

Diversity and distribution of Victoria Land biota

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Abstract

Understanding the relationship between soil biodiversity and ecosystem functioning is critical to predicting and monitoring the effects of ecosystem changes on important soil processes. However, most of Earth's soils are too biologically diverse to identify each species present and determine their functional role in food webs. The soil ecosystems of Victoria Land (VL) Antarctica are functionally and biotically simple, and serve as in situ models for determining the relationship between biodiversity and ecosystem processes. For a few VL taxa (microarthropods, nematodes, algae, mosses and lichens), species diversity has been intensively assessed in highly localized habitats, but little is known of how community assemblages vary across broader spatial scales, or across latitudinal and environmental gradients. The composition of tardigrade, rotifer, protist, fungal and prokaryote communities is emerging. The latter groups are the least studied, but potentially the most diverse. Endemism is highest for microarthropods and nematodes, less so for tardigrades and rotifers, and apparently low for mosses, lichens, protists, fungi and prokaryotes. Much of what is known about VL diversity and distribution occurs in an evolutionary and ecological vacuum; links between taxa and functional role in ecosystems are poorly known and future studies must utilize phylogenetic information to infer patterns of community assembly, speciation, extinction, population processes and biogeography. However, a comprehensive compilation of all the species that participate in soil ecosystem processes, and their distribution across

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regional and landscape scales is immediately achievable in VL with the resources, tools, and expertise currently available. We suggest that the soil ecosystems of VL should play a major role in exploring the relationship between biodiversity and ecosystem functioning, and in monitoring the effects of environmental change on soil processes in real time and space.

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1. Introduction

Integrated studies of the relationship between soil biodiversity and ecosystem functioning are hampered by a dearth of fundamental taxonomic knowledge of soil organisms and their contribution to ecosystem functioning. It is apparent that, at least for macrofauna, functional diversity can influence important soil processes, such as decomposition (Heemsbergen et al., 2004; Roscher et al., 2004). However, the relationship between species richness and ecosystem functioning in soils remains unclear, in part due to the lack of taxonomic information, numerous species and limited studies that have investigated this relationship (see Mikola et al., 2002 for review). However, species richness should be of greater importance in low-diversity ecosystems. A comprehensive compilation of all the species that participate in soil ecosystem processes, as well as how their distribution and abundance varies across variable spatial scales, is required (Wall, 2005). Such knowledge enables a better understanding and more realistic design of experiments that can determine how their interactions with the soil environment, and each other, facilitate ecosystem functioning.

The vast majority of Earth's soils are too biologically diverse to determine the functional role that each species plays in a food web. Although it is widely recognized that species, and not trophic groups, are the fundamental units of biology and ecology (Ghilselin, 1987; Bernard, 1992; Frost and Kluge, 1994; Wheeler, 1995; Adams, 1998; Brooks and McLennan, 2002), there have been a few major efforts made to recover all of the species in a given area. Two all taxa biodiversity inventories have been initiated in temperate North America (Great Smoky Mountains National Park; Mammoth Cave National Park). Others were conceived, but to date, the hyperdiversity of organisms smaller than 10 mm in each of these areas, and the lack of taxonomic expertise and infrastructure for dealing with these groups, poses an almost insurmountable task (Blackmore, 1996; Wheeler et al., 2004). Also, while recent initiatives have attempted to characterize a large portion of the soil biological community at a given site (e.g. Fitter et al., 2005), there are still no complete inventories for soil taxa. In species poor systems, such as Antarctica, richness is probably more important than other diverse systems, because there is less species redundancy, and a species inventory thus becomes feasible and a high priority.

Victoria Land (VL), Antarctica is devoid of vascular land plants and hence feedback mechanisms between plants and soil biota cannot operate, as they do in other ecosystems (Wardle et al., 2004). Also, there are far fewer species in Antarctic soils than tropical and temperate ecosystems (Bargagli et al., 1997). Because of this, Antarctic soils potentially serve as excellent models for understanding fundamental properties of the relationship between soil biota and ecosystem functioning across multiple spatial scales (Barrett et al., 2004), and are one of few places on Earth where the taxonomic resolution necessary to finally address these questions is tractable. Here, we summarize what is presently known of the diversity and distribution of VL soil biota, and establish a baseline of taxonomic information to facilitate future efforts towards understanding their functional roles in soil ecosystem processes.

For purposes of this assessment, we consider VL to be the part of Antarctica from the west side of the Ross Sea southward from 70°30'S to 78°00'S, and westward from the Ross Sea to the edge of the polar plateau (USGS, 2003). For ease of discussion we divide VL into two regions, northern Victoria Land (nVL) from about 70°30'S to about 76°S, encompassing Terra Nova Bay, Edmonson Point and Cape Hallett. We consider southern Victoria Land (sVL) to lie between 76°S and about 78°S including all of the McMurdo Dry Valleys and nearby coastal regions. The two areas correspond with a biogeographical split among some biota (i.e. Terra Nova Bay marks the southern limits of several taxa). In each of these regions, penguin rookeries, coastal areas and areas of moist and drier soils exist. Our coverage of biota includes bacteria, fungi, protozoa, rotifers, tardigrades, nematodes, mites, and springtails. Cyanobacteria and algae that occur in lakes and streams are included as the saturated sediments of lake margins and stream beds represent an important functional extension of the soil habitat (Treonis et al., 1999; Wall, 2006). Cryptoendoliths and cryoconites are other habitats for biodiversity, but their ecological linkages with soil biota are outside the scope of this paper, and are not considered in detail here. Our appraisal of the taxonomic diversity of soils in VL, which was explored only in the last hundred years, shows that identification and biogeographical distribution is limited by the same taxonomic restrictions shown for soil communities elsewhere. These include intensity of sampling effort across the various habitats within each region.

2. Biodiversity and distribution of Victoria Land biota

2.1. Prokaryotes

To date there have been no systematic surveys of bacterial diversity in the Dry Valleys. The soils of this region support a potentially diverse microbial community that for the most part is uncharacterized (Wynn-Williams, 1996; Cowan and Tow, 2004). Although there is relatively little detailed taxonomic information on the identities of soil microorganisms, there is a developing body of evidence for microbial activity in these soils (Burkins et al., 2001; Treonis et al., 2002; Parsons et al., 2004). Using the polymerase chain reaction, preliminary investigation has shown the presence of ammonia oxidising bacteria in soils of the Garwood Valley (A.G. O'Donnell, I.S. Waite, C.V. Lanyon, O. Owen, D.W. Hopkins, unpubl.) whilst molecular methods targeting the gene for methanogenesis specific methyl co-enzyme reductase (Hales et al., 1996) indicate the presence of methanogens between 20 and 50 m from lake margins (Hopkins et al., 2005). Similar genetic investigations of dry mineral soils from the Upper Miers Valley, Taylor Valley, and Cape Hallett (Luther Vale) show the microbial communities to be in low abundance yet highly diverse and heterogeneous (S.C. Cary and D. Cowan, unpubl.). Miers Valley soils appear dominated by Actinobacteria, α Proteobacteria, and Cyanobacteria until organically enriched when a completely different community (Bacilli and γ proteobacteria) becomes dominant (L. Robson and S.C. Cary, unpubl.). These observations suggest VL dry soils harbor a more highly diverse microbial community than would be predicted by the extreme nature of the system. The environmental parameters that specifically drive this microbial diversity are currently unknown.

2.1.1. Cultured bacterial diversity

Molecular studies such as those outlined above that detect the presence of an amplifiable gene or fragment of a gene (DNA) do not necessarily establish that the organisms are intact and active. The cold and dry environment is a perfect setting to preserve DNA, in or out of the cell, indefinitely. More extensive molecular analyses (molecular probing or direct analysis of specific genetic transcripts), coupled with process related analyses (Griffiths et al., 2004; Malosso et al., 2004; Hopkins et al., 2005), are required to ascertain the viability of these bacteria. To definitively show that the organisms are active and capable of growth requires isolation and cultivation. To date most investigations of bacteria in soils of VL have focused on the abundance and diversity of cultivable bacteria in surface cold desert mineral soils of the Dry Valleys (reviewed by Vishniac, 1993). The bacteria described were aerobic heterotrophs that formed pigmented colonies on solid media. Anaerobic bacteria have not been widely reported. In early (pre 1990) studies the bacteria were assigned to known genera including *Arthrobacter*, *Micrococcus*, *Bacil-*

lus and *Pseudomonas*. Coryneforms (Actinobacteria) were typically dominant in Ross Desert mineral soil whereas *Pseudomonas* and *Bacillus* were rare (Johnson et al., 1978). These studies led to the conclusion that bacteria from Antarctic soils may be cosmopolitan in distribution.

16S rDNA sequencing and phylogenetic analysis is providing new insights into the genetic affinities and diversity of Antarctic bacteria (Table 1). Consequently, using 16S rRNA sequencing some cultured bacteria have been assigned to known genera such as *Arthrobacter* and *Bacillus* whilst others, including *Hymenobacter roseosali-varius* (Hirsch et al., 1998) and *Modestobacter multiseptatus* have been recognized as belonging to novel genera (Mevs et al., 2000). Thermophilic bacteria have also been isolated from thermally heated soils near Mts Melbourne and Rittman in nVL (reviewed by Broady, 1993; Logan et al., 2000; Stevens and Hogg, 2006a).

Notwithstanding the limitations of culture-based approaches to understanding community structure and diversity in soils (O'Donnell et al., 2005) comparisons of bacterial diversity and abundance between sites in these cold desert soils is compromised by the use of different media. Typically, the highest numbers of cultured bacteria are from relatively moist coastal soils, compared with the small bacterial communities of dry inland soils. However, using luminometry to estimate ATP levels, Cowan et al. (2002) concluded that the numbers of bacteria in cold desert mineral soil in Taylor Valley were higher than previously believed. The highest numbers of heterotrophic bacteria were cultured from nutrient-enriched ornithogenic soils of Cape Hallett (O'Brien et al., 2004) where bacteria tend to be most abundant at the surface and decline with depth. Similarly, higher numbers have been reported in samples at the interface of the soil and the ice-cemented permafrost (Vishniac, 1993).

2.1.2. Cyanobacterial diversity

In contrast to the eubacteria, the diversity of the cyanobacteria has been more extensively studied though we still lack detailed understanding of biogeographic distribution and relative abundance. Surveys of cyanobacteria date back to the beginning of the 20th Century and the expeditions of Shackleton (1907–1909; West and West, 1911) and Fritsch ('Discovery Expedition', 1912).

Cyanobacteria are found in all types of aquatic habitats in VL and often dominate the microbial biomass of streams and lake sediments (Vincent, 1988). They are the most important mat-forming component in VL lakes and ponds. In particular, *Leptolyngbya frigida* (Fritsch) Anagnostidis and Komárek (Anagnostidis and Komárek, 1988) is dominant in all benthic mats of nVL and sVL (Seaburg et al., 1979; Wharton et al., 1983; Fumanti et al., 1995, 1997). This species is also frequently found in soils and as an epiphyte on mosses (Alfinito et al., 1998) revealing its high capability for adaptation.

In VL soils, the cosmopolitan *Nostoc commune* Vaucher 1803 can, if supplied with a thin water film, develop to sizes

Table 1
Bacteria cultured from soils of Victoria Land

Division	Genera or species	Source	GenBank accession #
<i>Cold desert mineral soils</i>			
Actinobacterium	<i>Arthrobacter</i>	Cape Evans	AJ495808
		Harrows Peak	O'Brien et al., 2004
	<i>Brevibacterium antarcticum</i>	Dry Valleys	AJ577724
	<i>Modestobacter multiseptatus</i>	Asgard Range	Y18646
	<i>Pseudonocardia antarctica</i>	Dry Valleys	AJ576010
Firmicutes	<i>Paenibacillus</i>	Cape Evans	AJ495806
	<i>Planococcus</i>	Cape Evans	AJ496039
α -Proteobacteria	<i>Aquaspirillum</i> ^a	Marble Point	AF411851 and AF413109
	<i>Azospirillum</i>	Wright Valley	AF411852
	<i>Brevundimonas</i>	Cape Evans	AJ495803
β -Proteobacteria	<i>Massila</i>	Cape Evans	AJ496038
γ -Proteobacteria	<i>Acinetobacter</i>	Cape Evans	AJ495807
	<i>Pseudomonas</i>	Marble Point	AF411853-5
		Crater Circe	O'Brien et al.
	<i>Psychrobacter</i>	Cape Evans	AJ495805
	<i>Stentrophomonas</i>	Cape Evans	AJ495804
Bacteroidetes	<i>Hymenobacter roseosalivarius</i>	Dry Valleys	Y18834
	<i>Chryseobacterium</i>	Cape Evans	AJ495802
	<i>Sphingobacterium</i>	Cape Evans	AJ496037
<i>Ornithogenic soils</i>			
Firmicutes	<i>Planococcus</i>	Cape Hallett	O'Brien et al.
<i>Thermally heated soils</i>			
Firmicutes	<i>Bacillus fumarioli</i>	Mt. Rittmann	AJ250056
	<i>Bacillus thermoantarcticus</i>	Mt. Melbourne	AJ493665
	<i>Alicyclobacillus acidocaldarius</i>	Mt. Rittmann	AJ493667

All bacteria included in this table have been identified to genus level by 16S rRNA gene sequence analysis.

^aTwo variants of the 16S RNA gene in this bacterium.

visible to the naked eye (Cavacini, 2001). Although found as an epiphyte on nVL mosses (Alfinito et al., 1998) and in sVL soils (Holm-Hansen, 1964) these organisms are also widespread in aquatic environments in both regions (Howard-Williams et al., 1986; Fumanti et al., 1995). The genus *Gloeocapsa* is one of the few cryptoendolithic taxa with a high adaptation to extreme environmental conditions in rocks of the Dry Valleys (Friedmann and Ocampo, 1976; Friedmann et al., 1988). To date approximately 180 different cyanobacterial taxa have been recorded in VL (Fumanti and Cavacini, 2005) with aquatic environments showing the greatest diversity.

2.2. Algae

Algae and cyanobacteria are present in almost all ice-free areas of VL and occur in soils, as epiphytes on mosses, in cyanobacterial mats and in plankton of lakes and ponds. It is also possible to find algae associated with rocks or living in the thin film of melted water in the snow patches. Early algal surveys in VL were carried out by Van Heurck (1909; Belgica expedition, 1897–1899), West & West (1911; E. Shackleton expedition, 1907–1909) and Fritsch (1912;

Discovery Expedition, 1901–1904). Presently there are records of more than 300 algal taxa (Fumanti and Cavacini, 2005) belonging to the following divisions: Chlorophyta, Heterokontophyta (Bacillariophyceae, Xanthophyceae and Chrysophyceae), Dinophyta, Cryptophyta, and Euglenophyta, with the first two representing more than 97% of the total.

As with the entire Antarctic continent, Bacillariophyceae (Diatoms) and Chlorophyta are the most widespread algae in VL. Diatoms are abundant in aquatic environments decreasing in number in terrestrial habitats, especially in soils of northern and southern VL (Seaburg et al., 1979; Cavacini, 2001). On the other hand, Xanthophyceae are almost absent from benthic cyanobacterial mats in both regions, but are an important component of the flora in soils of nVL (Cavacini, 2001). Chlorophyta are also important components of the mats in lakes and ponds of VL but tend to increase their relative importance in terrestrial environments and especially in soils, where they are the densest algal group (Holm-Hansen, 1964; Seaburg et al., 1979; Cavacini, 2001). Records from other algal groups (Dinophyta, Cryptophyta, and Euglenophyta) are mainly limited to freshwater communities of the Dry

Valleys (Cathey et al., 1981; Alger et al., 1996; Laybourn-Parry et al., 1997). The Dry Valleys have about 80 algal species, with 50 confirmed species of freshwater diatoms (Esposito et al., 2006).

The VL algal diversity contains, based on present knowledge, a low number of endemics (Broady, 1996; Jones, 1996), probably due to the extensive use of European and North American literature for identifications (Sabbe et al., 2003). The most widespread species are, among the Heterokontophyta, the diatom *Pinnularia borealis* Ehrenberg 1843 which shows a uniform distribution in nVL from Cape Adare to Granite Harbour, mostly in association with sediments but also as an epiphyte on mosses (Broady, 1987). The cosmopolitan diatom *Hantzschia amphioxys* (Ehrenberg) Grunow in Cleve et Grunow 1880 tolerates a wide range of environmental conditions being recorded from high altitude sites (Mt. Feather, Barrett et al., 1997) to ponds located close to the sea in Cape Adare (Fritsch, 1912). *Luticola muticopsis* (Van Heurck) Mann in Round et al. 1990 previously described as endemic, has a homogeneous distribution in VL, but this needs further investigation as to its taxonomic stability. *Kentrosphaera facciolae* Borzi 1883 and *Prasiola crispa* (Lightfoot) Meneghini 1838 (Chlorophyta) are also key VL taxa. *K. facciolae* has a distribution limited to cyanobacterial mats and soils in nVL (Fumanti et al., 1997; Cavacini, 2001), whereas *P. crispa* is often recorded in southern and northern VL soils (West and West, 1911; Broady, 1985), as well as being widespread across the maritime and sub-Antarctic, and also known from the Arctic. Species of Xanthophyta show more restricted distributions. *Xanthonema exile* (Klebs) Silva 1979 is widespread in nVL soils (Cavacini, 2001) whereas *Xanthonema bristolianum* (Pascher) Silva 1979, *Monodus coccomyxa* Pascher 1939 and *Heterococcus moniliformis* Vischer 1937 are known only from Dry Valley lakes and soils (Seaburg et al., 1979).

2.3. Yeasts and filamentous fungi

The yeasts and filamentous fungi encountered in VL soils are in most cases cosmopolitan, globally distributed species. In the majority of studies on these organisms, the fungi were isolated and cultured on agar media and identified by classical taxonomic methods, rather than by analysis of nucleic acid sequence data. The commonly isolated fungi fall within the zygomycetes and the anamorphic or teleomorphic ascomycetes and basidiomycetes. In nVL, the most frequently isolated filamentous soil fungi are species of *Alternaria*, *Aspergillus*, *Cladosporium* (typically *C. cladosporioides* (Fresen.) G.A. de Vries and *C. herbarum* (Pers.) Link), *Geomyces* (almost exclusively *G. pannorum* (Link) Sigler and J.W. Carmich., often reported as *Chrysosporium pannorum*), *Phialophora* (typically *P. fastigiata* (Lagerb. and Melin) Conant, often reported as *Cadophora fastigiata*), *Phoma* (often *P. herbarum* Westend.), *Thelebolus microsporus* (Berk. and Broome) Kimbr.

and *Mortierella antarctica* Linnemann (Del Frate and Caretta, 1990; Zucconi et al., 1996; Fenice et al., 1997; Tosi et al., 2002, 2005). *Chaetomium gracile* Udagawa is frequently isolated from geothermally heated soil on Mount Melbourne in nVL (e.g. Broady et al., 1987; Zucconi et al., 1996). Filamentous fungi are more commonly isolated from soils in coastal regions, with many species recorded from bryophyte-dominated habitats around Terra Nova and Wood Bays by several Italian expeditions. Fewer species of yeasts than filamentous fungi have been isolated from nVL soils, but species of *Cryptococcus* (typically *C. albidus* (Saito) C.E. Skinner) and *Rhodotorula* (typically *R. minuta* (Saito) F.C. Harrison) are regularly isolated from soils in the northern region (Del Frate and Caretta, 1990; Tosi et al., 2002, 2005).

In sVL, where there have been relatively few studies on filamentous soil fungi, species of *Aspergillus* (e.g. *Aspergillus ustus* (Bainier) Thom and Church) and *Penicillium* (e.g. *Penicillium jensenii* K.M. Zalessky) are commonly isolated from soil (Sugiyama et al., 1967; Baublis et al., 1991). Less frequently isolated filamentous fungi from southern VL soils are *Phialophora* spp., *Cladosporium* spp. (typically *C. cladosporioides*) and *G. pannorum* (Baublis et al., 1991; Onofri et al., 2000; Tosi et al., 2002). The diversity of filamentous fungi in sVL soils is apparently lower than that in the northern region (cf. Baublis et al., 1991; Tosi et al., 2005), but it is unclear whether filamentous fungal diversity is actually lower in the southern region, or the difference is owing to higher sampling effort in nVL. The diversity of yeasts, by contrast, is apparently higher in sVL soils (cf. Atlas et al., 1978; Tosi et al., 2005). The yeasts *Aureobasidium pullulans* (de Bary) G. Arnaud, *Debaryomyces hansenii* (Zopf) Lodder and Kreger, *Leucosporidium scottii* (Fell, Statzell, I.L. Hunter and Phaff) and species of *Candida* (often *C. psychrophila* (Goto, Sugiy. and Iizuka) S.A. Meyer and Yarrow), *Cryptococcus* (frequently *C. albidus*) and *Rhodotorula* (often *R. rubra* (Schimon) F.C. Harrison but also *R. minuta*) are commonly isolated from sVL soils (Tubaki, 1961; Sugiyama et al., 1967; Cameron et al., 1977; Atlas et al., 1978; Baublis et al., 1991; Vishniac, 1996; Connell et al., 2006). Yeasts are the only forms of soil fungi isolated from some soils in the Dry Valleys (Victoria and Wright Valleys) (Atlas et al., 1978; Vishniac, 1996). One species, *Cryptococcus vishniacii* Vishniac and Hempfling, appears to be indigenous to upland soils of the Dry Valleys (Vishniac, 1996). Animal pathogens in the basidiomycete yeast genus *Trichosporon* (*T. cutaneum* (Beurm., Gougerot and Vaucher) N. Ota and *T. beigeli* (Küchenm. and Rabenh.) Vuill.) have also been recorded from sVL soils (Tubaki, 1961; Baublis et al., 1991).

The ecological role of most of the fungi listed above is in the primary decomposition of plant material. Most filamentous fungi utilize simple plant-derived carbon sources such as cellulose (Fenice et al., 1997), and yeasts such as *Cryptococcus* spp. are able to utilize simple sugars (Vishniac and Baharaeen, 1982), which may explain the

greater fungal diversity in soil close to bryophyte-dominated areas in nVL. The observation of Baublis et al. (1991) that the highest abundance of fungi in Dry Valley soil was under moss also corroborates this view. Most of the fungi are incapable of decomposing lignin, which may reflect the absence of the polymer from uninhabited VL ecosystems. Several fungi, notably *G. pannorum*, are strongly keratinophilic (Mercantini et al., 1989), and frequently occur in ornithogenic soil (Onofri et al., 2000). A restricted number of fungi are found in consistent association with other organisms: notable examples are the springtail-capturing *Arthrobotrys ferox* Onofri and Tosi, the entomophthoralean fungus *Conidiobolus antarcticus* Tosi, Caretta and Humber, found in the southern region (Tosi et al., 2004a), and the nematode-trapping *A. tortor* Jarow. and *Nematoctonus* sp. in nVL (Onofri and Tosi, 1992; Tosi et al., 2004b).

Fell et al. (2006), have performed the only molecular-based study of fungal diversity in VL soils. Analyzing sequences of large and small subunit rDNA extracted from Dry Valley soil they found *Cryptococcus* and *Trichosporon* spp. corroborating culture-based studies. These authors also noted the presence of fungal taxa different from those recorded by culture-based methods, such as nematode-trapping fungi in the genus *Hohenbuehelia* and the saprotrophs *Phaeosphaeria* sp., *Coniochaeta ligniaria* (Grev.) Massee and *Cochliobolus heliconiae* Alcorn. Many of the fungal species present in VL soils are cosmopolitan in nature, however some species and clades are unknown (Fell et al., 2006), which suggests the presence of an endemic mycoflora.

2.4. Lichens and mosses

The first lichen collections from continental Antarctica were made at Cape Adare on H.J. Bull's Antarctic expedition to nVL in January 1895, by C. Borchgrevinck. The first moss collections in VL were also made by Borchgrevinck, in 1899, during the Southern Cross Expedition (Gepp, 1902; Darbishire, 1910). The National Antarctic Discovery Expedition 1901–1904 provided the earliest published account of the flora of sVL (Cardot, 1907; Darbishire, 1910), listing seven mosses and 15 lichens collected from Granite Harbour, Mt. Terror, Discovery Winter Quarters, McMurdo Sound, and the Western Mountains (Taylor Valley region). Moss collections from Cape Royds, Hut Point, Cape Irizar, Cape Barne, high moraines at Cape Royds and the Strand Moraines in McMurdo Sound were made by the British Antarctic Nimrod Expedition 1907–1909 (Cardot, 1910). Lichens were collected by the British Antarctic Terra Nova Expedition 1910–1913, from Cape Adare, Cape Sastrugi and Evans Cove (Darbishire, 1923).

Further botanical exploration in sVL was not undertaken until the International Geophysical Year of 1958–1959. Most Antarctic lichens known at this time, including those collected during the Byrd expeditions, were

enumerated by Dodge (1973) (see also Castello and Nimis, 1995). Greene (1967) studied collections of mosses and discussed general taxonomic difficulties while using collections to produce distribution maps that concentrated on the Ross Sea area (from about 80°S to 70°S). Numerous opportunistic collections from the Ross Sea region have been made since then, principally by American, New Zealand, Australian, British, Japanese and Italian scientists, but there are few published reports on the flora or vegetation (Hale, 1987; Seppelt et al., 1992, 1995, 1996, 1998; Seppelt and Green, 1998; Søchting and Seppelt, 2003). The most southerly regional records for moss were published by Wise and Gressitt (1965) from the east side of the Massam Glacier, and on the east side of the Barrett Glacier. Broady and Weinstein (1998) reported cyanobacteria, fungi, algae, and two lichen species (*Lecidea cancriformis* and *Carbonea vorticosa*) from the La Gorce Mountains.

The VL bryophyte and lichen flora is not rich, and the degree of endemism is much lower than formerly supposed. The number of species and endemic elements are more numerous in the maritime Antarctic and there appear to be no endemic genera. The bryophyte flora of nVL includes at least 11 species of moss: *Sarconeurum glaciale* Cardot and Bryhn, *Bryoerythrophyllum recurvirostre* (Hedw.) Chen, *Hennediella heimii* (Hedw.) R.H. Zander, *Syntrichia princeps* (De Not.) Mitt.; *Campylopus pyriformis* (Schultz) Brid. (restricted to specific geothermal sites) (Skotnicki et al., 2001); *Ceratodon purpureus* (Hedw.) Brid.; *Anomobryum (Bryum) subrotundifolium* (A. Jaeg.) J.R. Spence and H.P. Ramsay, *Bryum pseudotriquetrum* (Hedw.) P. Gärtner, B. Mey. and Scherb.; *Pohlia nutans* (Hedw.) Lindb.; *Grimmia plagiopodia* Hedw.; *Schistidium (Grimmia) antarctici* (Cardot) L.I. Savicz and Smirnova 1, and one hepatic *Cephaloziella varians* (Gottsche) Steph. at Mt. Melbourne fumaroles, Edmonson Point, Harrow Peaks, and other ice-free areas (Bednarek-Ochyra et al., 2000; Broady et al., 1987; Lewis Smith, 1997).

In recent years a number of moss species recorded in VL have undergone nomenclatural changes: *Grimmia antarctici* is now more appropriately placed in the genus *Schistidium*; *Didymodon gelidus* has been synonymized with *Didymodon brachyphyllus* (Ochyra and Zander, 2002); and *Bryum algens* Cardot was synonymized by Ochi (1979) in *B. pseudotriquetrum*. The genus *Bryum* exhibits in Antarctica a perplexing range of morphological variation (Ochi, 1979; Seppelt and Kanda, 1986) and considerably altered features occur in aquatic forms (Seppelt, 1983a,b). Kaspar et al. (1982) reported cf. *B. algens* from sediments in Lake Vanda; this material should be referred to *B. pseudotriquetrum* despite the assertion by Webby et al. (1996) that there are flavonoid chemotype differences between material determined as *B. algens* and other specimens referred to *B. pseudotriquetrum*. *Bryum subrotundifolium* was transferred to the genus *Anomobryum* by Spence and Ramsay (2002). In VL this predominantly coastal species is usually a yellowish green but in shaded localities may be entirely

green. *Bryum argenteum* Hedw. has been reported from a number of localities. Longton (1973) used material collected from near McMurdo Station in his global interpopulational studies of the species but whether or not this material was really *B. argenteum* and not *A. subrotundifolium* remains equivocal. Recent collections made from the Cape Hallett area in December 2004, and initially considered to be morphologically very close to *B. argenteum* and not to *A. subrotundifolium*, have been shown by molecular studies to be identical to any other Ross Sea region collections of *A. subrotundifolium* (Stevens et al., in press).

The number of lichen species in VL (< 100 spp.) is much lower than the number of lichen species reported for Arctic regions (north America and Greenland—ca. 470 spp.) at about the same latitude (Thomson, 1997). Ice-free areas in VL show a great diversity of habitats, characterized by wide ranges of water and nutrient availabilities and substrates (different types of granites, schistose metamorphites, amphibolites, basalt and volcanic rocks). Many ice-free areas and especially those at low altitude and close to the coast have suitable climatic, topographic and edaphic conditions for the development of around 12 bryophyte species and about 57 lichen taxa, 51 of which were identified to species level by Castello (2003). Macrolichens such as *Usnea sphacelata* R.Br., *U. antarctica* Du Rietz, *Umbilicaria decussata* (Vill.) Zahlbr. or *U. aprina* Nyl., and communities of weakly- or non-nitrophilous lichens (e.g., *Pseudophebe minuscula* (Nyl. ex Arnold) Brodo and D. Hawksw., *Rhizocarpon superficiale* (Schaerer) Malme and *R. geographicum* DC, and several species of *Acarospora* and *Buellia*) are relatively widespread in coastal ice-free areas. Sites with substrates influenced by seabirds are colonized by well-developed communities of nitrophilous lichen species (e.g., *Caloplaca athallina* Darb., *C. citrina* (Hoffm.) Th.Fr., *Candelariella flava* (C.W. Dodge and C.E. Baker) Castello and Nimis, *Lecanora expectans* Darb., *Physcia caesia* (Hoffm.) Fűrnrrohr, *P. dubia* (Hoffm.) Lettau, *Rhizoplaca melanophthalma* (Ram.) Leuck. and Poelt, *Xanthoria elegans* (Link.) Th.Fr., *X. mawsonii* C.W. Dodge). A rich lichen flora (by continental Antarctic standards) has been described at Cape Hallett (Murray, 1963), Birthday Ridge (Kappen, 1985), Harrow Peaks (Lewis Smith, 1997), Crater Cirque, Cape King, Vegetation Island, Prior Island (Castello, 2003), with a large number of circumpolar or wide-distributed species, some of which (e.g., *Buellia subfrigida* May. Inoue, *Lecanora physciella* (Darb.) Hertel or *Lecidea andersonii* Filson) are known from geographically very distant areas.

During the 1990s Italian researchers collected about 400 lichen samples from 41 localities between Hallett Peninsula and Starr Nunatak (between 72°–76°S and 162°–170°E). The nVL lichen flora contains at least 23 genera (all of them widespread in both hemispheres), and 57 taxa. Among the 51 identified species, 10 were continental endemic, 26 were Antarctic–subantarctic in distribution, one Antarctic–South American, 16 species were bipolar,

and seven cosmopolitan. Most taxa are crustose (47), seven are foliose and three fruticose (Castello, 2003). The collection has also been used for the revision of some critical taxa such as yellow *Acarosporaceae* (Castello and Nimis, 1994a), *Candelariella* (Castello and Nimis, 1994b), *Usnea* (Walker, 1985) and *Sarcogyne* (Seppelt et al., 1998) and to prepare a database of nVL lichens and a preliminary key for their identification (Castello and Nimis, 2000).

Taxonomic uncertainties and the lack of comprehensive surveys make any rigorous comparison of lichen and moss diversity between nVL and sVL exceedingly difficult. Most moss and lichen species in nVL possess physiological attributes to allow their colonization and survival throughout VL coastal ice-free areas (Green et al., 2000; Kappen and Schroeter, 1997; Kappen and Valladares, 1999; Pannewitz et al., 2005; Schlenzog and Schroeter, 2000; Schlenzog et al., 2004). The lichen diversity (about 31 species) of Ross Island (e.g. Longton, 1973) and Granite Harbour (Seppelt et al., 1995, 1996) is comparable to that in coastal areas of nVL with similar substrates. Among mosses only *S. princeps* and *P. nutans* have not been reported from sVL. However, *Didymon brachyphyllus* (Sull.) R.H. Zander (formerly known in Antarctica as *D. gelidus* Card.) seems to occur only in sVL. The liverwort *C. varians (exiflora)* is known from Botany Bay, Granite Harbour (Seppelt and Green, 1998).

The main difference between ice-free areas in sVL and those in nVL is the reduced variety of habitats and lower free water availability in the former region. Most ice-free areas in sVL are localized far from the coast, have low free water availability, lack concentrations of breeding sea birds (nitrogen and sea salts input), and are less diverse geologically. While in nVL communities of epi-, chasmo-, and hypolithic lichens predominate on the widespread igneous and metamorphic substrates that are generally of low porosity, the porous sedimentary rocks of the Beacon Supergroup found in the extreme desert conditions of the Dry Valleys support a suite of endo- and chasmolithic species. Lichens fill the interstitial spaces beneath the surface of the porous rock and grow between and around crystals. They lose their distinctive morphology and usually do not form reproductive structures (i.e., their taxonomic identification becomes exceedingly difficult). On granitic or metamorphic substrates in the Dry Valleys, the occurrence of chasmolithic and crustose taxa is, to a large extent, determined by moisture availability (in the form of cloud condensates and snow). In the Dry Valleys the normally epilithic lichen species (*Acarospora gwynnii* C.W. Dodge and E.D. Rudolph, *Buellia frigida* Darb., *B. grisea* C.W. Dodge and G.E. Baker, *B. pallida* C.W. Dodge and G.E. Baker, *C. vorticosa* (Flörke) Hertel (formerly *Carbonea capsulata* (C.W. Dodge and G.E. Baker) Hale), *Lecanora fuscobrunnea* C.W. Dodge and G.E. Baker, *L. cancriformis* C.W. Dodge and G.E. Baker, and *Lecidella (Lecidea) siplei* (C.W. Dodge and G.E. Baker) May. Inoue) are found primarily in protected niches beneath the rock surface occupying a cryptoendolithic ecological niche (Nienow and

Friedmann, 1993). Although it was assumed that along VL environmental–climatic gradients, there are also gradients of lichen morphological forms (Hale, 1987; Hertel, 1988), geological features rather than climatic conditions determine the occurrence of cryptoendolithic communities in nVL. They appear to be widespread in areas where suitable porous sandstones occur (e.g. at Timber Peak), although they are conspicuously absent in sandstones at Vulcan Hills and Mt. Mackintosh.

2.5. Protozoa

Protozoa in VL soils have thus far been studied by culture methods. The water-filled soil pore spaces generally have two domains: (1) the $\leq 8 \mu\text{m}$ “protozoan region” of small pores and pore spaces inhabited by flagellates and small amoebae; and (2) the $> 8 \mu\text{m}$ “protozoan-nematode” domain of larger pores and pore spaces inhabited by all groups of protozoa, nematodes, rotifers, and tardigrades (Bamforth, 1985). VL protozoa are essentially limited to flagellates, small amoebae and a few ciliates, and were found in 92% of samples collected from several Dry Valleys of sVL, where they were several orders of magnitude more abundant and diverse than nematodes. No endemic taxa have been found (Bamforth et al., 2005). Flagellates included *Oikomonas termo* Ehrenberg, *Bodo saltans* Ehrenberg, *B. mutabilis* Klebs, *B. edax* Kent and *Heteromita globosa* Stein. The small amoebae were of two types. The most abundant were *Acanthamoeba* and *Echinamoeba*, irregularly triangular amoebae with short subpseudopodia. The second group consisted of monopodal worm-like amoebae, the subcylindrical *Hartmanella* and *Saccaamoeba*, and the lingulate *Platyamoeba stenopodia* Page.

2.6. Tardigrada

Tardigrades (water bears) are widely distributed in soils, cryptogamic vegetation and freshwaters across Antarctica (Block, 1984; Convey, 2001), but few specific studies have been made on Antarctic (including VL) taxa. In VL, tardigrades are found primarily in moist or wet soils (Wall Freckman and Virginia, 1998). Identification by non-specialists is difficult, and many taxonomic issues remain unresolved. Their presence in VL and elsewhere in the Ross Sea sector of Antarctica was noted by some of the earliest scientific expeditions (Richters, 1909; Murray, 1910), and during predominantly American terrestrial biological surveys during the 1960s (Armitage and House, 1962; Dougherty and Harris, 1963; Janetschek, 1967), but more thorough taxonomic evaluations of tardigrades from VL have been published over the two decades (Binda and Pilato, 1992, 1994, 2000; Pilato and Binda, 1990, 1997, 1999). Thus, reliable taxonomic knowledge is extremely limited, while distributional data are effectively restricted to the specific collection localities in which specialists have collected material or to one or two specific expeditions (e.g. Cathey et al., 1981). Other studies (e.g. Schwarz et al.,

1993; Suren, 1990) often only give general reference to location (“Victoria Land”) or do not identify specimens beyond genus.

Other than the critical taxonomic studies carried out in the region of Terra Nova Bay (nVL) most records would now appear to require taxonomic confirmation. These studies give the greatest recorded species diversity for this region (seven species; for comparison, approximately 18 tardigrade taxa have been reported across the continental Antarctic (Convey and McInnes, 2005)), but comparable data are lacking from elsewhere. One species (*Acutuncus antarcticus* Richters 1904) is currently recorded from both nVL and sVL. Species reported from nVL include *Minibiotus furcatus* Ehrenberg 1859, *M. vinciguerrae* Binda and Pilato 1992 (Binda and Pilato, 1992); *Macrobiotus mottai* Binda and Pilato 1994 (Binda and Pilato, 1994), *Diphascion (Adropion) tricuspdatum* Binda and Pilato 2000, *A. antarcticus* (Binda and Pilato, 2000), *Ramazzottius frigidus* Pilato and Binda 1992 (Pilato and Binda, 1990), *Diphascion (Diphascion) polare* Pilato and Binda 1999, *D. (D.) dastychi* Pilato and Binda 1999 and *D. (D.) victoriae* Pilato and Binda 1999 (Pilato and Binda, 1999).

Species reported from sVL (including some coastal areas that are close to, but not circumscribed within sVL as defined in the current paper—including Dailey Island, McMurdo Sound, Blue Lake, Terraced Lake, and Ross Island) include: *A. antarcticus* (Cathey et al., 1981); *Macrobiotus* sp., *Hypsibius convergens* Urbanowicz 1925, *Hypsibius* cfr *mertoni simoizumii*, *Hypsibius (Diphascion) scoticus* Murray 1905 \equiv *Diphascion (Adropion)* sp; *Hypsibius (Diphascion)* sp. (Janetschek, 1967); *Macrobiotus arcticus* \equiv *A. antarcticus*; *Macrobiotus* cfr *polaris*; *Macrobiotus oberhäuseri* Doyère 1840 \equiv *Ramazzottius oberhäuseri*; *Diphascion alpinum* Murray 1906 \equiv *Diphascion (Diphascion)* sp.; *Diphascion (?)* sp \equiv ?*Hebesuncus* sp (Murray, 1910). From the McMurdo Dry Valleys area, *Hypsibius alpinus* \equiv *Diphascion (Diphascion)* sp.; *Hypsibius arcticus* \equiv *A. antarcticus*; *Hypsibius oberhäuseri* \equiv *Ramazzottius* sp.; *Macrobiotus polaris* (Dougherty and Harris, 1963) have been recovered. Porazinska et al. (2004) found tardigrades (*A. antarcticus* and *Hypsibius* spp.) in cryoconite holes of glaciers in Taylor Valley, always in the presence of rotifers. It should be emphasized that most of these records have not been subjected to recent critical taxonomic re-evaluation.

2.7. Rotifera

Murray (1910) provided one of the earliest reports of rotifers in VL, observing 15 species (four Monogononta and 11 Bdelloidea) in lakes of McMurdo Sound area, sVL. Further sampling of the lakes in this area added only a few additional species (Armitage and House, 1962; Dougherty and Harris, 1963; Spurr, 1975; Laybourn-Parry et al., 1997). Porazinska et al. (2004) reported two rotifer species (*Philodina gregaria* Murray 1910 and *Cephalodella catellina* Muller 1786) from cryoconite holes located on five glaciers

(Commonwealth, Canada, Howard, Hughes and Taylor) in sVL. However, despite the apparent similarities between cryoconite sediment and soil, the biotic community consisted of species typical of lake and stream sediment (Porazinska et al., 2004), thus the occurrence of these rotifer species in Antarctic soils remains uncertain. In a study that identified terrestrial rotifers to species in VL, three species (*Philodina* sp., *Habrotrocha* sp. and *Epiphanes* sp.) were found in moss-dominated moist soil near Canada Glacier, sVL (Schwarz et al., 1993). Despite the paucity of data on rotifer species occurrence, it is evident that as a taxon rotifers are widely distributed across VL soils, having been observed in southern (e.g. Wall Freckman and Virginia, 1998) and northern regions (Adams and Wall, unpubl.), as well as on nearby islands (Sinclair and Sjørnsen, 2001; Porazinska and Wall, 2002). Clearly we currently have very limited knowledge of the diversity of rotifers in VL. Several studies have reported total numbers of rotifers (albeit typically not identified to species) across a range of habitats and environmental gradients. However, since all published studies are limited to sVL it is impossible to determine broad scale distributional patterns. Rotifers, like most terrestrial invertebrates in Antarctica, are patchily distributed. For instance, they were found in only 4–14% of soil samples collected from the Dry Valleys, sVL (Wall Freckman and Virginia, 1998) and, although they were consistently found in penguin rookeries on Ross Island, near sVL, there was much spatial and temporal variation in abundance within each rookery (Porazinska and Wall, 2002). Soil moisture appears to be an important driver of rotifer abundance; Schwarz et al. (1993) reported a three-fold increase in their abundance after glacial melt water had moistened soil and Treonis et al. (1999) observed greater populations of rotifers in stream sediments than in soils 8–32 m from the stream. In contrast, Sinclair and Sjørnsen (2001) found no relationship between rotifer abundance and soil moisture, but a positive correlation with soil organic matter was observed. These differences may be due to differences in habitat between coastal nVL and the Dry Valleys of sVL. In cryoconite holes rotifer abundance decreased with elevation, and variation in rotifer abundance was explained by differences in pH, nutrient availability and hole diameter (Porazinska et al., 2004). At a larger scale (10–50 km), Courtright et al. (2001) demonstrated variation in rotifer abundance along three valleys in sVL, generally with greater abundances further up the valley although it is not clear what caused this pattern.

2.8. Nematoda

The British Discovery expedition of 1901–1903 yielded the first nematode specimens from VL, collected near Discovery Bay, sVL. Steiner (1916) later described the specimens as *Dorylaimus antarcticus* (syn. *Eudorylaimus antarcticus* Yeates, 1970) but over 50 years passed before taxonomic work on the nematodes of VL was resumed (Yeates, 1970; Timm, 1971).

Nematodes are the most commonly encountered and abundant metazoans of VL soils (Wall Freckman et al., 1997; Wall Freckman and Virginia, 1998). However, identification by non-specialists is difficult, and the taxonomic status of many VL species is currently unresolved. The most geographically ubiquitous and taxonomically stable of the VL soil nematodes is *Scottinema lindsayae* Timm 1971. *S. lindsayae* is present throughout VL where it tolerates a wide range of soil moisture and geochemical conditions. Species of the genus *Plectus* have been reported from north and south VL; *P. antarcticus* de Man 1904 Timm 1971, *P. frigophilus* Kirjanova 1958, and *P. accuminatus* Bastian 1865. All three purportedly occur in coastal nVL (Terra Nova Bay; Vinciguerra, 1994) whereas only *P. antarcticus* and *P. accuminatus* have been reported from sVL where they are common in wet soils near streams and lakes. However, it has been suggested that *P. antarcticus* occurs only in maritime Antarctica, and that specimens identified as *P. antarcticus* in VL are *P. murrayi* Yeates 1970 (Andrássy, 1998; see also Maslen and Convey, this volume).

E. antarcticus Steiner 1916, *E. shirasei* Kito, Shishida and Ohyama 1996, and *E. glacialis* Andrásy 1998 have been reported throughout VL where they occur in moist soils and stream and lake sediments. However, the taxonomic identity of *E. antarcticus* reported from ecological studies done in the Dry Valleys of sVL has been questioned, with the suggestion that they are more likely *E. glacialis* or *E. shirasei* (Andrássy, 1998). *Geomonhystera antarctica* Andrásy 1998 has been recovered from moist soils in sVL, but it is not yet clear whether these populations represent one or more species. They are very rare and patchily distributed in the Dry Valleys of sVL, and occur in greater abundance in the wetter, more productive coastal nVL soils of Edmonson Point and Cape Hallett. *Panagrolaimus davidi* Timm 1971 has been recorded primarily from coastal regions of VL, and is both common and abundant in moist, productive environments. It is only rarely encountered in Dry Valley soils of sVL.

In the Dry Valley soils of sVL, *Plectus*, *Eudorylaimus* and *Scottinema* have been shown to have distributions that are sensitive to available moisture, pH, EC (electrical conductivity), and inorganic C (Freckman and Virginia, 1997; Powers et al., 1998; Treonis et al., 1999; Virginia and Wall, 1999; Courtright et al., 2001; Porazinska and Wall, 2002). The definitive taxonomic treatise on the diversity of VL nematofauna remains the treatment of Andrásy (1998). However, constraints on the condition, number, and geographic representation of the specimens examined by Andrásy (1998) indicate the need for careful taxonomic studies that encompass a larger number of specimens sampled across a broader range of environmental gradients, particularly for *Plectus*, *Geomonhystera* and *Eudorylaimus*.

2.9. Arthropoda

Springtails (Collembola), and mites (Acari), are the largest endemic terrestrial invertebrates, indeed the largest

year round terrestrial animals, found in VL and the Queen Maud Mountains (Wise, 1967; Stevens et al., 2002a). They have received attention from a number of researchers owing to their relatively conspicuous nature and presence in locations of historical importance. For example, some of the first springtails collected in VL were during the British Antarctic Expedition, 1898–1900, and again during the British National Antarctic Expedition, 1901–1904 (see Wise, 1967; Stevens et al., 2006a). Accordingly, their diversity is relatively well known, and their distribution is known to be limited to areas of high soil moisture and/or access to water, such as streams, or snow meltwater (see Kennedy, 1993; Hogg and Stevens, 2002). They are found throughout nVL and sVL (including the Dry Valleys), and as far south as the Queen Maud Mountains (see also Sinclair and Stevens, 2006). Their taxonomic diversity is limited in VL (seven species of springtail and ten species of mites), although three species of springtail (all endemic) and four species of mites (two endemic) are found in the less studied vicinity of the Queen Maud Mountains.

Distinct biogeographic breaks occur in the distribution of arthropods in VL, and indeed the Ross Dependency. The Drygalski ice tongue corresponds to a major biogeographic break separating northern from southern VL biota. Northern VL contains the greatest species diversity for both springtails and mites. Of the ten mite species in nVL, six are endemic (three are cosmopolitan) and three are shared with sVL, where only one of the four sVL species is endemic (*Coccorhagidia keithi*). The two main species of springtails found in nVL are *Desoria klovstadi* Carpenter 1902 and *Gressittacantha terranova* Wise 1967, both belonging to the Isotomidae. The distribution of *D. klovstadi* covers the northern part of the VL, from Cape Adare to the northern margins of the Mariner Glacier (Wise, 1967, 1971; Frati et al., 1997; Stevens et al., 2006a). The presence of *D. klovstadi* ends abruptly at the Mariner Glacier, and south of this glacier, it is replaced by *G. terranova* as the most abundant collembolan. The distribution of *G. terranova* is mainly restricted to the area from the Mariner Glacier to the David Glacier, although a partial overlap with *D. klovstadi* has been reported with few specimens collected at Crater Cirque and Football Saddle (Frati et al., 1997). A detailed survey using genetic markers (Fanciulli et al., 2001) shows the populations of *G. terranova* are arranged in three genetically distinct groups, each one limited by major glacier systems (the Aviator and the Campbell Glaciers) and with very little gene flow among them. A third collembolan relatively common in nVL (but not as common as *D. klovstadi* or *G. terranova*) is the neanurid *Friesea grisea* Schäffer 1891. Its distribution is scattered, and records are available from Cape Hallett in the north (Wise, 1967, 1971), to the Tinker Glacier in the south (Frati et al., 1997), but it is also known from outside the region (see Stevens and Hogg, 2006a). The fourth collembolan species inhabiting nVL is the isotomid *Cryptopygus cisantarcticus* Wise 1967. This species has been recorded from the Cape Hallett area (Wise and

Shoup, 1967), Crater Cirque and Cape Phillips (Wise, 1967, 1971), but in terms of abundance it is always outnumbered by the sympatric *D. klovstadi*.

In sVL, the springtail *Gomphiocephalus hodgsoni* Carpenter 1908 and the mite *Stereotydeus mollis* Womersley and Strandtmann, 1963 are by far the most widely distributed species. Both species show highest levels of genetic diversity in the McMurdo Dry Valleys (e.g. Stevens and Hogg, 2003; Stevens and Hogg, 2006). Two other species of springtail (*Neocryptopygus nivicolus* Salmon, 1965, *Antarcticinella monoculata* Salmon, 1965) and three other species of mite (*C. keithi* Strandtmann, 1967, *Tydeus setsukoae* Strandtmann, 1967, *Nanorchestes antarcticus* Strandtmann, 1967) have more restricted distributions, and in some cases are known only from one or two sites (e.g. Strandtmann, 1967; Wise, 1967, 1971). This pattern is repeated further south in the Queen Maud Mountains. Of the mites, three species are common across nVL and sVL, and two of these are also found further south in the Queen Maud Mountains. No springtails are common across these three regions (see Table 1, Sinclair and Stevens, 2006).

3. Discussion

To date, biotic surveys of VL have focused on highly localized populations. Sampling effort has been greatest for the microarthropods, but even this has been targeted at relatively few locations in VL. The proportion of known to unknown taxa found in studies of other groups appears to decrease in relation to sampling effort and body size. Microeukaryotes and prokaryotes are two of the most understudied groups, yet are likely the most diverse. A similar trend is seen in respect to endemism. Species endemic to VL are rare; endemism is highest for microarthropods and nematodes, less so for tardigrades and rotifers, and (based on present data) very low for mosses, lichens, microeukaryotes and prokaryotes.

The presence of a wide range of taxa in VL terrestrial ecosystems indicates that soil habitats are diverse in the region and vary spatially across broad and often steep environmental gradients. Several VL taxa appear to have localized distributions associated with highly specific soil properties. A general observation is that diversity appears to vary from low to high across a latitudinal gradient from sVL to nVL, and this is broadly associated with increased ecosystem productivity (Barrett et al., 2006). Another trend indicates an increase in diversity with available soil moisture, soil carbon and moderate salinities. For example, microarthropods and nematodes seem to follow these patterns of abundance and diversity across all three gradients. However, such generalizations are yet to be examined rigorously in functional or comparative community contexts (e.g. latitudinal differences in biodiversity are not observed among penguin rookery soils).

Regardless of sampling intensity and taxonomic work, links between taxa and their functional contribution to ecosystems have not been adequately explored for the

majority of VL taxa. VL soil food webs are likely among the simplest on the planet, yet the existence or importance of trophic relationships among the majority of taxa are still unknown, as are their net contribution to ecosystem functioning (see Hogg et al., this volume). Novel trophic relationships for metazoans are still emerging, and at present most of these relationships are only inferred or predicted based on similarities with better characterized, but non-indigenous taxonomic groups. In particular, trophic relationships between microscopic eukaryotes and other VL soil biota are very poorly known, yet could be major contributors to key soil processes. Future work will require careful observation of these taxa in situ (where possible), and will take advantage of approaches that trace resource pulses through food webs. Additionally, species' contributions to ecosystem functioning vary spatially and temporally, and the distinction between functional (active) and non-functioning (inactive) taxa must be made. For example, numerous taxa may persist in a cryptobiotic state without contributing to ecosystem processes during a given environmental extreme (e.g., of altered temperature, moisture or salinity). Approaches that fail to distinguish active from inactive species artificially inflate the number of taxa involved in ecosystem functioning at any one time, and mask the role played by what may be more vulnerable species (including endemics), which are interpreted as being redundant.

Existing studies of taxonomy and distribution serve largely to illustrate the gaps remaining in contemporary knowledge, rather than allowing biogeographical analyses and patterns to be used with any level of confidence. Furthermore, most of what is known of the biodiversity and distribution of VL biota exists in an evolutionary and ecological vacuum. Surveys and inventories to date have been taxon specific, and there have been no coordinated, integrated all-taxon inventories of these species as they exist in their respective communities. Taxon specific surveys are often devoid of any phylogenetic context (but see Stevens et al., 2006b), which restricts what can be logically inferred about their historical biogeography or how they came to be distributed and structured into their present communities. Syntheses of multi-species phylogeographies with geophysical variables will allow for more precise tests of what drives patterns of diversification and distribution of VL biota (for example, Lapointe and Rissler, 2005; Stevens et al., 2006b).

There are clear community differences in some groups (particularly the arthropods) between nVL and sVL, although whether these can simply be related to latitudinal (proxy for environmental) gradients or are a more fundamental indicator of historical processes through vicariance remains an area of active research (e.g. Stevens and Hogg, 2003; Stevens et al., 2006b; Stevens and Hogg, 2006b). As yet, there remains a virtually complete absence of detailed autecological studies of specific taxa across all functional groups, with assessments of the existence and importance of ecological function largely being little more

than inference, based on knowledge of related taxa or comparable communities elsewhere.

Sampling effort has varied widely across groups, currently being greatest (but still inadequate) for microarthropods, mosses and lichens. Likewise, molecular taxonomic approaches have so far focused mostly on limited representatives of the microarthropods, and there is a clear and urgent need to apply these more widely, in concert with classical taxonomic and autecological approaches, across the various higher taxa. Such studies are an urgent requirement, not least, so as to provide the requisite baseline against which to monitor the consequences of regional and global change on ecosystems within VL. They will also allow accurate assessment in the virtually unaddressed field of cryptic speciation.

Amongst the fauna, the ubiquity and abundance of protozoa (predominantly flagellates and small amoebae), compared to metazoans emphasizes their importance in food webs and nutrient cycling in this most extreme ecosystem on Earth. However, the metazoans have received considerably more attention, both in VL and more widely across the Antarctic. To exist in these extreme environments, fauna, algae, mosses and lichens have survival strategies that allow them to persist across a wide range of habitats, alone and as communities. Across the Dry Valleys, for example, well-developed communities of many invertebrate taxa can be found close to soils in which no invertebrates exist. These patterns also occur at broader scales, where 40% of the soils are without nematodes, and some soils harbor no fauna at all.

Our present knowledge of the diversity and abundance of biota in VL is extremely limited, and in need of coordinated, rigorous sampling. Based on trends of previous efforts in temperate ecosystems, campaigns may (a) reveal new species, (b) aid in resolving taxonomic problems and (c) extend the known ranges of species further south. Even soil algae, which have the highest recorded diversity (about 300 taxa), have yet to be examined in many remote sites. The application of molecular phylogenetic techniques will doubtless considerably advance knowledge of faunal, algal, lichen and microbial phylogeny and cryptic speciation. Comprehensive biogeographical research will allow the recognition of hot-spots of biodiversity. Even where there is much known about the distribution on continental and polar scales, such as with lichens and mosses, there is a need for adding to the knowledge of the factors limiting distribution. The lichen and moss flora of VL is characterized by the occurrence of many circum-Antarctic species and, in spite of a high incidence of endemic lichens in the Antarctic as a whole (about 50%, Øvstedal and Lewis Smith, 2001), it also shows clear affinities with the Arctic flora (about 27% of bipolar elements for the lichens). However, these data are not definitive because of the relatively poor knowledge of species distribution and the taxonomic uncertainty of many taxa. Without the identification to species levels of all taxa and critical revision of many widespread genera (which are

very polymorphic, and often have closely related counterparts in the Northern Hemisphere), it is impossible to compare the lichen and moss diversity and distribution in nVL and sVL ice-free areas. On the basis of current data, there seems to be very little systematic difference in lichen or moss diversity between nVL and sVL, except for the Dry Valleys region, which has peculiar geological and climatic features.

A combination of classical and modern research techniques, including support for the preparation of specific monographs and reliable and user-friendly identification keys, the proper deposition of descriptions, and the curation and accessibility of type collections, all in close integration with molecular approaches (both phylogenetic and population genetic), are required and should attract and involve wider interaction across appropriate specialists at a global scale. Molecular tools will facilitate efforts to explore the diversity and function of these groups, but these tools need to be applied to all VL taxonomic groups in order to resolve nomenclatural problems, aid identification, reveal cryptic species, and provide information about population processes, such as effective size, structure, dispersal and gene flow. These data also are amenable to statistical and comparative phylogeographic studies, which can reveal the concerted response of species and communities to the historical environmental changes that have shaped their present distributions. In the near future, technical advances will allow expression arrays of numerous taxa to be established for some of the gene products involved in fundamental soil ecosystem processes, such as nitrogen mineralization, catabolism of carbon substrates, and sulfur reduction. With replication and rigorous statistical analysis, comparisons among species, and not just different soil communities, will become possible allowing assessment of the relative contributions of not just functional groups, but individual species, to ecosystem processes.

Understanding the relationship between soil biodiversity and ecosystem functioning remains a huge obstacle to predicting the global effects of environmental change. Integrated studies of the relationship between soil biodiversity and ecosystem functioning generally requires a comprehensive and integrated compilation of the species that participate in soil ecosystem processes, their distribution, and limits to distribution, across regional and landscape scales, something which is currently achievable in VL with the resources, tools, and expertise currently available. Because VL is a microcosm of more diverse and complex temperate and tropical ecosystems, the knowledge gained would be of great benefit for biodiversity and ecosystem dynamics (Wall 2004, 2005). Additionally, given the sensitivity of polar ecosystems to environmental change (Freckman and Virginia, 1997; Convey, 2003; Wall, 2005, 2006), a comprehensive baseline knowledge of VL biota and how it is distributed will allow for the monitoring of environmental changes to VL soil ecosystems in real time and space. As such, and with concerted funding and

focused international collaboration, the soil ecosystems of VL are well positioned to play a major role in resolving some of the most pressing ecological issues we face.

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References

- Adams, B.J., 1998. Species concepts and the evolutionary paradigm in modern nematology. *Journal of Nematology* 30, 1–21.
- Alfinito, S., Fumanti, B., Cavacini, P., 1998. Epiphytic algae on mosses from Northern Victoria Land (Antarctica). *Nova Hedwigia* 66, 473–480.
- Alger, A.S., McKnight, D.M., Spaulding, S.A., Tate, C.M., Shupe, G.H., Welch, K.A., Edwards, R., Andrews, E.D., House, H.R., 1996. Ecological processes in a cold desert ecosystem: the abundance and species distribution of algal mats in glacial meltwater streams in Taylor Valley, Antarctica. *Institute of Arctic and Alpine Research Occasional Paper* 51, 1–102.
- Anagnostidis, K., Komárek, J., 1988. Modern approach to the classification system of cyanophytes. 3. Oscillatoriales. *Algalogical Studies* 50–53, 327–472.
- Andrassy, I., 1998. Nematodes in the sixth continent. *Journal of Nematode Morphology and Systematics* 1, 107–186.
- Armitage, K.B., House, H.B., 1962. A limnological reconnaissance in the area of McMurdo Sound, Antarctica. *Limnology and Oceanography* 7, 36–41.
- Atlas, R.M., DiMenna, M.E., Cameron, R.E., 1978. Ecological investigations of yeasts in Antarctic soils. *In: Packer, B.C. (Ed.), Terrestrial Biology III, Antarctic Research Series. The William Byrd Press, Richmond, VA, pp. 27–34.*
- Bamforth, S.S., 1985. Symposium on “Protozoan Ecology”: the role of protozoa in litters and soils. *Journal of Protozoology* 32, 404–409.
- Bamforth, S.S., Wall, D.H., Virginia, R.A., 2005. Distribution and diversity of soil protozoa in the McMurdo Dry Valleys of Antarctica. *Polar Biology* 28, 756–762.
- Bargagli, R., Wynn-Williams, D., Bersan, F., Cavacini, P., Ertz, S., Frati, F., Freckman, D., Smith, R.L., Russell, N., Smith, A., 1997. Field report, Biotex 1: first BIOTAS expedition (Edmonson Point—Baia Terra Nova, Dec. 10, 1995–Feb. 6, 1996). *In: Newsletter of the Italian Biological Research in Antarctica, pp. 42–58.*
- Barrett, P.J., Bleakley, N.L., Dickinson, W.W., Hannah, M.J., Harper, M.A., 1997. Distribution of siliceous microfossils on Mount Feather, Antarctica, and the age of the Sirius group. *In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. Terra Antarctica Publication, Siena, pp. 763–770.*
- Barrett, J.E., Virginia, R.A., Wall, D.H., Parsons, A.N., Powers, L.E., Burkins, M.B., 2004. Variation in biogeochemistry and soil biodiversity across spatial scales in a polar desert ecosystem. *Ecology* 85, 3105–3118.
- Barrett, J.E., Virginia, R.A., Hopkins, D.W., Aislabie, J., Bargagli, R., Bockheim, J.G., Campbell, I.B., Lyons, W.B., Moorhead, D., Nkem, J., Sletten, R.S., Steltzer, H., Wall, D.H., Wallenstein, M., 2006. Terrestrial ecosystem processes of Victoria Land, Antarctica. *Soil Biology and Biochemistry*, this issue (doi:10.1016/j.soilbio.2006.04.041)
- Baublis, J.A., Wharton, R.A.J., Volz, P.A., 1991. Diversity of micro-fungi in an Antarctic dry valley. *Journal of Basic Microbiology* 31, 11–20.

- Bednarek-Ochyra, H., Váňa, J., Ochyra, R., Smith, R.I.L., 2000. The Liverwort Flora of Antarctica. Institute of Biology, Polish Academy of Science, Cracow, 236pp.
- Bernard, E.C., 1992. Soil nematode biodiversity. *Biology and Fertility of Soils* 14, 99–103.
- Binda, M.G., Pilato, G., 1992. *Minibiotus furcatus*, nuova posizione sistematica per *Macrobotus furciger* Ehrenberg, 1859, e descrizione di due nuove specie (Eutardigrada). *Animalia* 19, 111–120.
- Binda, M.G., Pilato, G., 1994. *Macrobotus mottai*, nuova specie de eutardigrado dell' Antartide. *Animalia* 21, 56–66.
- Binda, M.G., Pilato, G., 2000. *Diphascion (Adropion) tricuspdatum*, a new species of eutardigrade from Antarctica. *Polar Biology* 23, 75–76.
- Blackmore, S., 1996. Knowing the earth's biodiversity: challenges for the infrastructure of systematic biology. *Science* 274, 63–64.
- Block, W., 1984. Terrestrial microbiology, invertebrates and ecosystems. In: Laws, R.M. (Ed.), *Antarctic Ecology*. Academic Press, London, pp. 163–236.
- Broady, P.A., 1985. A preliminary report of phycological studies in Northern Victoria Land on Ross Island during 1984–85. In: Melbourne University Programme in Antarctic Studies. Melbourne University, Melbourne, p. 132.
- Broady, P.A., 1987. A floristic survey of algae at four locations in Northern Victoria Land. *New Zealand Antarctic Record* 7, 8–19.
- Broady, P.A., 1993. Soils heated by volcanism. In: Friedmann, E.I. (Ed.), *Antarctic Microbiology*. Wiley-Liss, New York, pp. 413–432.
- Broady, P.A., 1996. Diversity, distribution and dispersal of Antarctic terrestrial algae. *Biodiversity and Conservation* 5, 1307–1335.
- Broady, P.A., Weinstein, R.N., 1998. Algae, lichens and fungi in La Gorce Mountains, Antarctica. *Antarctic Science* 10, 376–385.
- Broady, P., Given, D., Greenfield, L., Thompson, K., 1987. The biota and environment of fumaroles on Mt. Melbourne, Northern Victoria Land. *Polar Biology* 7, 97–113.
- Brooks, D.R., McLennan, D.A., 2002. *The Nature of Diversity: An Evolutionary Voyage of Discovery*. University of Chicago Press, Chicago, 668pp.
- Burkins, M.B., Virginia, R.A., Wall, D.H., 2001. Organic carbon cycling in Taylor Valley, Antarctica: quantifying soil reservoirs and soil respiration. *Global Change Biology* 7, 113–125.
- Cameron, R.E., Honour, R.C., Morelli, F.A., 1977. Environmental impact studies of Antarctic sites. In: Llano, G.A. (Ed.), *Adaptations within Antarctic Ecosystems*. Smithsonian Institution, pp. 1157–1176.
- Cardot, J., 1907. Musci. In: National Antarctic Expedition, 1901–1904: Natural History. British Museum, London, pp. 1–6.
- Cardot, J., 1910. Musci. Note sur les mousses rapportées par l'Expédition du "Nimrod". In: Murray, J. (Ed.), *British Antarctic Expedition 1907–1909 under the command of Sir E.H. Shackleton, CVO*. William Heinemann, London, pp. 77–79.
- Castello, M., 2003. Lichens of the Terra Nova Bay Area, northern Victoria Land (continental Antarctica). *Studia Geobotanica* 22, 3–54.
- Castello, M., Nimis, P.L., 1994a. Critical Notes on Antarctic Yellow Acarosporaceae. *Lichenologist* 26, 283–294.
- Castello, M., Nimis, P.L., 1994b. Critical notes on the genus *Candelariella* (Lichenes) in Antarctica. *Acta Botanica Fennica* 150, 5–10.
- Castello, M., Nimis, P.L., 1995. A critical revision of Antarctic lichens described by C.W. Dodge. *Bibliotheca Lichenologica* 57, 71–92.
- Castello, M., Nimis, P.L., 2000. A key to the lichens of Terra Nova Bay (Victoria Land, Continental Antarctica). *Italian Journal of Zoology* 67, 175–184.
- Cathey, D.D., Parker, B.C., Simmons Jr., G.M., Yongue Jr., W.H., Van Brunt, M.R., 1981. The microfauna of algal mats and artificial substrates in Southern Victoria Land Lakes of Antarctica. *Hydrobiologia* 85, 3–15.
- Cavacini, P., 2001. Soil algae from northern Victoria Land (Antarctica). *Polar Bioscience* 14, 45–60.
- Connell, L., Redman, R., Craig, S., Rodriguez, R., 2006. Distribution and abundance of fungi in the soils of Taylor Valley, Antarctica. *Soil Biology and Biochemistry* 38, this issue (doi:10.1016/j.soilbio.2006.02.016)
- Convey, P., 2001. Antarctic ecosystems. In: Levin, S.A. (Ed.), *Encyclopedia of Biodiversity*. Academic Press, San Diego, pp. 171–184.
- Convey, P., 2003. Maritime Antarctic climate change: signals from terrestrial biology. In: Domack, E., Burnett, A., Leventer, A., Convey, P., Kirby, M., Bindschadler, R. (Eds.), *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*. American Geophysical Union, Washington, DC, pp. 145–158.
- Convey, P., McInnes, S.J., 2005. Exceptional tardigrade-dominated ecosystems in Ellsworth Land, Antarctica. *Ecology* 86, 519–527.
- Courtright, E.M., Wall, D.H., Virginia, R.A., 2001. Determining habitat suitability for soil invertebrates in an extreme environment: the McMurdo Dry Valleys, Antarctica. *Antarctic Science* 13, 9–17.
- Cowan, D.A., Tow, A.L., 2004. Endangered Antarctic environments. *Annual Review of Microbiology* 58, 649–690.
- Cowan, D.A., Russell, N.J., Mamais, A., Sheppard, D.M., 2002. Antarctic Dry Valley mineral soils contain unexpectedly high levels of microbial biomass. *Extremophiles* 6, 431–436.
- Darbishire, O.V., 1910. *National Antarctic Expedition 1901–1904*. London.
- Darbishire, O.V., 1923. *British Antarctic "Terra Nova" Expedition 1910*. In: Botany, Part III, Lichens. London.
- Del Frate, G., Caretta, G., 1990. Fungi isolated from Antarctic material. *Polar Biology* 11, 1–7.
- Dodge, C.W., 1973. *Lichen Flora of the Antarctic Continent and Adjacent Islands*. Phoenix Publishing, Canaan, NH, 399pp.
- Dougherty, E.C., Harris, L.G., 1963. Antarctic micrometazoa: freshwater species in McMurdo Sound area. *Science* 140, 497–498.
- Esposito, R.M.M., Horn, S.L., McKnight, D.M., Cox, M.J., Grant, M.C., Spaulding, S.A., Doran, P.T., Cozetto, K.D., 2006. Antarctic climate cooling and response of diatoms in glacial meltwater streams. *Geophysical Research Letters* 33 (7) (doi:10.1029/2006GL025903)
- Fanciulli, P.P., Summa, D., Dallai, R., Frati, F., 2001. High levels of genetic variability and population differentiation in *Gressittacantha terranova* (Collembola, Hexapoda) from Victoria Land, Antarctica. *Antarctic Science* 13, 246–254.
- Fell, J.W., Scorzetti, G., Connell, L., Craig, S., 2006. Biodiversity of microeukaryotes in Antarctic Dry Valley soils with <5% soil moisture. *Soil Biology and Biochemistry*, this issue (doi:10.1016/j.soilbio.2006.01.014)
- Fenice, M., Selbmann, L., Zuconi, L., Onofri, S., 1997. Production of extracellular enzymes by Antarctic fungal strains. *Polar Biology* 17, 275–280.
- Fitter, A.H., Gilligan, C.A., Hollingworth, K., Kleczkowski, A., Twyman, R.M., Pitchford, J.W., 2005. Biodiversity and ecosystem function in soil. *Functional Ecology* 19, 369–377.
- Frati, F., Fanciulli, P.P., Carapelli, A., Dallai, R., 1997. The Collembola of northern Victoria Land (Antarctica): distribution and ecological remarks. *Pedobiologia* 41, 50–55.
- Freckman, D.W., Virginia, R.A., 1997. Low diversity Antarctic soil nematode communities: distribution and response to disturbance. *Ecology* 78, 363–369.
- Friedmann, E.I., Ocampo, R., 1976. Endolithic blue-green algae in the dry valleys: primary producers in the Antarctic desert ecosystem. *Science* 193, 1247–1249.
- Friedmann, E.I., Hua, M., Ocampo-Friedmann, R., 1988. Cryptoendolithic lichen and cyanobacterial communities of the Ross Desert, Antarctica. *Polarforschung* 58, 251–259.
- Fritsch, F.E., 1912. National Antarctic "Discovery" expedition 1902–1904. In: *Freshwater Algae*, vol. 6. British Museum Natural History, pp. 1–60.
- Frost, D.R., Kluge, A.G., 1994. A consideration of epistemology in systematic biology, with special reference to species. *Cladistics* 10, 259–294.
- Fumanti, B., Cavacini, P., 2005. ANTADATA: a database on biogeography of non-marine algae in continental Antarctica. CD-ROM: Casa Editrice Università "La Sapienza".

- Fumanti, B., Alfinito, S., Cavacini, P., 1995. Floristic studies on freshwater algae of Lake Gondwana, Northern Victoria Land (Antarctica). *Hydrobiologia* 316, 81–90.
- Fumanti, B., Cavacini, P., Alfinito, S., 1997. Benthic algal mats of some lakes of Inexpressible Island (northern Victoria Land, Antarctica). *Polar Biology* 17, 25–30.
- Gepp, A., 1902. Cryptogamia: Musci. In: Report on the collections of natural history made in Antarctic regions during the voyage of the "Southern Cross", vol. 21. The Trustees of the British Museum (Natural History), London, p. 319.
- Ghilselin, M.T., 1987. Species concepts, individuality, and objectivity. *Biology and Philosophy* 2, 127–143.
- Green, T.G.A., Schroeter, B., Seppelt, R.D., 2000. Effect of temperature, light and ambient UV on the photosynthesis of the moss *Bryum argenteum* Hedw., in continental Antarctica. In: Davidson, W., Howard-Williams, C., Broady, P. (Eds.), *Antarctic Ecosystems: Models for Wider Ecological Understanding*. The Caxton Press, Christchurch, New Zealand, pp. 165–170.
- Greene, S.W., 1967. Bryophyte distribution. In: Bushnell, V. (Ed.), *Terrestrial Life of Antarctica*. American Geographical Society, pp. 11–13.
- Griffiths, R.I., Manefield, M., Ostle, N., McNamara, N., O'Donnell, A.G., Bailey, M.J., Whiteley, A.S., 2004. (CO₂)-C-13 pulse labelling of plants in tandem with stable isotope probing: methodological considerations for examining microbial function in the rhizosphere. *Journal of Microbiological Methods* 58, 119–129.
- Hale, M.E., 1987. Epilithic lichens in the beacon sandstone formation, Victoria Land, Antarctica. *Lichenologist* 19, 269–287.
- Hales, B.A., Edwards, C., Ritchie, D.A., Hall, G., Pickup, R.W., Saunders, J.R., 1996. Isolation and identification of methanogen-specific DNA from blanket bog peat by PCR amplification and sequence analysis. *Applied and Environmental Microbiology* 62, 668–675.
- Heemsbergen, D.A., Berg, M.P., Loreau, M., van Haj, J.R., Faber, J.H., Verhoef, H.A., 2004. Biodiversity effects on soil processes explained by interspecific functional dissimilarity. *Science* 306, 1019–1020.
- Hertel, H., 1988. Problems in monographing Antarctic crustose lichens. *Polarforschung* 58, 65–76.
- Hirsch, P., Ludwig, W., Hethke, C., Sittig, M., Hoffmann, B., Gallikowski, C.A., 1998. *Hymenobacter roseosalivarius* gen. nov., sp. nov. from continental Antarctic soils and sandstone: bacteria of the Cytophaga/Flavobacterium/Bacteroides line of phylogenetic descent. *Systematics and Applied Microbiology* 21, 306–314.
- Hogg, I.D., Stevens, M.I., 2002. Soil fauna of Antarctic coastal landscapes. *Ecological Studies* 154, 265–282.
- Holm-Hansen, O., 1964. Isolation and culture of terrestrial and freshwater algae of Antarctica. *Phycologia* 4, 43–51.
- Hopkins, D.W., Elberling, B., Greenfield, L.G., Gregorich, E.G., Novis, P., O'Donnell, A.G., Sparrow, A.D., 2005. Soil micro-organisms in Antarctic dry valleys: resource supply and utilization. In: Gadd, G., Semple, K., Lappin-Scott, H. (Eds.), *Micro-organisms and Earth Systems—Advances in Geomicrobiology*. Cambridge University Press, Cambridge, pp. 71–84.
- Howard-Williams, C., Vincent, W.F., Broady, P.A., Vincent, W.F., 1986. Antarctic stream ecosystems: variability in environmental properties and algal community structure. *Internationale Revue Der Gesamten Hydrobiologie* 71, 511–544.
- Janetschek, H., 1967. Arthropod ecology of South Victoria Land. *Antarctic Research Series* 10, 205–293.
- Johnson, R.M., Madden, J.M., Swafford, J.A., 1978. Taxonomy of Antarctic bacteria from soils and air primarily of the McMurdo Station and Victoria Land Dry Valleys region. In: Packer, B.C. (Ed.), *Terrestrial Biology III, Antarctic Research Series*. The William Byrd Press, Richmond, VA, pp. 35–64.
- Jones, V.J., 1996. The diversity, distribution and ecology of diatoms from Antarctic inland waters. *Biodiversity and Conservation* 5, 1433–1449.
- Kappen, L., 1985. Vegetation and ecology of ice-free areas of northern Victoria Land, Antarctica. 1. The lichen vegetation of Birthday Ridge and an Inland mountain. *Polar Biology* 4, 213–225.
- Kappen, L., Schroeter, B., 1997. Activity of lichens under the influence of snow and ice. *Proceedings of the NIPR Symposium on Polar Biology* 10, 163–168.
- Kappen, L., Valladares, F., 1999. Opportunistic growth and desiccation tolerance: the ecological success of poikilohydrous autotrophs. In: Pugnaire, F.I., Valladares, F. (Eds.), *Handbook of Functional Ecology*. Marcel Dekker, New York, pp. 9–80.
- Kaspar, M., Simmons, G.M., Parker, B.C., Seaburg, K.G., Wharton, R.A., Smith, R.I.L., 1982. *Bryum* Hedw. collected from Lake Vanda, Antarctica. *Bryologist* 85, 424–430.
- Kennedy, A.D., 1993. Water as a limiting factor in the Antarctic terrestrial environment: a biogeographical synthesis. *Arctic and Alpine Research* 25, 308–315.
- Lapointe, F.J., Rissler, L.J., 2005. Congruence, consensus, and the comparative phylogeography of codistributed species in California. *American Naturalist* 166, 290–299.
- Laybourn-Parry, J., James, M., McKnight, D., Priscu, J., Spaulding, S., Shiel, R., 1997. The microbial plankton of Lake Fryxell, Southern Victoria Land, Antarctica during the summers of 1992 and 1994. *Polar Biology* 17, 54–61.
- Lewis Smith, R.I., 1997. Oases as centres of high plant diversity and dispersal in Antarctica. In: Lyons, W.B., Howard-Williams, C., Hawes, I. (Eds.), *Ecosystem Processes in Antarctic Ice-free Landscapes*. A.A. Balkema, Rotterdam, pp. 119–128.
- Logan, N.A., Lebbe, L., Hoste, B., Goris, J., Forsyth, G., Heyndrickx, M., Murray, B.L., Syme, N., Wynn-Williams, D.D., De Vos, P., 2000. Aerobic endospore-forming bacteria from geothermal environments in northern Victoria Land, Antarctica, and Candlemas Island, South Sandwich archipelago, with the proposal of *Bacillus fumarioli* sp. nov. *International Journal of Systematic and Evolutionary Microbiology* 50, 1741–1753.
- Longton, R.E., 1973. A classification of terrestrial vegetation near McMurdo Sound, continental Antarctica. *Canadian Journal of Botany* 57, 2264–2278.
- Malosso, E., English, L., Hopkins, D.W., O'Donnell, A.G., 2004. Use of ¹³C-labelled plant materials and ergosterol, PLFA and NLFA analyses to investigate organic matter decomposition in Antarctic soil. *Soil Biology and Biochemistry* 36, 165–175.
- Mercantini, R., Marsella, R., Cervellati, M.C., 1989. Keratinophilic fungi isolated from Antarctic soil. *Mycopathologia* 106, 47–52.
- Mevs, U., Stackebrandt, E., Schumann, P., Gallikowski, C.A., Hirsch, P., 2000. *Modestobacter multiseptatus* gen. nov., sp. nov., a budding actinomycete from soils of the Asgard Range (Transantarctic Mountains). *International Journal of Systematic and Evolutionary Microbiology* 50, 337–346.
- Mikola, J., Salonen, V., Setälä, H., 2002. Studying the effects of plant species richness on ecosystem functioning: does the choice of experimental design matter? *Oecologia* 133, 594–598.
- Murray, J., 1910. Tardigrada, British Antarctic Expedition 1907–1909. In: *Reports on the Scientific Investigations*, vol. I, Biology (Part V), pp. 83–187.
- Murray, J., 1963. Lichens from Cape Hallett area, Antarctica. *Transactions of the Royal Society of New Zealand, Botany* 2, 59–72.
- Nienow, J.A., Friedmann, E.I., 1993. Terrestrial lithophytic (rock) communities. In: Friedmann, E.I. (Ed.), *Antarctic Microbiology*. Wiley-Liss, New York, pp. 343–412.
- O'Brien, A., Sharp, R., Russell, N.J., Roller, S., 2004. Antarctic bacteria inhibit growth of food-borne microorganisms at low temperatures. *FEMS Microbiology Ecology* 48, 157–167.
- Ochi, H., 1979. A revision of the genus *Bryum*, Musci. In: Matsuda, T., Hoshiai, T. (Eds.), *Proceedings of the Symposium on Terrestrial Ecosystems in the Syowa Station*. National Institute of Polar Research, Tokyo, pp. 70–80.
- Ochyra, R., Zander, R.H., 2002. The genera *Didymodon* and *Bryoerythrophyllum* (Pottiaceae) in Antarctica. *Journal of Bryology* 24, 33–44.
- O'Donnell, A.G., Colvan, S.R., Malosso, E., Supaphol, S., 2005. Twenty years of molecular analysis of bacterial communities in soils and what have we learned about function? In: Bardgett, R.D., Usher, M.B.,

- Hopkins, D.W. (Eds.), Biological Diversity and Function in Soils. Cambridge University Press, Cambridge, pp. 44–56.
- Onofri, S., Tosi, S., 1992. *Arthrobotrys ferox* sp. nov. a springtail-capturing hyphomycete from continental Antarctica. Mycotaxon 44, 445–451.
- Onofri, S., Fenice, M., Cicalini, A.R., Tosi, S., Magrino, A., Pagano, S., Selbmann, L., Zucconi, L., Vishniac, H.S., Ocampo-Friedmann, R., Friedmann, F.I., 2000. Ecology and biology of microfungi from Antarctic rocks and soils. Italian Journal of Zoology 67, 163–167.
- Øvstedal, D.O., Lewis Smith, R.L., 2001. Lichens of Antarctica and South Georgia. A Guide to their Identification and Ecology. Cambridge University Press, Cambridge, 424pp.
- Pannewitz, S., Green, T.G.A., Maysek, K., Schlenz, M., Seppelt, R., Sancho, L.G., Türk, R., Schroeter, B., 2005. Photosynthetic responses of three common mosses from continental Antarctica. Antarctic Science 17, 341–352.
- Parsons, A.N., Barrett, J.E., Wall, D., Virginia, R.A., 2004. Soil carbon dioxide flux in Antarctic dry valley ecosystems. Ecosystems 7, 286–295.
- Pilato, G., Binda, M.G., 1990. Tardigradi dell'antartide. I. *Ramajendas*, nuovo genere di eutardigrado. Nuovo posizione sistematica di *Hypsibius renaudi* Ramazzotti, 1972 e descrizione di *Ramajendas frigidus* n. sp. Animalia 17, 61–71.
- Pilato, G., Binda, M.G., 1997. *Acutuncus*, a new genus of Hypsibiidae (Eutardigrada). Entomologische Mitteilungen aus dem Zoologischen 12, 159–162.
- Pilato, G., Binda, M.G., 1999. Three new species of *Diphasco* of the pingue group (Eutardigrada, Hypsibiidae) from Antarctica. Polar Biology 21, 335–342.
- Porazinska, D., Wall, D., 2002. Population age structures of nematodes in the Antarctic Dry Valleys: perspectives on time, space, and habitat suitability. Arctic, Antarctic, and Alpine Research 34, 159–168.
- Porazinska, D., Fountain, A.G., Nylén, T., Tranter, M., Virginia, R.A., Wall, D.H., 2004. The biodiversity and biogeochemistry of cryoconite holes from McMurdo dry valley glaciers, Antarctica. Arctic, Antarctic, and Alpine Research 36, 84–91.
- Powers, L.E., Ho, M.C., Freckman, D.W., Virginia, R.A., 1998. Distribution, community structure, and microhabitats of soil invertebrates along an elevational gradient in Taylor Valley, Antarctica. Arctic and Alpine Research 30, 133–141.
- Richters, F., 1909. Tardigraden unter 77°S. Br. Zoologischer Anzeiger 34, 604–606.
- Roscher, C., Schumacher, J., Baade, J., Wilcke, W., Gleixner, G., Weisser, W.W., Schmid, B., Schulze, E.D., 2004. The role of biodiversity for element cycling and trophic interactions: an experimental approach in a grassland community. Basic and Applied Ecology 5, 107–121.
- Round, F.E., Crawford, R.M., Mann, D.G., 1990. The Diatoms. Biology & Morphology of the genera. Cambridge University Press, Cambridge, 747 pp.
- Sabbe, K., Verleyen, E., Hodgson, D.A., Vanhoutte, K., Vyverman, W., 2003. Benthic diatom flora of freshwater and saline lakes in the Larsemann Hills and Rauer Islands, East Antarctica. Antarctic Science 15, 227–248.
- Schlenz, M., Schroeter, B., 2000. Poikilohydry in Antarctic cryptogams and its role for photosynthetic performance in mesic and xeric habitats. In: Davidson, W., Howard-Williams, C., Broady, P. (Eds.), Antarctic Ecosystems: Models for Wider Ecological Understanding. The Caxton Press, Christchurch, pp. 175–182.
- Schlenz, M., Pannewitz, S., Green, T.G.A., Schroeter, B., 2004. Metabolic recovery of continental Antarctic cryptogams after winter. Polar Biology 27, 399–408.
- Schwarz, A.M.J., Green, J.D., Green, T.G.A., Seppelt, R.D., 1993. Invertebrates associated with moss communities at Canada Glacier, southern Victoria Land, Antarctica. Polar Biology 13, 157–162.
- Seaburg, K.G., Parker, B.C., Prescott, G.W., Whitford, L.A., 1979. The Algae of Southern Victoria Land, Antarctica: A Taxonomic and Distributional Study. J. Cramer, Vaduz, 168pp.
- Seppelt, R.D., 1983a. *Cephalozella exiliflora* (Tayl) Steph. from the Windmill Islands, continental Antarctica. Lindbergia 9, 27–28.
- Seppelt, R.D., 1983b. The status of the Antarctic moss *Bryum korotkeviciae*. Lindbergia 9, 21–26.
- Seppelt, R.D., Kanda, H., 1986. Morphological variation and taxonomic interpretation in the moss genus *Bryum* in Antarctica. Memoirs of the National Institute of Polar Research, Tokyo Series E 37, 27–42.
- Seppelt, R.D., Green, T.G.A., 1998. A bryophyte flora for Southern Victoria Land, Antarctica. New Zealand Journal of Botany 36, 617–635.
- Seppelt, R.D., Green, T.G.A., Schwarz, A.M.J., Frost, A., 1992. Extreme southern locations for moss sporophytes in Antarctica. Antarctic Science 4, 37–39.
- Seppelt, R.D., Green, T.G.A., Schroeter, B., 1995. Lichens and mosses from the Kar Plateau, Southern Victoria Land, Antarctica. New Zealand Journal of Botany 33, 203–220.
- Seppelt, R.D., Green, T.G.A., Schroeter, B., 1996. Additions and corrections to the lichen flora of the Kar Plateau, Southern Victoria Land, Antarctica. New Zealand Journal of Botany 34, 329–331.
- Seppelt, R.D., Nimis, P.L., Castello, M., 1998. The genus *Sarcogyne* (Agarosporaceae) in Antarctica. Lichenologist 30, 249–258.
- Sinclair, B.J., Sjursen, H., 2001. Terrestrial invertebrate abundance across a habitat transect in Keble Valley, Ross Island, Antarctica. Pedobiologia 45, 134–145.
- Sinclair, B.J., Stevens, M.I., 2006. Terrestrial microarthropods of Victoria Land and Queen Maud Mountains, Antarctica: implications of climate change. Soil Biology and Biochemistry 38, this issue (doi:10.1016/j.soilbio.2005.11.035)
- Skotnicki, M.L., Selkirk, P.M., Broady, P., Adam, K.D., Ninham, J.A., 2001. Dispersal of the moss *Campylopus pyriformis* on geothermal ground near the summits of Mount Erebus and Mount Melbourne, Victoria Land, Antarctica. Antarctic Science 13, 280–285.
- Søchting, U., Seppelt, R., 2003. *Caloplaca coeruleofrigida* sp. nova, a lichen from continental Antarctica. Mycotaxon 86, 163–168.
- Spence, J.R., Ramsay, H.P., 2002. The genus *Anomobryum* Schimp. (Bryopsida, Bryaceae) in Australia. Telopea 9, 777–792.
- Spurr, B., 1975. Limnology of Bird Pond, Ross Island, Antarctica. New Zealand Journal of Marine and Freshwater Research 9, 547–562.
- Steiner, G., 1916. Beiträge zur geographischen Verbreitung freilebender Nematoden. Zoologischer Anzeiger 46, 311–355.
- Stevens, M.I., Hogg, I.D., 2002. Expanded distributional records of Collembola and Acari in southern Victoria Land, Antarctica. Pedobiologia 46, 485–495.
- Stevens, M.I., Hogg, I.D., 2003. Long-term isolation and recent range expansion from glacial refugia revealed for the endemic springtail *Gomphiocephalus hodgsoni* from Victoria Land, Antarctica. Molecular Ecology 12, 2357–2369.
- Stevens, M.I., Hogg, I.D., 2006a. Molecular ecology of Antarctic terrestrial and limnetic invertebrates and microbes. In: Bergstrom, D.M., Convey, P., Huiskes, A.H.L. (Eds.), Trends in Antarctic Terrestrial and Limnetic Ecosystems. Springer, Dordrecht.
- Stevens, M.I., Hogg, I.D., 2006b. Contrasting levels of mitochondrial DNA variability between mites (Penthalodidae) and springtails (Hypogasturidae) from the Trans-Antarctic Mountains suggest long-term effects of glaciation and life history on substitution rates, and speciation processes. Soil Biology and Biochemistry, this issue (doi:10.1016/j.soilbio.2006.01.009).
- Stevens, M.I., Fjellberg, A., Greenslade, P., Hogg, I.D., Sunnucks, P., 2006a. Redescription of the Antarctic springtail *Desoria klovstadii* using morphological and molecular evidence. Polar Biology, in press (doi:10.1007/s00300-006-0120-y)
- Stevens, M.I., Greenslade, P., Hogg, I.D., Sunnucks, P., 2006b. Examining Southern Hemisphere springtails: could any have survived glaciation of Antarctica? Molecular Biology and Evolution 23, 874–882.
- Stevens, M.I., Hunger, S.A., Hills, S.F.K., Gemmill, C.E.C., in press. Phantom hitch-hikers mislead estimates of genetic variation in Antarctic mosses. Plant Systematics and Evolution.
- Strandtmann, R.W., 1967. Terrestrial Prostigmata (Trombidiform mites). Antarctic Research Series 10, 51–95.

- Sugiyama, J., Sugiyama, Y., Iizuka, H., Torii, T., 1967. Report of the Japanese summer parties in Dry Valleys, Victoria Land, 1963–1965. IV. In: Mycological Studies of the Antarctic Fungi. Part 2. Mycoflora of Lake Vanda, an Ice-free Lake. National Institute of Polar Research, Tokyo, pp. 23–32.
- Suren, A., 1990. Microfauna associated with algal mats in melt ponds of the Ross Ice Shelf. *Polar Biology* 10, 329–335.
- Thomson, J.W., 1997. *American Arctic Lichens II: The Macrolichens*. University of Wisconsin Press, Madison, 736pp.
- Timm, R.W., 1971. Antarctic soil and freshwater nematodes from the McMurdo Sound region. *Proceedings of the Helminthological Society of Washington* 38, 42–52.
- Tosi, S., Casado, B., Gerdol, R., Caretta, G., 2002. Fungi isolated from Antarctic mosses. *Polar Biology* 25, 262–268.
- Tosi, S., Caretta, G., Humber, R.A., 2004a. *Conidiobolus antarcticus*, a new species from continental Antarctica. *Mycotaxon* 90, 343–347.
- Tosi, S., Del Frate, G., Caretta, G., Vidari, G., 2004b. Funghi predatori di nematodi in Antartide continentale. *Informatore Botanico Italiano* 36, 282–285.
- Tosi, S., Onofri, S., Brusoni, M., Zucconi, L., Vishniac, H., 2005. Response of Antarctic soil fungal assemblages to experimental warming and reduction of UV radiation. *Polar Biology* 28, 470–482.
- Treonis, A.M., Wall, D.H., Virginia, R.A., 1999. Invertebrate biodiversity in Antarctic dry valley soils and sediments. *Ecosystems* 2, 482–492.
- Treonis, A.M., Wall, D.H., Virginia, R.A., 2002. Field and microcosm studies of decomposition and soil biota in a cold desert soil. *Ecosystems* 5, 159–170.
- Tubaki, K., 1961. Notes on some fungi and yeasts from Antarctica. *The Antarctic Record (Tokyo) Series E* 11, 161–162.
- USGS, 2003. *Atlas of Antarctic Research*. <http://usarc.usgs.gov/antarctic_atlas>.
- Van Heurck, H., 1909. *Botanique, Diatomées. Expédition Antartique Belge, Résultats Du Voyage Du S.Y. "Belgica" En 1897–1898–1899*. Buschmann, Anvers, 129pp.
- Vincent, W.F., 1988. *Microbial Ecosystems of Antarctica*. Cambridge University Press, Cambridge, 304pp.
- Vinciguerra, M.T., 1994. *Metacrolobus festonatus* gen. n. sp. n. and *Scottinema lindsayae* Timm, 1971 (Nemata: Cephalobidae) from Subantarctic and Antarctic regions with proposal of the new subfamily Metacrolobinae. *Fundamental and Applied Nematology* 17, 175–180.
- Virginia, R.A., Wall, D.H., 1999. How soils structure communities in the Antarctic dry valleys. *BioScience* 49, 973–983.
- Vishniac, H.S., 1993. The microbiology of Antarctic soils. In: Friedmann, E.I. (Ed.), *Antarctic Microbiology*. Wiley, New York, pp. 297–342.
- Vishniac, H.S., 1996. Biodiversity of yeasts and filamentous microfungi in terrestrial Antarctic ecosystems. *Biodiversity and Conservation* 5, 1365–1378.
- Vishniac, H.S., Baharaeen, S., 1982. Five new basidioblastomycetous yeast species segregated from *Cryptococcus vishniacii* emen. auct. an Antarctic yeast species comprising four new varieties. *International Journal of Systematic Bacteriology* 32, 437–445.
- Walker, F.J., 1985. The lichen genus *Usnea* subgenus *Neuropogon*. *Bulletin of the British Museum Natural History–Botany* 13, 1–130.
- Wall, D.H., 2004. Sustaining biodiversity and ecosystem services in soils and sediments. In: SCOPE. Island Press, Washington, DC, p. 275.
- Wall, D.H., 2005. Biodiversity and ecosystem functioning in terrestrial habitats of Antarctica. *Antarctic Science* 17, 523–531.
- Wall, D.H., 2006. Global change tipping points: Above- and belowground interactions in a low diversity ecosystem. *Philosophical Transactions of the Royal Society of London*, in press.
- Wall Freckman, D., Virginia, R.A., 1998. Soil biodiversity and community structure in the McMurdo Dry Valleys, Antarctica. In: Prisco, J.C. (Ed.), *Ecosystem Dynamics in a Polar Desert. The McMurdo Dry Valleys, Antarctica*. American Geophysical Union, Washington, DC, pp. 323–336.
- Wall Freckman, D., Blackburn, T.H., Brussaard, L., Hutchings, P., Palmer, M.A., Snelgrove, P.V.R., 1997. Linking biodiversity and ecosystem functioning of soils and sediments. *Ambio* 26, 556–562.
- Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setälä, H., van der Putten, W.H., Wall, D., 2004. Ecological linkages between above-ground and below ground biota. *Science* 304, 1629–1633.
- Webby, R.F., Markham, K.R., Smith, R.I.L., 1996. Chemotypes of the Antarctic moss *Bryum algens* delineated by their flavonoid constituents. *Biochemical Systematics and Ecology* 24, 469–475.
- West, W., West, G.S., 1911. Freshwater algae. In: *Reports on the scientific investigations. British Antarctic Expedition 1907–1909*, pp. 263–298.
- Wharton, R.A.J., Parker, B.C., Simmons, G.M.J., 1983. Distribution species composition and morphology of algal mats in Antarctic dry valley lakes. *Phycologia* 22, 355–365.
- Wheeler, Q.D., 1995. Systematics and biodiversity. *Bioscience: The Science and Biodiversity Policy Supplement*, S21–S28.
- Wheeler, Q.D., Raven, P.H., Wilson, E.O., 2004. Taxonomy: impediment or expedient? *Science* 303, 285.
- Wise, K.A.J., 1967. *Collembola (Springtails)*. *Antarctic Research Series* 10, 123–148.
- Wise, K.A.J., 1971. *The Collembola of Antarctica*. *Pacific Insects Monograph* 25, 57–74.
- Wise, K.A.J., Gressitt, J.L., 1965. Far southern animals and plants. *Nature* 207, 101–102.
- Wise, K.A.J., Shoup, J., 1967. Distribution of Collembola at Cape Hallett. In: Gressitt, L. (Ed.), *Entomology of Antarctica*, *Antarctic Research Series*. American Geophysics Union, Washington, DC, pp. 325–330.
- Wynn-Williams, D.D., 1996. Antarctic microbial diversity: the basis of polar ecosystem processes. *Biodiversity and Conservation* 5, 1271–1293.
- Yeates, G.W., 1970. Two terrestrial nematodes from the McMurdo Sound region Antarctica, with a note on *Anaplectus arenicola* Killick, 1964. *Journal of Helminthology* 44, 27–34.
- Zucconi, L., Pagano, S., Fenice, M., Selbmann, L., Tosi, S., Onofri, S., 1996. Growth temperature preferences of fungal strains from Victoria Land, Antarctica. *Polar Biology* 16, 53–61.