# Chapter 9
# Fungus-Invertebrate Interactions in Antarctica

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## 9.1 Introduction

Antarctica (Fig. 9.1) is characterised by its extreme isolation from other continents and lack of ice-free areas, which have a clear influence on its biodiversity. The intense glaciation and glacial cycling from the Miocene to Pleistocene time periods, combined with the isolated nature of this continent, reduce the possibility of refugia, contributing to the reduced diversity and distribution of terrestrial and freshwater organisms (microbial, plant and animal life alike) (Convey 2017; Convey et al. 2018). This is a major contrast with the Arctic, which had easier routes of terrestrial recolonisation due to its continuous contact with the landmasses of North America and Eurasia. Antarctic marine habitats, while much more extensive and biodiverse, have been isolated from lower latitudes over multimillion-year timescales, since the formation of the Antarctic Circumpolar Current (Clarke et al. 2005; Barnes et al. 2006; Fraser et al. 2017).

The marine diversity of the Southern Ocean that surrounds the continent of Antarctica and its outlying sub-Antarctic island groups has received considerable research attention (CAML 2005–2010; De Broyer et al. 2014). However, even though often perceived simply as ‘white rocks’ or frozen lakes/rivers devoid of life, the terrestrial habitats of the Antarctic also hide a complex network of biogeographic domains and unique and often endemic biodiversity, spread out across three main areas, the sub-, maritime, and continental (or frigid) Antarctic, and currently 16 ‘Antarctic Conservation Biogeographic Regions’ (ACBRs) (Pugh and Convey

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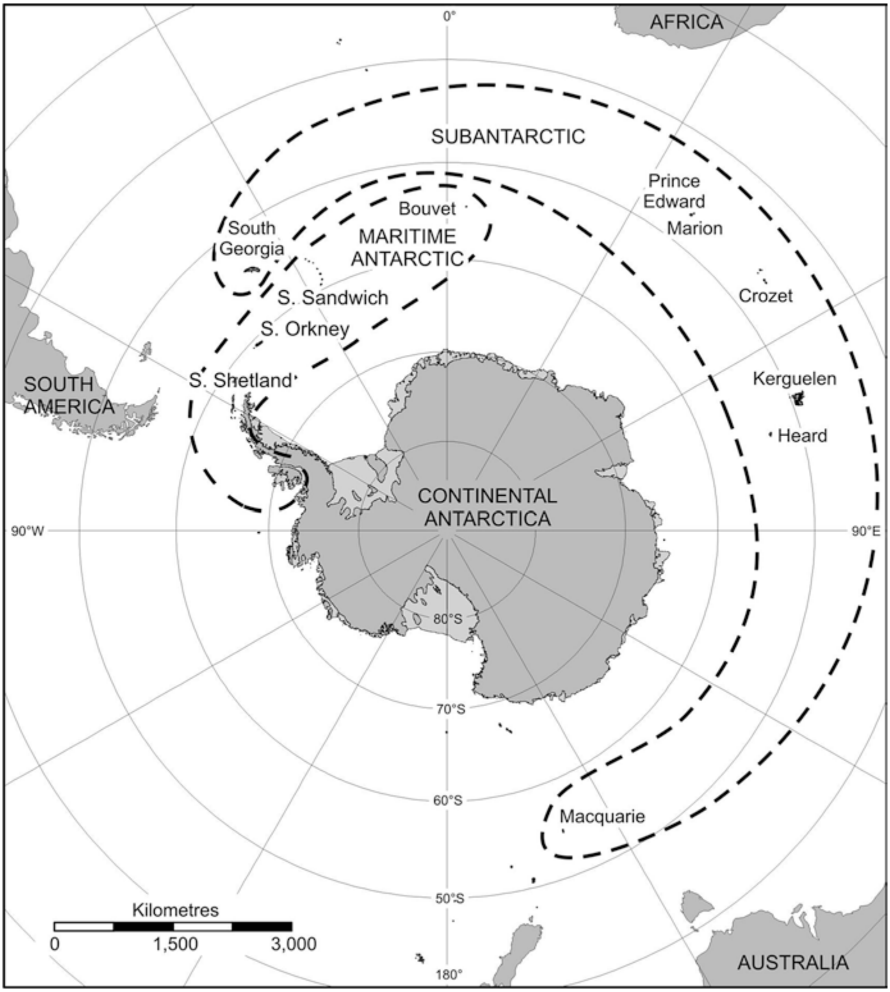

Fig. 9.1 The biogeographic regions of Antarctica (Convey 2017)

2008; Convey et al. 2008; Terauds et al. 2012; Chown and Convey 2016; Terauds and Lee 2016; Convey 2017). Most of the known Antarctic terrestrial biodiversity is found in fragmented and island-like areas of seasonally ice- and snow-free habitats in coastal regions, especially along the Antarctic Peninsula and continental coastline, and in the major mountain ranges inland (although the individual largest ice-free areas are formed by the McMurdo Dry Valleys of southern Victoria Land). Convey (2017) provided an overview of the terrestrial biogeography and biodiversity of the Antarctic and the natural and human-induced processes affecting its ecosystems.

Although it mostly reflects a history of long-term isolation, the invertebrate fauna of the Antarctic is also limited by the continent's extreme environmental conditions

(Convey 2017), and contemporary diversity is limited to extremophiles with the appropriate ecophysiological adaptations. The continent's current terrestrial fauna consists of nematodes, insects (only two species of dipterans on the continent), springtails, tardigrades, mites, and rotifers; other taxa such as molluscs, spiders and earthworms and a wider diversity of insect groups can be found in the less extreme sub-Antarctic regions (see Convey and Lebouvier 2009, Chown and Convey 2016 and Convey 2017, for reviews). Antarctic marine organisms are far more diverse (De Broyer et al. 2014); however, far less is known about marine fungi and their interactions with other taxa.

A wide variety of invertebrates has been studied in detail (terrestrial microarthropods, the krill *Euphausia superba* (Fig. 9.2c), the flightless midge *Belgica antarctica* (Fig. 9.3d) and various marine invertebrates being amongst the best-known examples (see, e.g. Block et al. 2009; Chown and Convey 2016; Cui et al. 2016; Everatt et al. 2014; Peck 2018) in terms of their physiology, adaptation, evolution and ecology. However, very few studies have addressed the interactions between fungi and Antarctic invertebrates. Indeed, Cui et al. (2016) highlighted the complete lack of previous studies regarding the diversity and ecological function of microorganisms associated with *E. superba*; this has resulted in a striking gap of knowledge given that krill are widely known as a key species in the Antarctic marine trophic web.

In this chapter, we review the limited available literature on the associations of invertebrates and fungi across the different environments of Antarctica and the

**Fig. 9.2** Examples of Antarctic marine invertebrates associated with fungi. (**a**) *Ophiuroidea* sp., (**b**) Echinodermata, (**c**) *Euphausia superba*, (**d**) *Glyptonotus antarcticus*, and (**e**) *Nacella concinna*. (Photos credits: FM Pellizari)

**Fig. 9.3** (**a**) Example of one of the few habitats of terrestrial invertebrates in Antarctica, with mosses and Acari (black spots) (King George Island, South Shetland Islands), (**b**) two Acari species: on the right (brown) *Gamasellus racovitzai* and on the left (black) *Alaskozetes antarcticus*, (**c**) *Cryptopygus antarcticus*, and (**d**) *Belgica antarctica*. (Photos credits: EM Biersma)

diversity involved in these associations, and discuss how interactions may be affected by impacts such as climate change, invasive species and increasing human presence and activity in the region. Research to date has largely focused on terrestrial ecosystems, and hence most examples described in this chapter are drawn from terrestrial studies, although we provide links to marine studies where possible.

### *9.1.1 Antarctic Terrestrial Biota*

In the maritime and continental Antarctic, with the exceptions of steep cliffs and exposed mountain ridges, most terrestrial habitats are covered seasonally by snow and/or ice, providing organisms protection from extreme temperature variations and wind abrasion (Convey et al. 2018). While habitats in the maritime and continental zones may be free of seasonal snow cover for periods ranging from only days or weeks to even 5 months, many sub-Antarctic islands experience only intermittent snow cover, which is often restricted to higher altitudes. Even on the coldest sub-Antarctic islands, subnivean microhabitat temperatures are often sufficient to allow year-round biological activity (Convey 1996a). This is not the case in the maritime and continental zones, where biological processes are arrested by low winter temperatures (Walton 1984).

Antarctic soils are typically poorly developed, with low organic content (Beyer and Bölter, 2002). Formation, development and stability of soils are heavily influenced by cryoturbation (Thomas et al. 2008). There is a clear dichotomy between the sub-Antarctic and the other two zones, with only the latter possessing a widespread permafrost layer. Brown soils are associated only with the larger stands of flowering plants in the maritime Antarctic but are more widespread in the sub-Antarctic. Deep peat deposits have developed since the last glaciation under extensive valley bog communities in the sub-Antarctic. Significant deep moss banks are much more restricted (Fig. 9.3a) in the maritime Antarctic and not found in the continental Antarctic (Fenton 1980, 1982; Fenton and Smith 1981; Royles and Griffiths 2014) and differ from those of the sub-Antarctic in being well preserved by inclusion in permafrost, with little or no decay, and even retaining viability over at least 1500 years of preservation (Roads et al. 2014).

Terrestrial vertebrates are mostly absent in the Antarctic and are limited to a single endemic insectivorous passerine and two species of freshwater ducks in South Georgia and Îles Kerguelen, and two scavenging sheathbills, one each present along the Antarctic Peninsula, Scotia Arc islands, South Georgia and on Marion Island. There are no native mammals, reptiles, amphibians or freshwater fish. Nutrient availability in terrestrial habitats is strongly dependent on the Antarctic marine vertebrate fauna (Bokhorst and Convey 2016). Most such habitats are coastal, but some birds also breed on nunataks several hundred kilometres inland. Antarctic terrestrial fauna, therefore, consist almost entirely of invertebrates.

The milder sub-Antarctic islands host a range of ‘higher’ insects and other arthropod groups. The most diverse groups are Diptera and Coleoptera although these, and all other groups (e.g. Araneae, Isopoda, Lepidoptera, Hymenoptera, Hemiptera) are represented by very few species in terms of absolute numbers. Terrestrial diversity also includes molluscs and annelid worms, as well as diverse communities of micro-arthropods [Acari (Fig. 9.3b), Collembola (Fig. 9.3c)] and micro-invertebrates (Nematoda, Tardigrada, Rotifera). Overall diversity is lower in the maritime Antarctic, with only two chironomid midges (Diptera) present. Micro-arthropods and other micro-invertebrates are well represented. Although, again, species diversity is low, population densities are often very high, and comparable with or greater than many temperate and even tropical ecosystems. The continental Antarctic fauna includes no insects, and is restricted to micro-arthropods and micro-invertebrates. Though they are of similar diversity overall to the maritime Antarctic, they are much more limited in their spatial distribution. This zone includes the simplest faunal ecosystems on the planet, where even nematodes are apparently absent (Convey and McInnes, 2005; Hodgson et al. 2010). In all three regions, the fauna present includes taxa with characteristic trophic preferences (e.g. algivory, bacterivory, fungivory, predation); however, little detailed autecological work has been attempted, and the specific diets of Antarctic taxa are virtually unknown (Hogg et al. 2006).

## 9.2 Fungi-Invertebrate Interactions

Interactions between fungi and invertebrates in the Antarctic (both on land and in water) have seldom been studied. This is partly because many taxa have only been found recently and also is a consequence of the known hardships of working with extremophiles. However, there is clearly an assortment of species that actively interact with each other (Bridge and Worland 2008; Bridge and Spooner 2012). Fungal species have been found in the carcasses of dead animals (e.g. Bridge et al. 2005, 2008), predating on micro-invertebrates (e.g. Onofri and Tosi 1992; McInnes 2003) or being utilised as a source of food (e.g. Bokhorst et al. 2007). In the following sections, we present an overview of the interactions known to date across some major invertebrate groups.

### *9.2.1 Fungal Isolation from Invertebrates*

Various methods to recover fungi from invertebrates have been described. Small invertebrates can be surface sterilised by washing in 70% ethanol for 30–60 s and after that transferring to Petri dishes containing culture media (Bridge and Worland 2004; Bridge et al. 2005, 2008; Bridge and Denton 2007). From the marine environment, Henríquez et al. (2014) obtained approximately 1 $cm^3$ pieces from the inner tissues of invertebrates, which were excised under sterile conditions using a scalpel and forceps, and directly spread them onto Petri dishes containing different culture media. Godinho et al. (2019) collected invertebrates, which were washed twice in a sterile solution 0.9% NaCl (for those sampled in land ecosystems) or seawater (for those from marine ecosystems) for 2–4 min. After that, the invertebrates were ground and placed in Petri dishes containing media for fungal growth. Different media were used for fungal development, such as Sabouraud agar, potato dextrose agar, malt extract agar, marine agar and others, which were supplemented with antibacterial antibiotics (usually chloramphenicol) for the inhibition of bacterial contamination. Table 9.1 summarises the fungi isolated from invertebrates in Antarctica.

### *9.2.2 Marine Invertebrates*

Relative to their abundance, the mycological associations of marine invertebrates are very poorly studied, and the literature is largely restricted to the studies reported by Duarte et al. (2013), who first reported the occurrence of species of yeasts isolated from Antarctic marine invertebrates, including gastropods, tunicates, and isopods (Table 9.1). Cui et al. (2016) recently reported 42 taxa of fungi from a single species of crustacean (the very abundant krill, *Euphasia superba*). Godinho et al. (2019) studied the distribution and diversity of fungi associated with 10 species of

**Table 9.1** Fungi isolated from terrestrial and marine invertebrates of Antarctica

| Island/ Region | Invertebrate | Proposed taxa | References |
|---|---|---|---|
| Signy Island | *Eretmoptera murphyi* (larvae) | *Alternaria* sp. | Bridge and Denton (2007) |
| | | *Arthroderma* sp. | |
| | | *Acremonium strictum* | |
| | | *Antarctomyces psychrotrophicus* | |
| | | *Mortierella gamsii* | |
| | | *Pythium* sp. | |
| Unknown | *Tetranychus urticae* | *Acremonium implicatum* | Bridge and Worland (2008) |
| | | *Cladosporium* sp. | |
| | | *Lecanicillium lecanii* | |
| | *Polyphagotarsonemus latus* | *Beauveria bassiana* | |
| | *Dinothrombium giganteum* | *Aspergillus flavus* | |
| | *Eotranchyus* sp. | *Cladosporium cladosporoides* | |
| | *Thrombidium gigas* | *Aspergillus flavus* | |
| | *Oribatid* sp. | *Lecanicillium lecanii* | |
| | | *Simplicillium lamellicola* | |
| | *Abacarus hystrix* | *Lecanicillium lecanii* | |
| Bird Island | *Hydromedion sparsutum* | *Pirella circinans* | Bridge et al. (2008) |
| Nelson Island | *Alaskozetes antarcticus* | *Neozygites acaridis* | Bridge and Worland (2004) |
| Adelaide Island | *Cryptopygus antarcticus* | *Paecilomyces antarcticus* | Bridge et al. (2005) |
| King George Island | Unidentified sea squirt | *Candida sake* | Duarte et al. (2013) |
| | | *Wickerhamomyces anomalus* | |
| | | *Rhodotorula mucilaginosa* | |
| | Unidentified sea sponge | *Debaryomyces hansenii* | |
| | | *Bullera pseudoalba* | |
| | | *Cryptococcus laurentii* | |
| | | *Rhodotorula mucilaginosa* | |
| | *Salpa* sp. | *Metschnikowia australis* | |
| | | *Cryptococcus victoriae* | |
| | | *Cystofilobasidium capitatum* | |
| | | *Cystofilobasidium infirmominiatum* | |

(continued)

**Table 9.1** (continued)

| Island/ Region | Invertebrate | Proposed taxa | References |
|---|---|---|---|
| | | *Rhodotorula mucilaginosa* | |
| | Unidentified sea star | *Meyerozyma guilliermondii* | |
| | | *Cryptococcus adeliensis* | |
| | | *Cryptococcus albidosimilis* | |
| | | *Cystofilobasidium infirmominiatum* | |
| | | *Guehomyces pullulans* | |
| | Unidentified sea isopod | *Meyerozyma guilliermondii* | |
| | Unidentified sea snail | *Meyerozyma guilliermondii* | |
| | *Nacella concinna* (Fig. 9.2e) | *Wickerhamomyces anomalus* | |
| | | *Cryptococcus laurentii* | |
| | | *Rhodotorula mucilaginosa* | |
| | Unidentified sea urchin | *Cryptococcus laurentii* | |
| | | *Rhodotorula laryngis* | |
| | | *Rhodotorula mucilaginosa* | |
| | Marine sponge | *Acremonium* sp. | Henríquez et al. (2014) |
| | | *Aspergillus versicolor* | |
| | | *Aureobasidium pullulans* | |
| | | *Cladosporium cladosporioides* | |
| | | *Cladosporium* sp. | |
| | | *Pseudogymnoascus pannorum* | |
| | | *Penicillium commune* | |
| | | *Cladosporium* sp. | |
| | | *Pseudogymnoascus* sp. | |
| | | *Penicillium polonicum* | |
| | | *Penicillium solitum* | |
| | | *Phoma herbarum* | |
| | | *Phoma* sp. | |
| | | *Pseudeurotium* sp. | |
| | | *Pseudogymnoascus pannorum* | |
| | | *Pseudogymnoascus* sp. | |

(continued)

**Table 9.1** (continued)

| Island/ Region | Invertebrate | Proposed taxa | References |
|---|---|---|---|
| | | *Thelebolus* sp. | |
| | | *Pseudogymnoascus* sp. | |
| | | *Thelebolus* sp. | |
| | *Tedania* sp. | *Cystofilobasidium infirmominiatum* | Vaca et al. (2013) |
| | | *Metschnikowia australis* | |
| | *Leucosporidiella* sp. | *Cystofilobasidium infirmominiatum* | |
| | *Dendrilla* sp., *Hymeniacidon* sp., *Poecilosclerida* sp. | *Metschnikowia australis* | |
| Antarctic Peninsula | *Laevilacunaria antarctica* | *Antarctomyces psychrotrophicus* | Godinho et al. (2019) |
| | | *Metschnikowia australis* | |
| | | *Pseudogymnoascus destructans* | |
| | | *Pseudogymnoascus verrucosus* | |
| | | *Vishniacozyma victoriae* | |
| | | *Pseudogymnoascus* cf. *destructans* | |
| | *Antarctonemertes valida* | *Cladosporium* sp. 1 | |
| | | *Didymella longicolla* | |
| | | *Glaciozyma martinii* | |
| | | *Metschnikowia* sp. 1 | |
| | | *Mollisia* sp. | |
| | | *Mortierella* sp. 1 | |
| | | *Mrakia* sp. | |
| | | *Penicillium brevicompactum* | |
| | | *Penicillium* sp. 1 | |
| | | *Penicillium* sp. 2 | |
| | | *Penicillium* sp. 3 | |
| | | *Pestalotiopsis kenyana* | |
| | *Ascidia* sp. | *Antarctomyces psychrotrophicus* | |
| | *Halyclystus antarticus* | *Metschnikowia* sp. 1 | |
| | | *Metschnikowia* sp. 2 | |
| | *Lumbricillus* sp. | *Aspergillus* sp. 1 | |
| | | *Aspergillus* sp. 2 | |
| | | *Didymella coffeae-arabicae* | |
| | | *Letendraea* sp. | |

(continued)

**Table 9.1** (continued)

| Island/ Region | Invertebrate | Proposed taxa | References |
|---|---|---|---|
| | | *Metschnikowia australis* | |
| | | *Nothophoma macrospora* | |
| | | *Penicillium* sp. 1 | |
| | | *Penicillium swiecickii* | |
| | | *Penicillium* sp. 2 | |
| | | *Pestalotiopsis kenyana* | |
| | | *Phoma* sp. | |
| | | *Pseudogymnoascus* cf. *destructans* | |
| | | *Thelebolus* cf. *globosus* | |
| | *Magelonidae* sp. | *Metschnikowia* sp. 2 | |
| | | *Mrakia frigida* | |
| | *Nacella concinna* | *Antarctomyces psychrotrophicus* | |
| | | *Aspergillus* sp. 1 | |
| | | *Aspergillus* sp. 2 | |
| | | Candida sp. | |
| | | *Candida spencermartinsiae* | |
| | | *Candida zeylanoides* | |
| | | *Cladosporium halotolerans* | |
| | | *Cladosporium* sp. 1 | |
| | | *Clavispora lusitaniae* | |
| | | *Debaryomyces hansenii* | |
| | | *Pseudogymnoascus destructans* | |
| | | *Geotrichum* sp. | |
| | | *Glaciozyma martinii* | |
| | | *Holtermanniella festucosa* | |
| | | *Metschnikowia* sp. 2 | |
| | | *Meyerozyma guilliermondii* | |
| | | *Mortierella* sp. 1 | |
| | | *Mortierella* sp. 2 | |
| | | *Mortierella* sp. 3 | |
| | | *Mrakia frigida* | |
| | | *Penicillium* sp. 1 | |
| | | *Penicillium* sp. 2 | |
| | | *Penicillium* sp. 3 | |
| | | *Penicillium* sp. 4 | |

(continued)

**Table 9.1** (continued)

| Island/ Region | Invertebrate | Proposed taxa | References |
|---|---|---|---|
| | | *Polypaecilum botryoides* | |
| | | *Pseudogymnoascus* cf. *destructans* | |
| | | *Pseudogymnoascus pannorum* | |
| | | *Pseudogymnoascus verrucosus* | |
| | | *Rhodotorula mucilaginosa* | |
| | | *Thelebolus balaustiformis* | |
| | | *Thelebolus* cf. *globosus* | |
| | | *Tolypocladium tundrense* | |
| | *Ophiuroidea* (Fig. 9.2a) | *Pseudogymnoascus* cf. *destructans* | |
| | | *Penicillium* sp. 5 | |
| | | *Metschnikowia* sp. 2 | |
| | *Tigriopus kingsejongensis* | *Debaryomyces hansenii* | |
| | | *Pseudogymnoascus pannorum* | |
| | | *Penicillium* sp. 3 | |
| | | *Penicillium* sp. 5 | |
| | | *Pseudogymnoascus appendiculatus* | |
| | | *Pseudogymnoascus* cf. *destructans* | |
| | | *Pseudogymnoascus verrucosus* | |
| | | *Septoria chromolaenae* | |
| | *Trepaxonemata* sp. | *Cladosporium* sp. 1 | |
| | | *Debaryomyces hansenii* | |
| | | *Penicillium* sp. 3 | |

invertebrates from Antarctica and recovered a rich and diverse community with 83 taxa from 27 distinct genera. The most abundant fungi associated with the Antarctic invertebrates were *Cladosporium* sp., *Debaryomyces hansenii*, *Glaciozyma martinii*, *Metschnikowia australis*, *Pseudogymnoascus destructans*, *Thelebolus* cf. *globosus*, *Pseudogymnoascus pannorum*, *Tolypocladium tundrense*, and different *Penicillium* and *Metschnikowia* species. Godinho et al. (2019) showed that the cryptic fungi recovered from Antarctic invertebrates displayed phylogenetic relationships with species that occurred in other cold, temperate and tropical regions of the world, including endemic and cosmopolitan cold-adapted taxa.

### *9.2.3 Nematodes*

Nematodes are among the most abundant and widespread invertebrates occurring on land in Antarctica, only being absent from some of the most isolated inland regions of the continent (Convey and McInnes 2005; Hodgson et al. 2010). Nematophagous (or ‘nematode-trapping’) fungi, which are globally widespread and occur naturally in habitats with organic detritus (Gray et al. 1982), are also present in Antarctica, with several taxa reported from locations in the maritime Antarctic (Duddington et al. 1973; Spaull 1973; Gray et al. 1982; Gray and Smith 1984; Gray 1985; Velázquez et al. 2017). As noted by Gray et al. (1982), these predacious fungi have a role in the transfer of energy through the food chain, while also potentially controlling the population levels of their prey. More generally, however, Nielsen et al. (2011) suggested that nematodes, which are mostly bacterial grazers, could help the growth of fungi by reducing the ecological dominance of bacteria in the habitat.

### *9.2.4 Tardigrada and Rotifera*

To date, the only study specifically mentioning fungal interactions with tardigrades (water bears) and rotifers is that of McInnes (2003), who reported a new fungal species (*Lecophagus antarcticus*) which was found attacking both invertebrates by means of trapping with adhesive pegs arising from vegetative hyphae (a behaviour previously reported in other members of the genus *Lecophagus*; Vechhi et al. 2016).

### *9.2.5 Collembola, Arachnida and Insecta*

The first published record of interaction between fungi and terrestrial Arthropoda in Antarctica is that of Onofri and Tosi (1992), who reported *Arthrobotrys ferox* predating on the springtail *Gressittacantha terranova* in Kay Island, Edmonson Point and Baker Rocks (Wood Bay, Victoria Land, Antarctica), by means of what they described as ‘organs consisting of ovoidal cells surrounded by an adhesive secretion (sic) and supported by a 2-celled stalk’. According to these authors, this species was the first sample of predaceous hyphomycetes collected in continental Antarctica and also the first recorded to predate on springtails in the Antarctic continent. The 2000s saw an increased number of studies, mostly from Bridge and collaborators (Bridge and Worland 2004, 2008; Bridge et al. 2005, 2008; Bridge and Denton 2007; Bridge and Spooner 2012).

Bridge and Worland (2004) discovered *Neozygites*, an entomophthoralean fungus, on living mites at Nelson Island, South Shetland Islands, off the north-west coast of the Antarctic Peninsula. Subsequently, Bridge et al. (2005) isolated a new species *Paecilomyces antarcticus* from the carapace of dead springtails collected near Rothera Research Station, Adelaide Island, although they could not identify a precise role of the fungus. *Paecilomyces* spp. have been previously reported to grow on wintering insect larvae (ARSEF 2018); however, in the study by Bridge et al. (2005), there was no visible fungal growth before the fungus was cultured in the laboratory. Bokhorst et al. (2007) suggested that the springtail *Cryptopygus antarcticus* feeds facultatively on fungi (among other organic material, such as algae and dead matter) (see also Tilbrook 1970; Broady 1979; Burn 1984; Block 1985; Cannon 1986), suggesting a closer relationship between the findings reported separately in these studies. However, *C. antarcticus* is thought to primarily be an algivore, preferentially grazing on certain microalgal species, rather than being a generalist microbivore (Worland and Lukešová, 2000). Members of the springtail genus *Friesea* are often considered to be fungivorous, but no autoecological studies have been carried out on any of the several Antarctic species to confirm this (Greenslade 2018a, b). Likewise, the oribatid mite *Halozetes belgicae* has been observed grazing on both microalgae and fungal hyphae within the thalli of supralittoral lichens at locations in the South Shetland Islands and along the Antarctic Peninsula (P. Convey, pers. obs.). The sub-Antarctic snail, *Notodiscus hookeri*, obtains specific micronutrients by grazing on lichens (Gadea et al. 2017, 2018).

Bridge and Denton (2007) isolated viable propagules of *Ascomycetes*, *Zygomycetes* and *Oomycetes* from the intestinal tract of *Eretmoptera murphyi*, a chironomid midge native to sub-Antarctic South Georgia, which was introduced accidentally by humans to Signy Island in the maritime Antarctic through plant transplant experiments (Block et al. 1984; Convey and Block 1996). This is a rare example of a study dealing directly with fungi found inside a living host in Antarctica. Normally, fungal growth only becomes apparent in dead animals, as reported by Bridge et al. (2008), who found an association between *Pirella circinans*, a coprophilous fungus, and the South Georgian endemic beetle *Hydromedion sparsutum*. This type of fungus is normally reported from the dung of small mammals, which are absent in South Georgia, and was the only fungus recovered in the insect cadavers, indicating a probable close association between the species.

The presence of entomopathogenic fungi gives potential for examination of their applicability as biological controls (see below). The studies of Bridge and Spooner (2012) and Velázquez et al. (2017) highlighted the importance of identifying and quantifying trophic interactions within the habitats where fungi and invertebrates are found. Bridge and Spooner (2012) noted that it is harder to determine the roles of fungi associated with invertebrates in Antarctica, mainly because the very specific life cycle and adaptive features required by these animals to survive in the extreme environmental conditions of the Antarctic influence the formation of fungal epizootics (see also Bridge and Worland 2008).

### 9.2.6 Entomopathogenic Fungi

No studies have yet formally documented the entomopathogenic potential of fungi in the Antarctic. As noted above, Bridge and Denton (2007) documented the microfungal composition of the intestinal tract of the South Georgian flightless midge *E. murphyi*, using materials collected from the invasive population on Signy Island, and suggested the possibility of the insect larvae working as vectors for fungal introductions. However, it was not possible to ascertain whether the fungal species identified were present on Signy Island before the fly's introduction, since all of them had previously been reported from Antarctica. Bridge and Worland (2008) found *Neozygites*, another pathogenic fungus, associated with the mite *Alaskozetes antarcticus*, and reviewed knowledge of fungal pathogens across Antarctica, highlighting the increasing number of studies on nematodes, flowering plants and mosses (Pegler et al. 1980; Gray and Smith 1984; Bridge et al. 2008) in comparison to those involving arthropods.

Bridge and Denton (2007) also considered the possibility of microfungi being found in hosts elsewhere in the world, such as *Lecanicillium lecanii*, and being able to adapt to the Antarctic if they were introduced, since they generally tolerate wide temperature ranges (Brasier et al. 1999; Nikoh and Fukatsu 2000; Hughes and Lawley 2003). Bridge et al. (2014) highlighted the potential of entomopathogenic fungi to make temperature-resistant mycoinsecticides. Edgington et al. (2014) studied the insecticidal potential of two fungi (*Pseudogymnoascus* and *Mortierella*) found around Rothera Research Station, Adelaide Island, and on Signy Island, finding two species of the latter (*M. alpina* and *M. sygniensis*) to cause significant mortality in larvae and adults of the tested insect species, suggesting a potential to be used elsewhere as pest control. Such pesticides may eventually play a role in combating biological invasions.

## 9.3 Invasive Species

The introduction of alien species is a matter of concern in any environment in the world, as it can have direct (e.g. predation of bird eggs and terrestrial invertebrates, trampling and grazing of plants) and indirect (e.g. alteration of habitat structure leading to changes in species dominance or behaviour) repercussions on native species and the stability of the local ecology. This is particularly the case in extreme environments where life has adapted very specifically to the driving physical environmental stressors and generally has very little ability to compete effectively with new arriving species (Convey 1996b). One of the main sources of biological invasions in the Antarctic, as globally, is human activity (e.g. Smith 1996; Azmi and Seppelt 1998; Frenot et al. 2005; Chwedorzewska 2009; Lee and Chown 2009; Convey 2010; Lityńska-Zając et al. 2012; Chwedorzewska et al. 2013; Galera et al. 2018). Accidental introductions and deliberate transplant experiments have shown that a wide range of flora, fauna and microbes are capable of surviving and establishing viable populations, while an even greater number have been recorded on a transient or synanthropic basis (Frenot et al. 2005; Greenslade 2006; Convey 2017).

Whilst survey data documenting the introduction of invertebrates, and their ecological impacts, remain limited in Antarctica, the subject has received increasing attention in recent years (see, e.g. Lee and Chown 2009; Lityńska-Zając et al. 2012; Bartlett 2018a, b; Hughes et al. 2015, 2018; Gonçalves et al. 2017a, b). It is not uncommon for invasive species to be restricted to areas where human occupation is continuous, disappearing as soon as humans leave (Convey 2017; Potocka and Krzemińska 2018). However, some non-native species do become established in the natural environment, where they can cause competitive displacement and local extinction of native species and add new trophic links in terrestrial ecosystems.

Introduction of flowering plants, bryophytes and microbes has accompanied human activity. Given the possible evolutionary isolation of Antarctic microbes, the introduction of fungal strains from outside Antarctica (or even between regions within Antarctica) and the consequential potential for damage to this unique biological resource should not be underestimated (Smith 1996; Wynn-Williams 1996a, b; Frenot et al. 2005; Chown and Convey, 2007; Bridge and Hughes 2010; Cowan et al. 2011; Augustyniuk-Kram et al. 2013; Hughes et al. 2015, 2018).

Finally, Gonçalves et al. (2017a) suggested that some continental Antarctic fungi may be pathogenic to humans and, through humans who come in contact with them, they could possibly spread to other parts of the world. The same can be said about the possibility of the major migrating vertebrates of the Antarctic (de Sousa et al. 2017; Gonçalves et al. 2017b), which can carry pathogens to other parts of the world.

## 9.4 Conclusion and Perspectives

As a demonstration of the untapped potential for discovery of fungi associated with invertebrates of Antarctica, Cui et al. (2016) reported 42 types of fungi isolated from a single crustacean species (*E. superba*). Some of these produce cytotoxic compounds that may help protect the crustacean against mammalian predators and pathogenic bacteria. The potential, for example, for the discovery of cytotoxic and entomopathogenic compounds from Antarctic fungi is likely to lead to an upsurge in bioprospecting studies. Clearly, much future effort is required to isolate fungi from marine invertebrate taxa, a virtually unexplored field at present. There is also an urgent need for the improved survey and monitoring of microbial – including fungal – diversity across Antarctica, including the assessment of the native or invasive status of isolates. Studies on the impacts of future climate changes must be extended to include microbial groups, and in the context of the current chapter, focus in particular on potential changes in the interactions between fungi and invertebrates (e.g. see Bridge and Spooner 2012).

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