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Contrasting patterns in lichen diversity in the continental and maritime Antarctic

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ABSTRACT

Systematic surveys of the lichen floras of Schirmacher Oasis (Queen Maud Land, continental Antarctic), Victoria Land (Ross Sector, continental Antarctic) and Admiralty Bay (South Shetland Islands, maritime Antarctic) were compared to help infer the major factors influencing patterns of diversity and biogeography in the three areas. Biogeographic patterns were determined using a variety of multivariate statistical tools. A total of 54 lichen species were documented from Schirmacher Oasis (SO), 48 from Victoria Land (VL) and 244 from Admiralty Bay (AB). Of these, 21 species were common to all areas. Most lichens from the SO and VL areas were microlichens, the dominant genus being *Buellia*. In AB, in contrast, many macrolichens were also present and the dominant genus was *Caloplaca*. In SO and VL large areas lacked any visible lichen cover, even where the ground was snow-free in summer. Small-scale diversity patterns were present in AB, where the number of species and genera was greater close to the coast. Most species recorded were rare in the study areas in which they were present and endemic to Antarctica.

1. Introduction

Though Antarctica covers about 14 million km^2, the majority of its area (99.66%) is permanently covered by ice or snow. The remaining area (0.34%, or about 44,000 km^2) is mostly only ice-free in summer and consists of bare rock, boulder fields, scree and simple soils (Brabyn et al., 2005). The region includes two widely recognised biogeographic zones: the continental Antarctic and the maritime Antarctic. Terrestrial vegetation mainly comprises isolated communities of lichens and mosses, with greatest diversity on the islands and archipelagos adjacent to the Antarctic Peninsula (Kappen, 2000; Øvstedal and Smith, 2001; Ochyra et al., 2008; Sung et al., 2008). The wide variety of unique adaptations possessed by these organisms enabling them to survive stresses due to the extreme growing conditions of the Antarctic has received considerable research attention (Hennion et al., 2006). It is also important to understand these unique ecosystems in order to manage and protect them, as is required under the obligations of the Antarctic Treaty System (Green et al., 1999; Brabyn et al., 2005; Hughes and Convey, 2010).

The small-scale distribution of lichens within Antarctica is thought to be determined by the local environment providing favourable conditions (in particular moisture availability, Green et al., 1999) or exerting limiting effects (i.e. surface disturbance/instability, damage by wind action, etc, see Øvstedal and Smith, 2001). However, although lichen specimens have been collected from Antarctica by researchers over many years, more detailed and small-scale distributional and biogeographical studies based on systematic sampling have not been completed to date for the three study areas considered here, despite these being amongst the better characterized areas in terms of overall diversity in Antarctica. The current study was therefore undertaken in order to compare the lichen communities of three geographically distinct areas within Antarctica, the Schirmacher Oasis (SO, continental Antarctic), Victoria Land (VL, continental Antarctic) and Admiralty Bay (AB, King George Island, maritime Antarctic). We aimed to determine the major factors underlying patterns in local diversity and biogeography of lichens in these three areas.

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2. Materials and methods

2.1. Study sites

The Schirmacher Oasis (SO, 70° 46′04'' – 70°44′21″S; 11°49′54'' – 11°26′03″E) is a hilly strip of ice-free land in Queen Maud Land, continental Antarctic (Figs. 1 and 2a). It is divided into distinct topographical units – the southern continental ice sheet, rocky hills, valleys, lakes and the northern undulatory shelf ice. Its elevation varies from 0 to 236 m asl. The Oasis is oriented along an east–west axis and has a maximum width of 3.5 km and length of about 20 km, with a total area of about 70 km^2. This includes 35 km^2 of solid bedrock (ice free area). Freshwater lakes, ponds and pools cover a total area of 3 km^2. Permanently ice-covered tidal (epi-shelf) lakes cover an area of 4 km^2. There are also several nunataks protruding from the ice sheet near to the Oasis. Air temperature ranges between +4.2 and –25.2 °C, with a mean annual air temperature of –10.4 °C. The typical annual precipitation (snow) is 250–300 mm (water equivalent) and relative air humidity 15–20%. The area is underlain by permafrost with active layer depths ranging between 7 and 80 cm. The oasis is characterized by high-grade polymetamorphosed ortho- and para-gneisses, the dominant rock types being biotite–garnet gneiss, pyroxene granulites, calc-gneiss, and khondalite along with migmatites and augen gneiss. The water content in loose soils of SO varies greatly. The meltwater of the inland ice and local snow and ice firn fields contributes significantly to the moisture content of sediments (Olech and Singh, 2010).

Victoria Land (VL) (Figs. 1 and 2b) is located in the Ross Sector of the continental Antarctic, and extends from Cape Hallett (72°S) along the coast (coastal continental Antarctic) southwards to the Dry Valleys (77°S), and connects to the Transantarctic Mountains. In Victoria Land 21 locations were investigated along a five degree latitudinal transect from Cape Hallett (72°26′S, 169°56′E) to Marble Point, in the McMurdo Dry Valleys region (77°24′S, 163°43′E). The climate of this region is frigid Antarctic (Øvstedal and Smith, 2001). In northern Victoria Land the mean annual air temperature is around –16 °C and the annual precipitation occurs mostly as snow (with c. 270 mm y^{-1} water equivalent). The monthly mean air temperature ranges between –25.9 °C (August) and –0.1 °C (January). Further south in Victoria Land the climate is drier and colder with a mean annual air temperature of –17.4 °C at McMurdo Station (77°51′S, 166°40′E). The monthly mean air temperature at McMurdo Station ranges between –27.9 °C (August) and –1 °C (January). All sites were characterized by the occurrence of continuous permafrost, with an active layer thickness of 0–93 cm in Northern VL and of 0–60 cm in the McMurdo region. Although the climate has cooled slightly in the last decade, in Northern VL active layer thickness is currently slowly increasing, probably due to an increase in radiation receipt at ground level (Guglielmin and Cannone, 2012; Guglielmin et al., 2014). In this wide region almost all substratum types (granite, basalt, gabbro, metamorphic rocks, moraine and old marine deposits) were sampled in ice-free areas, sometimes close to glacier margins. Several sites included ornithogenic soils.

Admiralty Bay (AB, 61°50' – 62°15′S; 57°30' – 59°01′W) is the largest marine embayment on King George Island in the South Shetland Islands archipelago, maritime Antarctic (Figs. 1 and 2c). It has an area of 122 km^2 and a depth of up to 500 m. Of the total 361 km^2 catchment of the Bay, 242 km^2 is ice-free land surface. Its geology is dominated by Tertiary effusive basalt andesite and related pyroclastic rocks, having lithified and loose sedimentary rocks. Most of the ice-free terrestrial areas are adjacent to the sea. The main ice cap surrounding and draining into AB is the Arctowski Icefield. AB experiences a monthly temperature range of 1.3 °C to –7.5 °C, with an annual mean of –2.8 °C (Kejna, 1999). Mean wind velocity is about 6.5 m s^{-1}. Air humidity is typically high (83%), with annual precipitation of 508.5 mm.

2.2. Sampling and species determination

It is a well-established feature of biodiversity studies that the observed taxonomic richness of a given region is heavily influenced

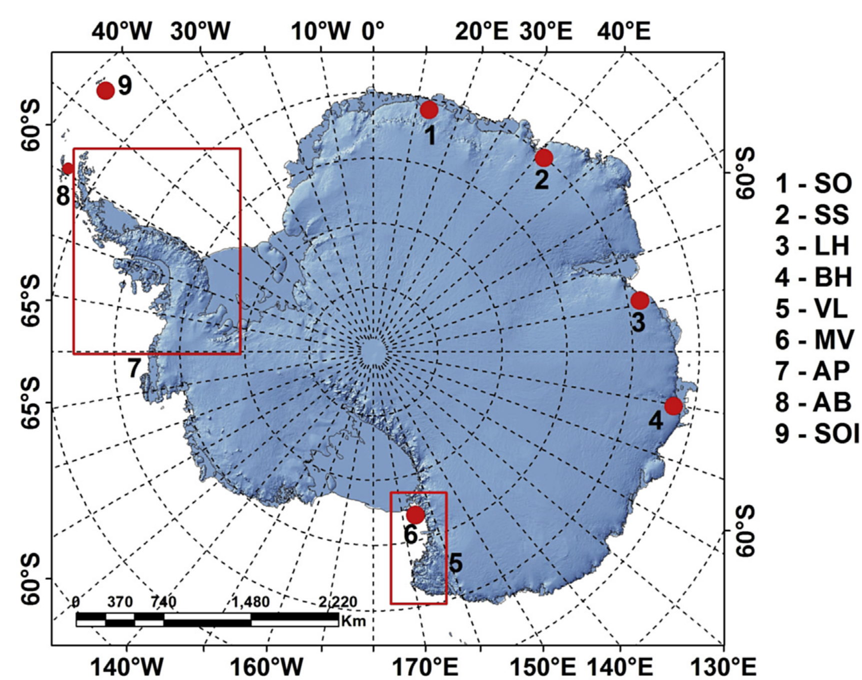

Fig. 1. Map of Antarctica showing the locations mentioned in the text. Legend: (1 = Schirmacher Oasis (SO), 2 = Syowa Oasis (SS), 3 = Larsemann Hills (LH), 4 = Bunger Hills (BH), 5 = Victoria land (Oasis (VL), 6 = McMurdo (MV), 7 = Antarctic Peninsula, 8 = Admiralty Bay (AB), 9 = South Orkney Island.

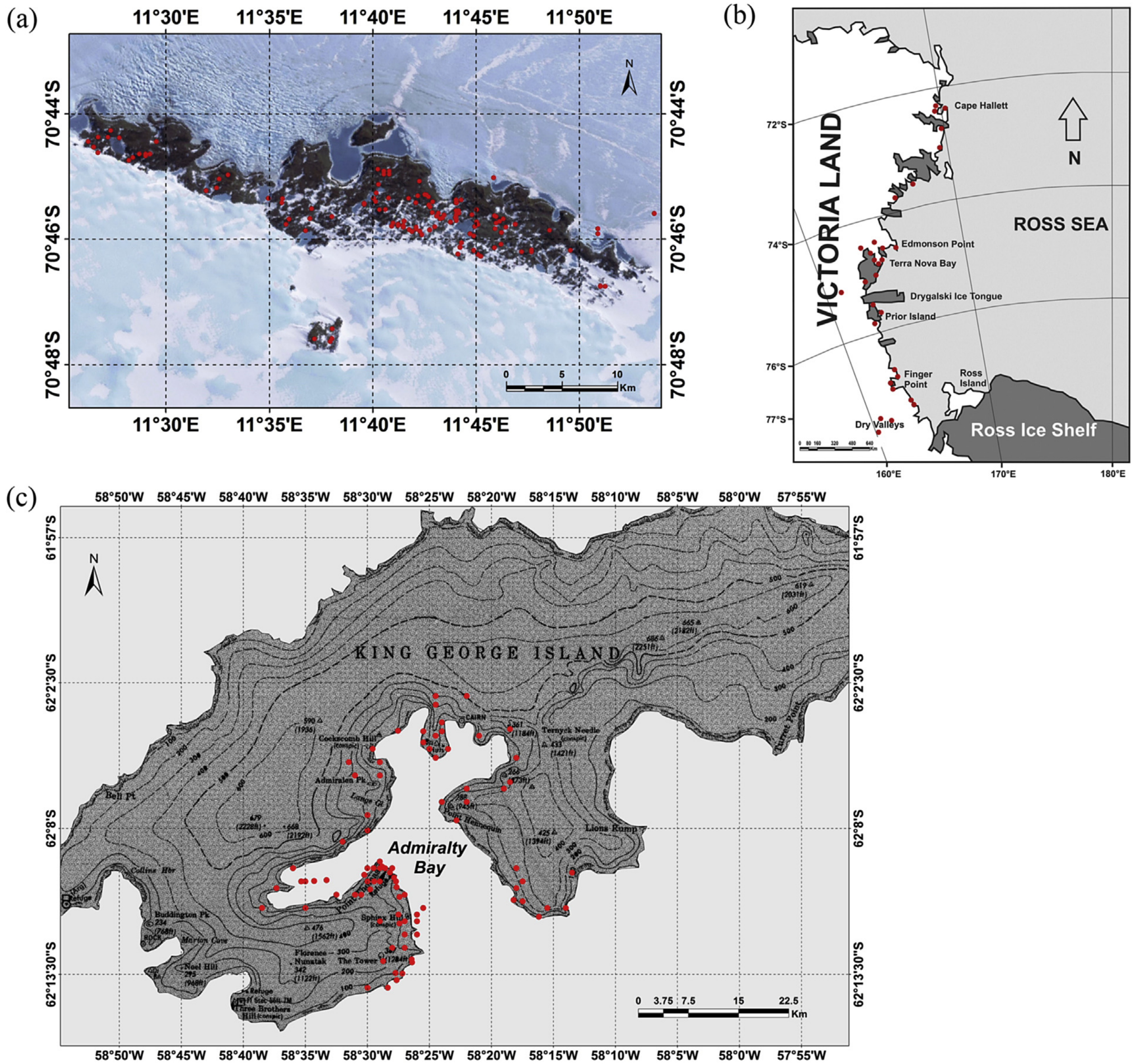

Fig. 2. a. Map of Schirmacher Oasis, showing grids-and sampling locations. b. Map of Victoria Land, showing grids and sampling locations. VL area shows 30 dots on map, and each dot represents about 7 sampling locations. c. Map of Admiralty Bay, showing grids and sampling locations.

by sampling intensity, as has been described in broad terms for Antarctica (Peat et al., 2007). In the present work, the potential impact of sampling heterogeneity for AB, VL and SO as a whole was determined by examining the relationship between the number of specimens collected and the number of species recorded at the survey scales used (rarefaction curve) (Peat et al., 2007; Cannone et al., 2013).

Lichen samples were collected from SO in the austral summer of 2003/04 during the XXIII Indian Antarctic Expedition (Olech and Singh, 2010), from VL in 2001/02 and 2002/03 during the XVI and XVII Italian Antarctic campaign and from AB in 1986–88, 1989/90, 1991–93, 1995/96, and 2001/02 during XI, XIII, XVI, XX and XXVI Polish Antarctic Expeditions (Olech, 2004). The specimens collected are deposited at the Herbarium of Polar Research and Documentation, Institute of Botany, Jagiellonian University (KRA-L), Krakow, Poland (AB, SO) and at Insubria University (VL). The three areas are likely to include significant environmental gradients (e.g. in temperature, water availability, associated with factors such as altitude, distance from the coast). However, in the absence of detailed micro-environmental data from each of the sampling locations, our analysis of the spatially explicit species occurrence data is limited to the identification of patterns associated with simple spatial gradients within each area, and inference from these as to the likely environmental parameters they act as proxy for. The three study areas included 101 (AB), 149 (SO) and 213 (VL) specific sampling locations.

Lichens were classified based on their growth form into three groups (crustose, fruticose, foliose), and based on substratum type into four groups (saxicolous, terricolous, epiphytic on mosses and ubiquitous). Morphological and anatomical details were used for identification of lichen species. Secondary metabolites were analyzed using standard TLC methods. Specimens were identified by the authors (N. Cannone, M. Olech and S.M. Singh) following the most recent literature (Øvstedal and Smith, 2001; Olech, 2004; Castello, 2003; Olech and Singh, 2010) and current nomenclatural rules (following Eriksson et al., 2001).

2.3. Biodiversity analyses

An important criterion for characterizing the local lichen biota is the frequency of occurrence of each lichen species. The status of lichen species found in the three study areas was classified based on a simple arbitrary assessment of their % frequency of occurrence across the sampled locations within each area, separating rare (<5% of sampling locations), occasional (6–10%), common (11–50%) and abundant species (>51%). The % frequency (%F) of each lichen species was calculated for each study area using the following formula:

$$\%F = (So/Stot)*100$$

where So is the number of sampling locations where the species occurred and Stot is the total number of sites sampled within the study area.

Data were retrieved from earlier checklists published by the authors for SO and AB (Olech, 2004; Olech and Singh, 2010) and VL (Cannone, 2006; Cannone and Seppelt, 2008; Cannone unpublished data). Numbers of taxa recorded for spatially explicit localities were enumerated at species and higher taxonomic levels (genus, family).

2.4. Biogeographical patterns

The biogeographic patterns were analyzed among the three study sites by means of cluster analysis (ordination by Correspondence Analysis, CA, performed by CANOCO for Windows, ter Braak and Smilauer, 1998) based on presence/absence data. As the study areas are of widely different sizes and the sampling effort in each was inevitably dissimilar, only presence/absence data were used in the analyses. Comparisons of the three study areas were also made in terms of dominant genera, wider biogeographical distribution of recorded species, status of occurrence of species and habitat type from which they were recorded.

A hierarchical classification (dendrogram) was performed for the original data obtained from the locations sampled in the three study areas (AB, SO and VL) using Statistica® to analyse the vegetation community types and structure among the selected areas.

3. Results

A total of 3035 samples representing 244 species were collected from AB, 875 samples including 54 species from SO and 1570 samples and 48 species in VL. The rarefaction curves (Fig. 3a–c) indicated that sufficient samples were obtained at all locations to give a reasonable estimate of overall lichen diversity.

Morphological, substratum, biogeographic and status information on the lichen taxa found at all locations are summarised in Tables 1 and 2. In all study sites most lichens were found on rock, with differences among sites for epiphytic, soil and 'other' substrata (Table 1). Overlaps between the substratum preferences of some taxa were also observed. The majority of species recorded in all three locations are endemic to Antarctica, followed by the bipolar (with a peak at AB) and cosmopolitan groups. Species restricted to the Southern Hemisphere were the least frequently encountered. The majority of species found at SO were classified as rare, followed by common, occasional and most common. Similarly, in AB most species were rare, followed by occasional, common and most common classes. At VL more than half of the recorded species were common, while about 25% were rare. In all areas most lichens were of crustose growth form, followed by foliose (AB) or fruticose (SO and VL) (Table 2).

There was a common pool of species occurring in all three study

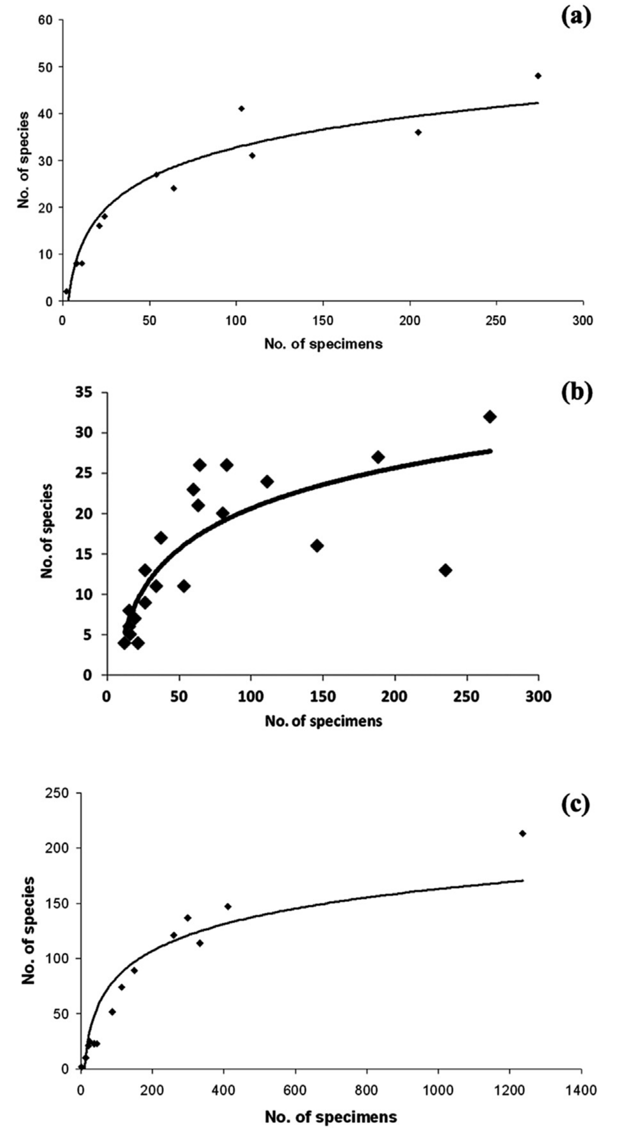

Fig. 3. Rarefaction curves for a) Schirmacher Oasis, b) Victoria Land and c) Admiralty Bay.

areas, including *Rhizocarpon* (both *R. geographicum* and *R. geminatum*) and widespread epilithic species (*Umbilicaria decussata*, *Xanthoria elegans*, *Usnea antarctica*) and common muscicolous and ubiquitous species (*Buellia papillata*, *Leproloma cacuminum*, *Candelariella flava*, *Caloplaca citrina*, *Rinodina olivaceobrunnea*, *Physcia dubia*, *P. caesia*). Twenty-one species were shared among the three areas, with somewhat more being shared between each pair of areas (SO with VL, 31; SO with AB, 31; VL with AB, 28) (Supplementary Table 1). The most frequently shared species differed depending on the selected sites: *Umbilicaria antarctica*, *Arthonia rufidula*, *Bacidia stipata*, *Sarcogyne privigna*, *Lecanora mawsonii* between AB and SO; *Buellia frigida*, *Lecanora aff. orosthea*, *L. aff. geophila*, *L. fuscobrunnea*, *Lecidea andersonii*, *L. cancriformis* between SO and VL and *Buellia cladocarpiza* and *Tephromela atra* between AB and VL.

Buellia, *Caloplaca* and *Lecanora* were the most dominant genera common to the three study areas, with *Umbilicaria* also being commonly encountered. Genera such as *Lecania* and *Rhizocarpon* were common at AB but not at SO and VL. A range of genera such as *Cladonia*, *Pertusaria*, *Psoroma*, *Stereocaulon* and *Tephromela* present

Table 1
Comparison of lichen features and biogeography at the three sites (AB = Admiralty Bay; SO = Schirmacher Oasis; VL = Victoria Land).

Features		AB	SO	VL
Habitat (substratum) type	Rocks (%)	71.7	75.9	60
	Epiphytic (%)	33.6	38.9	8.9
	Soil (%)	17.6	16.7	11.1
	Other substrates (%)	9.0	1.8	20
Biogeographic elements	Cosmopolitan (%)	10.3	10.5	11.1
	Bipolar (%)	41	29.8	35.6
	Endemic (%)	40.3	54.4	48.9
	Restricted to Southern Hemisphere (%)	8.3	5.3	4.4
Status	Rare (%)	43.8	37	25.5
	Occasional (%)	27.9	25.9	11.8
	Common (%)	25.8	33.3	49
	Most common (%)	2.5	3.7	13.7

Table 2
Comparison of thallus growth form type at various Antarctic sites.

Antarctic sites	Crustose (%)	Fruticose (%)	Foliose (%)	Reference
SO	79	3.5	17.5	Present study
SS	77	6	17	Inoue (1991)
SG	66	17	17	Claridge et al. (1971)
LH	76	4	20	Singh et al. (2007)
BH	76	7	17	Andreev (1990)
VL	71.1	6.7	22.2	Present study
NVL	72	10	18	Kappen (1985)
CVL	82.45	5.26	12.28	Castello (2003)
BSF	100	–	–	Hale (1987)
MRL	67	7	27	Filson (1966)
CA	72	7	22	Øvstedal and Smith (2001)
AB	68	15	17.1	Present study
FP	79	9	11	Inoue (1991)
AP	67	8	24	Øvstedal and Smith (2001)
SOI	65	8	27	Øvstedal and Smith (2001)

SO = Schirmacher Oasis; SS = Syowa station area; SG = Scott Glacier region, Queen Maud Range; LH = Larsemann Hills; BH = Bunger Hills; VL = Victoria Land; NVL = N. Victoria Land; CVL = Continental Victoria land; BSF = Beacon Sandstone Formation Victoria Land; MRL = Mac Robertson Land; CA = Continental Antarctic; AB = Admiralty Bay; FP = King George Island (Fildes Peninsula); AP = Antarctic Peninsula and SOI = South Orkney Island.

at AB were absent at SO and VL.

At SO higher species richness was recorded at sample locations close to the coast (Fig. 4a). A similar effect was present at AB (Fig. 4c), with the highest species richness in protected sites such as bays and coves. Across the much larger scale of VL, species richness did not show a linear trend with latitude but rather a split distribution, with minimum numbers of species, genera and families at around 76°S Fig. 4b).

Correspondence analysis (CA) allowed analysis of the relationships among the three sampling locations (AB, SO, VL) with reference to their floristic composition. In the sampling locations graph (Fig. 5a) it is possible to identify two main clusters located at the two opposite parts of the x axis: the maritime Antarctic locations (AB) are clustered in the left part of the graph, while the continental Antarctic locations (VL, SO) cluster at the opposite side of the graph. The continental Antarctic cluster can be divided in two sub-clusters along the y-axis: the first sub-cluster (SO) is in the upper right side of the graph, while the second sub-cluster (VL) is located in the lower right (Fig. 5a). The separation of sampling locations is due to the differences in their floristic composition, which is shown in the species graph (Fig. 5b). The species are grouped in two main clusters along the x-axis: those occurring only in the maritime Antarctic location (AB) are located at the left side of the graph, while those recorded in the continental Antarctic locations (VL, SO) are clustered in the right part of the graph. In the right part of the species biplot it is possible to observe also a progressive transition in terms of floristic composition between the continental Antarctic locations (Fig. 5a,b).

The results of the CA are confirmed also by the hierarchical classification illustrated in the dendrogram (Fig. 6). The sampling locations (AB, SO, VL) are indicated at the bottom of the dendrogram. Each branch indicates a group of sampling locations characterized by similar floristic composition: the whole left branch and the first (left) sub-branch of the right branch include records from AB, while the remaining two sub-branches mainly include records from SO and VL. This analysis highlights that the floristic composition of AB is very distinct from both VL and SO. In particular, the separation of four main branches (corresponding to four different community types) indicates that the AB locations are characterized by four main vegetation types (left part of the dendrogram). SO and VL cluster together in the right part of the dendrogram with two main vegetation types dominated by microlichens and macrolichens, respectively.

4. Discussion

The present study was undertaken to determine and compare patterns in lichen diversity in AB, SO and VL, three of the better-known locations that can be regarded as representative of habitats typical of the maritime and continental Antarctic. AB lies in the South Shetland Islands, which are in the Northern Province of the maritime Antarctic, having a cold moist maritime climate and higher diversity than the Southern Province (Peat et al., 2007). SO lies in the Maud Sector and the slope province of the continental Antarctic, with a cold arid climate. VL lies in the Ross Sector and encompasses a wide variety of environments across a latitudinal gradient from 72 to 77°S, and is characterized by a frigid Antarctic climate (Øvstedal and Smith, 2001).

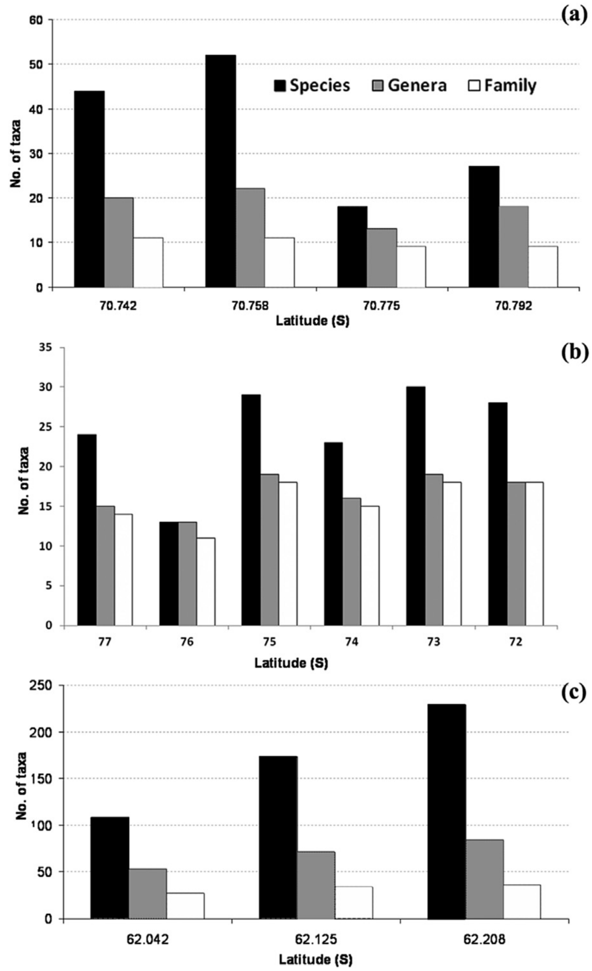

Fig. 4. Richness at species and higher taxonomical levels (genera, family) at a) Schirmacher Oasis, b) Victoria Land, c) Admiralty Bay. In (a) and (c) increasing latitude is effectively a proxy for increasing distance from the coast (cf. Fig. 2a, c).

4.1. Biogeographical distribution of lichens within Antarctica

There is a widely held but largely untested assumption that at least the majority of the Antarctic flora originated after the last Pleistocene glacial maximum and the subsequent retreat of glaciers and ice-sheets (Hertel, 1987; Galloway, 1991; but see Pisa et al., 2014). However, our site-specific data are consistent with the assessment of the high species-level rates of endemism of the entire Antarctic lichen flora (Øvstedal and Smith, 2001, 2004, 2009; Søchting et al., 2004; Green et al., 2011), with a somewhat higher percentage of species endemic to Antarctica recorded at the sites located in continental Antarctic (54.4% at SO, 48.9% at VL) than in maritime Antarctica (40.3% at AB) (Table 1). These values are comparable to values reported across a range of other groups in Antarctica (Rudolph, 1970; Kappen and Straka, 1988; Smith, 1991; Linskens et al., 1993; Marshall and Pugh, 1996). Moreover, while the occurrence of cosmopolitan species and species restricted to the Southern Hemisphere is comparable, there are differences relating to bipolar species, which are better represented at AB. The relative proximity of the AB region to South America (~800 km distant) and its limited geographic isolation could explain the lower percentage of endemic and higher percentage of bipolar species at this site as compared to the much more isolated SO and VL. However, although it might be predicted that its proximity to South America would favour colonization by exotic species, AB is not characterized by a larger occurrence of cosmopolitan and Southern Hemisphere species than SO and VL. This may indicate that the harsh climatic and environmental conditions are too limiting to allow species colonization. These high levels of endemism are, rather, consistent with the hypothesis that lichens are one of the terrestrial groups that persisted within Antarctica through glacial cycles (Convey and Stevens, 2007; Green et al., 2011). High levels of endemism amongst the lichens of VL and SO may also be a reflection both of their physical isolation from other terrestrial habitats in the region and, perhaps, that extreme conditions at these locations have over time selected for a specialized endemic community.

Bipolar species formed the next most important biogeographic element of the lichen floras, contributing 29.8% of species from SO, 35.6% from VL and 41.1% from AB (Table 1). The differences may reflect the simple scale of geographic isolation of SO and VL, with AB being much closer to the atmospheric circulation barriers that must be crossed by any colonizing propagule. It is apparent that Antarctica experiences a continuous input of airborne propagules from the other Southern Hemisphere continents and further afield (Marshall, 1996), and bipolar elements have similarly been reported in the Antarctic bryophyte flora (Ochyra et al., 2008).

4.2. Environmental factors influencing lichen distribution

Although Antarctic lichens are capable of growing and photosynthesizing even at sub-zero temperatures, they grow more luxuriantly in regions where liquid water is more reliably available (Green et al., 1999). Kappen (2000) identified snowmelt as the major source of hydration underlying the productivity of lichens. Also, the higher precipitation received in coastal areas can dilute the influence of salt concentration in sea spray (Inoue, 1991). The lowland coastal and high humidity area of AB may, therefore, support a more diverse range of lichens and more complex community than the drier continental SO and VL. Amongst the various thallus types, crustose lichens are generally hardier and grow in more extreme environments, followed by the foliose and fruticose groups. A greater proportion of crustose lichens are therefore found at SO and VL.

AB supported more lichen growth and the area was taxonomically more diverse than SO and VL. One of the factors most likely to influence such differences is clearly the less extreme climatic conditions existing in the maritime Antarctic. This includes warmer temperatures, greater precipitation (also in form of rain, which is completely absent from the continental Antarctic), higher water availability for biological processes and low wind velocity. Similar observations have been reported from another continental region (Syowa Station) by Inoue (1989), who concluded that lichens which received very low precipitation in summer nevertheless grew luxuriantly at sites where adequate moisture was maintained due to snow and ice moved by katabatic winds from the surface of the neighbouring glaciers, while lichens were absent or poorly developed at drier sites which were influenced by cyclonic winds over the surface of sea ice.

The large-scale extent of ice cover (and hence site isolation) also affects wider biological distributions, as organisms such as lichens clearly require ice-free areas in which to colonise and establish. This however, does not indicate that the ice-free ground available at any particular time will necessarily determine the number of species existing there. Rather, the time elapsed after ice has retreated from the area will play a large role in determining the establishment rate (Peat et al., 2007). At SO and VL extensive areas lacked lichen cover, even where the ground was normally snow-free in summer.

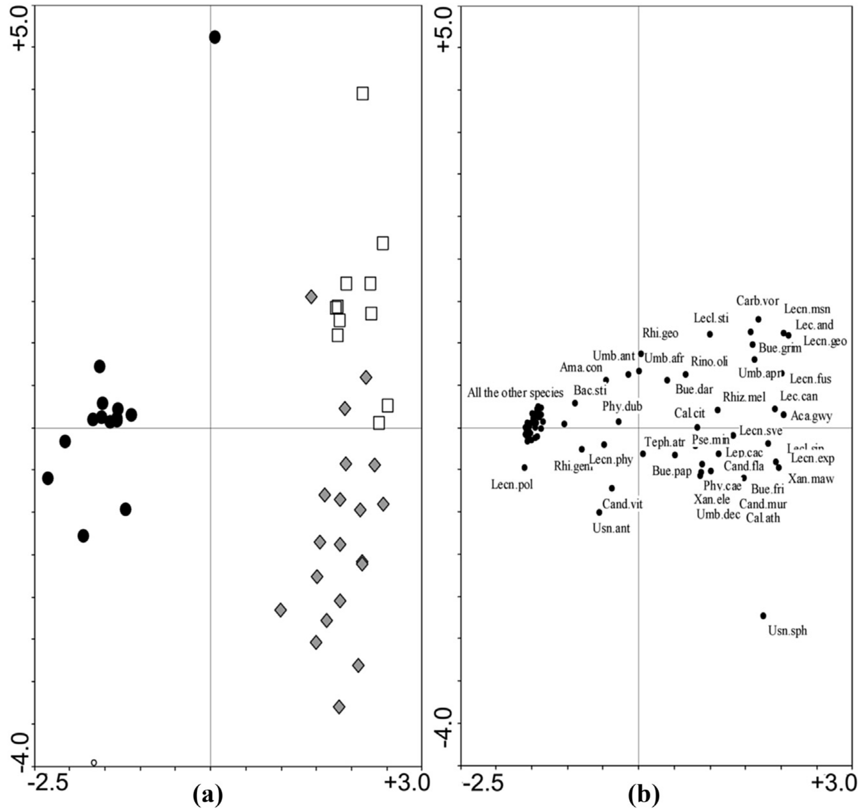

Fig. 5. Correspondence analysis diagram of the sites (a) and of the species (b) surveyed at AB (black circles), SO (white squares) and VL (grey rhomboids).

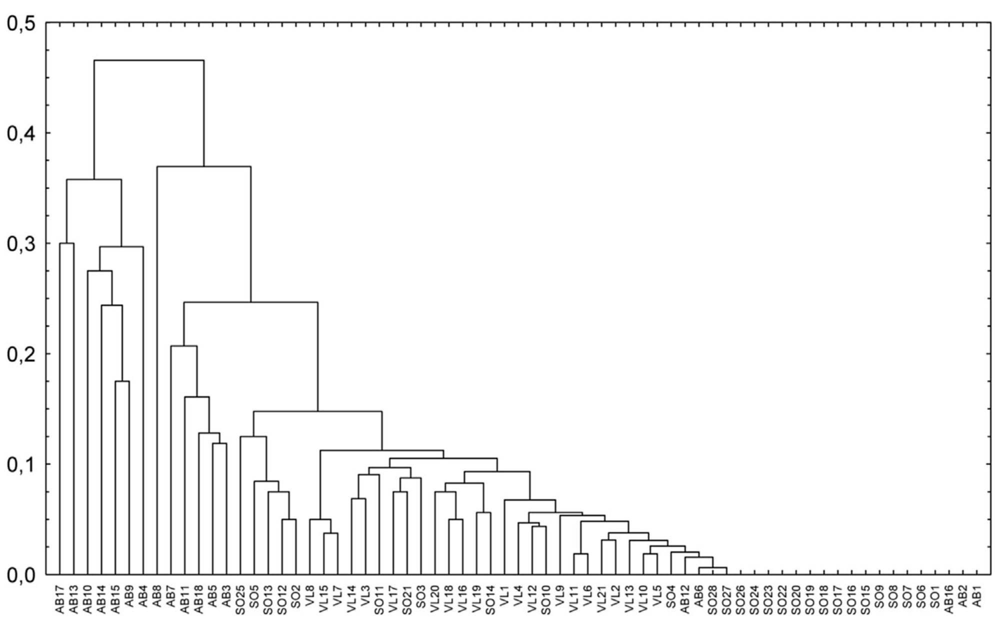

Fig. 6. Hierarchical classification of the vegetation of the three study sites (AB, SO, VL). The separation of the groups has been carried out at a linking distance >0.1.

4.3. *Lichen diversity at the three areas and comparison with other studies*

The described lichen flora of Antarctica currently stands at 397 taxa (Øvstedal and Smith, 2001, 2004, 2009). The present study reports 244 species from the 242 km^2 area of AB located on King George Island, which is about 80% of the 294 taxa known from the entire island (Olech, 2004). Previously, Andreev (1988) reported 119 species from King George Island (mainly from the Fildes Peninsula), while Inoue (1991) reported 198 species in total from the Fildes Peninsula and Nelson Island. Signy Island (approx. 25 km^2) hosts 221 species (Øvstedal and Smith, 2001). Guzman and Redon (1981) reported 47 species of lichens from the Ardley Peninsula.

Previous lichenological investigations in the SO have documented the occurrence of 34 species (Richter, 1990; Nayaka and Upreti, 2005). In Victoria Land the present study documents the occurrence of 48 species of the 58 species known from Victoria Land (Cannone and Seppelt, 2008; Castello, 2010). Comparison of present data with other diversity studies carried out within the continental Antarctic shows that SO (70 km^2 area) with 54 species was richer than the Larsemann Hills, (50 km^2 and 25 species; Singh et al., 2007). Of these, 19 species were common to both the areas. The same total of 54 species was also recorded from the larger 175 km^2 Syowa Station area (Inoue, 1991). Other reports from the continental Antarctic include 42 species from the Bunger Hills (Andreev, 1990) and 32 species from MacRobertson Land (Filson, 1966).

Although analogous studies have been carried at specific locations in other parts of Antarctica (Inoue, 1991; Andreev, 1988; Øvstedal and Smith, 2001; Castello, 2010; Smykla et al., 2011; Green et al., 2011), the current study is one of the first to examine small-scale distribution patterns of lichens in both the continental and maritime Antarctic biogeographic regions. Overall differences between the three study locations were consistent with both the differing levels of geographical isolation and the environmental severity experienced at each. At smaller scales, patterns within each site were apparent, although linking these explicitly to specific environmental features and variables would require a detailed network of physical monitoring sites. Such a network has now been established in Victoria Land incorporating 19 permanent monitoring sites in nine different locations (Cannone, 2006; Guglielmin and Cannone, 2012).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.polar.2015.07.001.

References

Andreev, M.P., 1988. De lichenoflora insulae King-George (Antarctis) notula. Nov. Syst. Plant Non Vasc. 25, 118–124.
Andreev, M.P., 1990. Lichens of the Bunger Oazis (East Antarctic). Nov. Sist. Nizsh. Rast. 27, 85–93.
Brabyn, L., Green, A., Beard, C., Seppelt, R., 2005. GIS goes nano: vegetation studies in Victoria Land, Antarctica. New Zeal. Geogr. 61, 139–147.
Cannone, N., 2006. A network for monitoring terrestrial ecosystems along a latitudinal gradient in Continental Antarctica. Antarct. Sci. 18, 549–560.
Cannone, N., Seppelt, R., 2008. A preliminary floristic classification of Northern and Southern Victoria Land vegetation (Continental Antarctica). Antarct. Sci. 20, 553–562.
Cannone, N., Convey, P., Guglielmin, M., 2013. Diversity trends of bryophytes in continental Antarctica. Polar Biol. 36, 259–271.
Castello, M., 2003. Lichens of the Terra Nova Bay area, northern Victoria land (Continental Antarctica). Stud. Geobot. 22, 3–54.
Castello, N., 2010. Notes on the lichen genus *Rhizoplaca* from Continental Antarctica and on some other species from Northern Victoria Land. Lichenologist 42, 429–432.
Claridge, G.C., Campbell, B., Stout, J.D., Dutch, M.E., 1971. The occurrence of soil organisms in the Scott Glacier Region, Queen Maud Range, Antarctica. New Zeal. J. Sci. 14, 306–312.
Convey, P., Stevens, M.I., 2007. Antarctic biodiversity. Science 317, 1877–1878.
Eriksson, O.E., Baral, H.O., Currah, R.S., Hansen, K., Kurtzman, C.P., Rambold, G., Laessøe, T., 2001. Outline of Ascomycota. Myconet 7, 1–88.
Filson, R.B., 1966. The lichens and mosses of MacRobertson land. ANARE Sci. Rep. Ser. B (11) 82, 1–66.
Galloway, D., 1991. Phytogeography of southern hemisphere lichens. In: Nimis, P.L., Crovello, T.J. (Eds.), Quantitative Approaches to Phytogeography. Kluwer, Dordrecht, pp. 233–262.
Green, T.G.A., Schroeter, B., Sancho, L.D., 1999. Plant life in Antarctica. In: Pugnaire, F.I., Valledares, F. (Eds.), Handbook of Functional Plant Ecology. Marcel Dekker Inc., Basel, New York, pp. 495–543.
Green, T.G.A., Sancho, L.G., Türk, R., Seppelt, R.D., Hogg, I.D., 2011. High diversity of lichens at 84°S, Queen Maud Mountains, suggests preglacial survival of species in the Ross Sea region, Antarctica. Polar Biol. 34, 1211–1220.
Guglielmin, M., Cannone, N., 2012. A permafrost warming in a cooling Antarctica? Clim. Chang. 111, 177–195. http://dx.doi.org/10.1007/s10584-011-0137-2.
Guglielmin, M., Worland, M.R., Baio, F., Convey, P., 2014. Permafrost and snow monitoring at Rothera Point (Adelaide Island, Maritime Antarctica): implications for rock weathering in cryotic conditions. Geomorphology 225, 47–56.
Guzman, G.G., Redon, F., 1981. Los liquenes de Peninsula Ardely y zonas adyacentes, Isla Rey Jorge, Antarctica Occidental. INACH Ser. Cient. 27, 19–37.
Hale, M.E., 1987. Epilithic lichens in the Beacon Sandstone Formation, Victoria Land, Antarctica. Lichenologist 19, 269–287.
Hennion, F., Huiskes, A., Robinson, S., Convey, P., 2006. Physiological traits of organisms in a changing environment. In: Bergstrom, D.M., Convey, P., Huiskes, A.H.L. (Eds.), Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator. Springer, Dordrecht, pp. 129–159.
Hertel, H., 1987. Progress and problems in taxonomy of Antarctic saxicolous lecideoid lichens. Bibl. Lichenol. 25, 219–242.
Hughes, K.A., Convey, P., 2010. The protection of Antarctic terrestrial ecosystems from inter and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. Glob. Environ. Chang. 20, 96–112.
Inoue, M., 1989. Factors influencing the existence of lichens in the ice-free areas near Syowa Station, East Antarctica. Proc. NIPR Symp. Polar Biol. 2, 167–180.
Inoue, M., 1991. Ecological notes on the differences in flora and habitat of lichens between the Syowa Station area in continental Antarctic and King George Island in Maritime Antarctic. Proc. NIPR Symp. Polar Biol. 4, 91–106.
Kappen, L., 2000. Some aspects of the great success of lichens in Antarctica. Antarct. Sci. 12, 314–324.
Kappen, L., Straka, H., 1988. Pollen and spores transport into Antarctica. Polar Biol. 8, 173–180.
Kappen, L., 1985. Vegetation and ecology of ice-free areas of northern Victoria Land, Antarctica. 2. Ecological conditions in typical microhabitats of lichens in Birthday Ridge. Polar Biol. 4, 227–236.
Kejna, M., 1999. Air temperature on King George Island, South Shetland Islands. Antarct. Pol. Polar Res. 20, 183–201.
Linskens, H.F., Bargagli, R., Cresti, M., Focardi, S., 1993. Entrapment of long distance transported pollen grains by various moss species in coastal Victoria Land, Antarctica. Polar Biol. 13, 81–87.
Marshall, D.J., Pugh, P.J.A., 1996. Origin of the inland Acari of Continental Antarctica with particular reference to Dronning Maud Land. Zool. J. Linn. Soc. 118, 101–118.
Marshall, W.A., 1996. Biological particles over Antarctica. Nature 383, 680.
Nayaka, S., Upreti, D.K., 2005. Schirmacher Oasis, East Antarctica, a lichenologically interesting region. Curr. Sci. 89, 1069–1071.
Ochyra, R., Smith, R.I.L., Bednarek-ochyra, H., 2008. Illustrated Moss Flora of Antarctica. Cambridge University Press, Cambridge.
Olech, M., 2004. Lichens of King George Island, Antarctica. The Institute of Botany of the Jagiellonian University, Poland.
Olech, M., Singh, S.M., 2010. Lichen and Lichenicolous Fungi from Schirmacher Oasis, Antarctica. National Centre for Antarctic and Ocean Research. NISCAIR, New Delhi India.
Øvstedal, D.O., Smith, R.I.L., 2001. Lichens of Antarctica and South Georgia. A Guide to Their Identification and Ecology. Cambridge University Press, Cambridge.
Øvstedal, D.O., Smith, R.I.L., 2004. Additions and corrections to the lichens of Antarctica and South Georgia. Cryptogam. Mycol. 25, 323–331.
Øvstedal, D.O., Smith, R.I.L., 2009. Further additions to the lichen flora of Antarctica and South Georgia. Nova Hedwig. 88, 157–168.
Peat, H.J., Clarke, A., Convey, P., 2007. Diversity and biogeography of the Antarctic flora. J. Biogeogr. 34, 132–146.
Pisa, S., Biersma, E.M., Convey, P., Patiño, J., Vanderpoorten, A., Werner, O., Ros, R.M., 2014. The cosmopolitan moss *Bryum argenteum* in Antarctica: recent colonization or *in situ* survival? Polar Biol. 37, 1469–1477.
Richter, W., 1990. The Lichens of Schirmacher Oasis (East Antarctica). Geodätische und Geophysikaliische Veröffentlichungen, Reihe I, Berlin 16, pp. 471–488.
Rudolph, E.D., 1970. Local dissemination of plant propagules in Antarctica. In: Holdgate, M.W. (Ed.), Antarctic Ecology 2. Academic Press, London, pp. 812–817.
Singh, S.M., Nayaka, S., Upreti, D.K., 2007. Lichen communities in Larsemann Hills, East Antarctica. Curr. Sci. 93, 1670–1672.
Smith, R.I.L., 1991. Exotic sporomorpha as indicators of immigrant colonists in Antarctica. Grana 30, 313–324.
Smykla, J., Krzewicka, B., Wilk, K., Emslie, S.D., Śliwa, L., 2011. Additions to the lichen flora of Victoria Land, Antarctica. Pol. Polar Res. 32, 123–138.
Søchting, U., Øvstedal, D.O., Sancho, L., 2004. The lichens of Hurd Peninsula, Livingston Island, South Shetlands, Antarctica. In: Dobbeler, P., Rambold, G. (Eds.), Contributions to Lichenology, Festschrift in Honour of Hannes Hertel. Bibl. Lichenol, vol. 88, pp. 607–658.
Sung, L.J., Lee, H.K., Hur, J.-S., Andreev, M., Hong, S.G., 2008. Diversity of the lichenized fungi in King George Island, Antarctica, revealed by phylogenetic analysis of partial large subunit rDNA Sequences. J. Microbiol. Biotechnol. 18, 1016–1023.
ter Braak, C.J.F., Smilauer, P., 1998. CANOCO Reference Manual and User's Guide to Canoco for Windows – Software for Canonical Community Ordination (Version 4). Microcomputer Power, Ithaca, New York.