 20 years of observations. Several very small patches of *Sphagnum* were recorded along the major walking routes on the island. *Sphagnum* was recorded from just above sea level to more than 220 m altitude.

It was not possible to ascertain meaningful growth measurements of the *Sphagnum* moss using the cranked wires for two main reasons. Firstly, *S. falcatulum* is a semi-aquatic species, where the moss becomes more filiform (Seppelt 2000) and tends to float along the water surface. Secondly, skuas (*Stercorarius skua lonnbergi*) tended to be attracted to the cranked wires and either disturbed the mossbeds around the cranks or dislodged the cranks. Out of a total of 35 cranks installed, only 17 remained by 2004. Lengths of electrical conduit cut in half lengthwise were securely installed at some sites, but the *Sphagnum* tended to grow up on the leeward side of the conduit and was often several centimetres above the general moss bed height.

It was not possible to calculate whether the trend in areal extent of *Sphagnum* moss on Macquarie Island is statistically significant as the initial aerial measurements were not as detailed as those from 1996 onwards. However, a general pattern of decline after 1992 can be identified (Table 1). Initially, there is a large decline in area at the majority of sites and then little change in area. The area of moss beds originally surveyed in 1992 varies from 0.1 m^2 to a massive 351 m^2, whereas the sites measured in detail from 1996 range from 0.1 m^2 to 32.4 m^2. A total of 23 sites were pegged and tagged by 1996 but only 14 of these sites still had *Sphagnum* moss present by 2004 and only one site was above 9.0 m^2 (Table 1). Of these sites, only 19 had *Sphagnum* moss continually present from 1996 through to 2004. Three of these sites had only individual *Sphagnum* tendrils remaining by 2002, with a fourth site with a single tendril by 2004. Three further sites had no *Sphagnum* by 2002, but one of these had a small amount of moss recolonised by 2004. One site had two moss patches join together, exaggerating the rate of expansion. Four sites had significant disturbance from skua activity. The birds seemed to be attracted by the axis markers (we trialled several types) and tended to bathe near the markers, destroying some moss patches and flooding others. An elephant seal caused major disturbance by crossing over one *Sphagnum* moss bed in 1999. Five sites appeared to become drier, with other species, such as *Luzula crinita*, *Colobanthus muscoides*, and *Marchantia* sp. invading and replacing the *Sphagnum* moss. Dead and desiccated *Sphagnum* moss was recorded at three sites.

The bright green of *S. falcatulum* stands out well in colour photographs. Comparison of photographs from fixed photo-points taken in 1992 and 1996 (Figs 2, 3) shows a similar pattern of new patches appearing (noticeably in the Green Gorge catchment), followed by some areal expansion and then contraction.

Climate data

The comparison of the meteorological data means for the eight year periods 1988–95 and 1996–2003 showed little change in the humidity, a drop in the precipitation, and rises in both temperature and wind speed (Table 2).

The means of the humidity, precipitation, temperature, and wind speed for each month between 1988 and 2003 inclusive were compared to the monthly means over the whole 16-year period. Individual months when the mean humidity or precipitation was lower than, or the mean temperature or wind speed was higher than, the 1988–2003 means were identified (Table 3). Months when two or more of these conditions coincided were also identified.

On several occasions individual selected criteria varied from the 16-year mean over several consecutive months,

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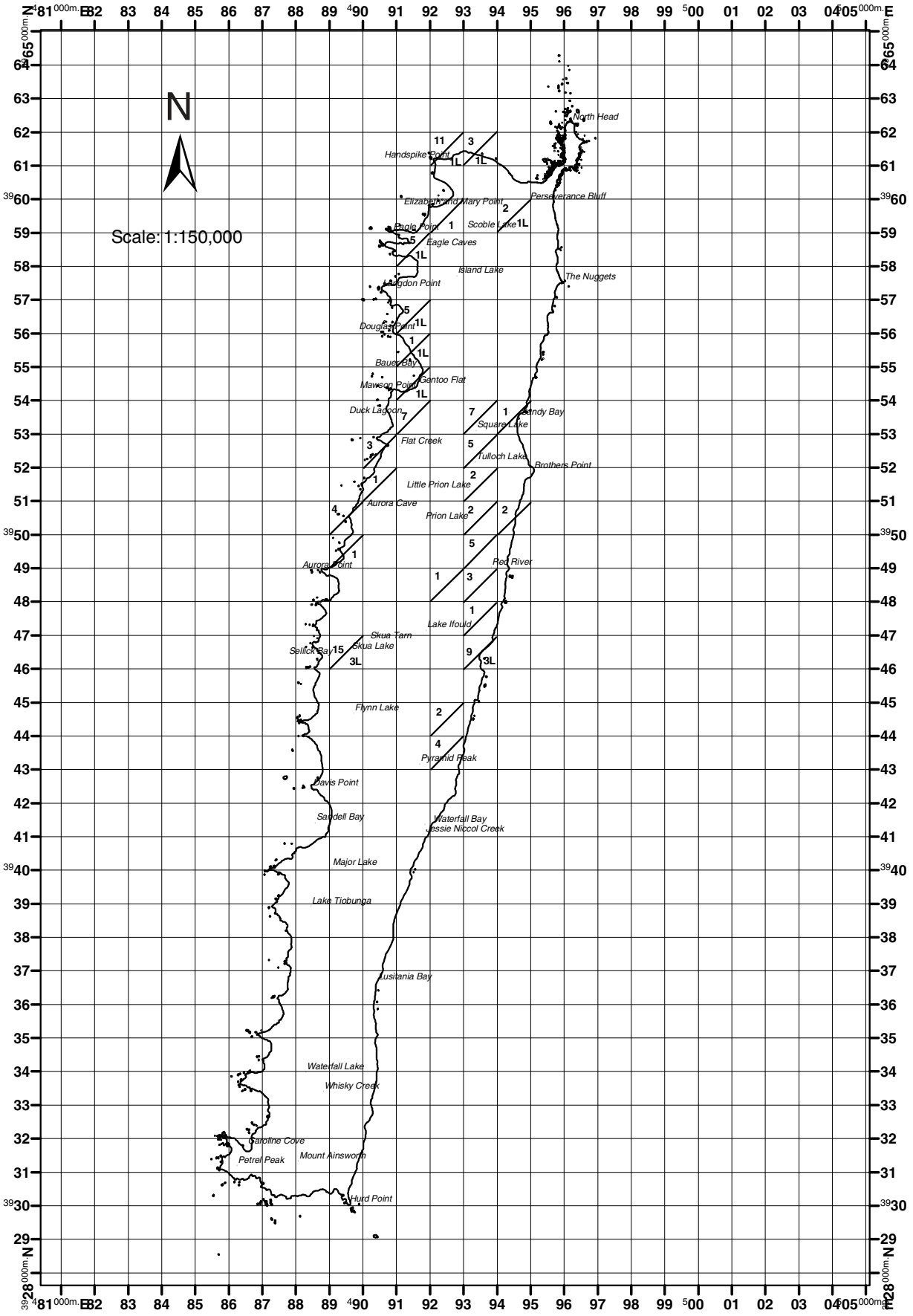

Fig. 1. Distribution map of *Sphagnum falcatulum* on Macquarie Island, based on a 1 km square grid. The numbers in the grid squares indicate the number of *Sphagnum* moss patches, and the numbers followed by L indicate the number of large *Sphagnum* moss beds ($\geq$3 m^2).

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Table 1. Area (m^2) of *Sphagnum* moss at each site by year. *November 1992 figures have been calculated by using length and width measurements for each moss patch and do not have the same accuracy as subsequent area measurements. – Indicates that the site was not established at that date.

Site Name & Tag No.	Nov. 1992	Nov. 1996	Nov. 1998	Nov. 1999	Mar. 2004
Douglas Point 26	–	–	2.3	3.4	2.1
Douglas Point 69	–	0.9	0.9	1.9	0.0
Eagle Point 70	4.8	2.0	2.8	2.6	2.5
Green Gorge 38	0.5	2.0	2.4	3.2	0.0
Green Gorge 52	0.2	0.0	0.0	0.0	0.0
Green Gorge 53	0.2	0.2	0.1	0.1	0.1
Green Gorge 62	28.1	22.8	23.5	32.3	29.3
Green Gorge 63	–	0.4	0.5	0.6	0.8
Green Gorge 77	12.9	7.1	7.4	7.5	7.5
Handspike 36 (1)	16.7	8.9	8.9	8.9	6.4
Handspike 36 (2)	15.3	0.0	0.0	0.0	0.0
Handspike 81	2.3	1.2	1.1	1.2	2.3
Mawson Point 67	3.9	4.9	4.4	0.0	0.0
Mawson Point 68	–	3.9	8.0	0.0	1.0
Scoble Lake 12	351.0	0.0	0.0	0.0	0.0
Square Lake 31	5.4	0.0	0.0	0.0	0.0
Above Square Lake 32a	0.4	0.3	0.3	0.0	0.0
Above Square Lake 32b	–	0.2	0.0	0.0	0.0
Above Square Lake 33	0.1	0.0	0.0	0.0	0.2
Above Tulloch Lake 34	1.3	3.9	3.5	5.1	5.0
Above Tulloch Lake 66	–	0.2	0.3	0.3	0.4
Brothers Lake 64	–	0.5	0.0	0.1	0.0
West Brothers Lake 65	0.2	0.2	0.1	0.1	0.0
AVERAGE AREA	27.7	2.7	2.9	2.9	2.5

Fig. 2. Photograph from same fixed photo-point as Figure 3, taken at Green Gorge catchment in 1992, showing new patches of *Sphagnum* moss appearing.

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Fig. 3. Photograph from same fixed photo-point as Figure 2, taken at Green Gorge catchment in 1996, showing new patches of *Sphagnum* moss appearing.

Table 2. Means of meteorological data (based on monthly means) for the periods 1988–95, 1996–2003, and 1988–2003.

	1988–95	1996–2003	1988–2003
Humidity (%)	85.8	85.9	85.8
Precipitation (mm)	1062.9	1047.7	1055.3
Temperature (°C)	4.8	5.0	4.9
Wind speed (mps)	9.5	10.3	9.9

Table 3. Number of occasions and ways that monthly means of selected meteorological events varied from the 1988 to 2003 16-year mean.

	1988–95	1996–2003	1988–2003
Lower mean humidity	43 (45%)	46 (48%)	89 (46%)
Lower mean precipitation	50 (52%)	53 (55%)	103 (54%)
Higher mean temperature	39 (41%)	56 (58%)	95 (49%)
Higher mean wind speed	31 (32%)	65 (68%)	96 (50%)

but they rarely coincided with extended periods of variation in any of the other criteria. An example of variation in a single criteria occurred between November 1988 to October 1989 when there were 12 consecutive months with the temperature above the 16-year mean. However, while lower-than-mean precipitation occurred on seven of these months and higher-than-mean wind speeds on six, only on two separate months did all three defined variations occur together.

On only 10 months during the 1988–2003 period did lower means for both humidity and precipitation coincide with higher means for both temperature and wind speeds. Two of these months occurred in the 1988–95 period (September 1993 and March 1994), one in March 1996, two in 1997, and five in 1999. In 1999 this coincidence of defined variations occurred over four consecutive months (August–November) during a period of 14 consecutive months (April 1999–May 2000) with lower-than-mean humidity and higher-than-mean wind speeds. From May 1999 to November 1999, this coincidence occurred in seven consecutive months with higher-than-mean temperatures (the 1999 survey was undertaken in mid to late November). These drier conditions may have resulted in a lowering of the watertable during this time. During this period, the authors, along with several scientists experienced in fieldwork conditions on Macquarie Island (Patricia Selkirk, personal communication; the late D.A. Adamson, personal communication) observed drier walking conditions.

Discussion

By 1988 the distribution of *Sphagnum falcatulum* on Macquarie Island had increased to the extent that it become noticeable to researchers involved in long-term

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studies on the island. At this point the authors collated all recorded data and undertook an extensive survey of the island. There was a dramatic decline in area in 1996 at most of the sites pegged in 1992. After 1999, the moss beds further contracted in area, with some plots retaining little or no *Sphagnum* moss. Photographic monitoring showed a similar initial expansion in *Sphagnum* moss beds in 1992, followed by contraction in 1996. *Sphagnum* either disappeared completely or showed major areal contraction at both coastal and plateau locations and at both small and large moss patches, with no trends evident. Further major decline in moss area coincided with the extended period of drier conditions in 1999.

There was an increase in mean annual temperature on Macquarie Island from 1949 to 1986 of 1°C (Adamson and others 1988). Tweedie and Bergstrom (2000) identified a trend indicating an increase in monthly mean surface air temperature of 0.3°C over the 50 years from 1948 to 1998. By analysing the monthly maximum and minimum surface air temperatures they found that the warming trend was mainly due to an increase in the maximum temperatures with little change in the mean minimum temperatures (Tweedie and Bergstrom 2000).

Analysis of aspects of meteorological data over the longer term indicated that desiccation through changes in evapotranspiration may be the cause of these changes in the *Sphagnum* beds. One of the major factors limiting the development of *Sphagnum* peatlands in Australia is moisture availability, in particular evapotranspiration in the driest month (Whinam and others 2003). The climatic conditions (higher than average temperatures and wind speeds and lower than average humidity and precipitation) that occurred between April 1999 and May 2000 are likely to have resulted in a period of desiccation prolonged and severe enough to account for the destruction of the smaller and/or shallower *Sphagnum* beds on the island. While rainfall may be less important in peatlands that receive significant catchment runoff, the generally small size of the moss beds affects their sensitivity to hydrologic changes (Whinam and others 2003). Macquarie Island is the southerly most location for the occurrence of *Sphagnum* moss. This may mean that conditions on Macquarie Island are marginal for *Sphagnum* growth and therefore *Sphagnum* is particularly sensitive to changes in local climatic conditions. As *Sphagnum* moss is a species that is known to be sensitive to changes in evapotranspiration, these results confirm its suitability as a sensitive climatic-change indicator, especially for episodes of altered weather patterns, as opposed to significant changes in the means of individual climatic elements.

The distribution of *Sphagnum* moss on Macquarie Island shows a northerly distribution pattern, similar to some of the vascular plant species that are not found south of Pyramid Lake, such as the native species *Hymenophyllum peltatum*, *Blechnum penna-marina*, *Hydrocotyle novae-zeelandiae*, *Nematoceras dienena*, and the introduced species *Stellaria media* and *Cerastium fontanum* (Copson 1984). The absence from the southern part of the island is surprising as suitable wet bog habitat occurs in several of the major catchments, for example, the Jessie Niccol Creek catchment. More surprising is the absence of *Sphagnum* from suitable wet boggy areas in the north of the island, such as the area that the species was originally recorded from in 1912. Although most of the grid squares with *Sphagnum* include tracks, many of the sites are some distance from walking tracks and in wet habitats that are less likely to be frequented by expeditioners.

It is possible that, with favourable climatic conditions, *Sphagnum* moss may again occur at some of the sites it has previously been recorded from, as suitable habitat is still present. Dispersal of vegetative material is likely to be by birds. The authors observed skuas bathing in pools amongst *Sphagnum* moss and then flying to other pools without *Sphagnum* present for further washing. However, the predictions of climatic change in the sub-Antarctic (Bergstrom and Chown 1999) would suggest that further periods of higher than average temperatures and wind speeds combined with lower than average precipitation and humidity are likely to occur more frequently. If these predictions are correct, then it is highly likely that both the spatial distribution and size of *Sphagnum* moss beds on Macquarie Island will continue to decline.

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