Human Impacts on Soils

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T.A. O'Neill, J. Aislabie, and M.R. Balks

15.1 Introduction

Antarctic soils are vulnerable to disturbance due to their physical properties and naturally slow recovery rates that are suppressed by low temperatures and low availability of liquid moisture (Campbell et al. 1998a; O'Neill et al. 2013a). As most human activities are concentrated in relatively small ice-free areas, particularly in the Ross Sea region and Antarctic Peninsula, the potential for adverse human impacts on the soil landscape is great. Ice-free areas are home to the majority of the historic huts, research stations, and biologically rich sites, and thereby attract a short influx of visitors each summer. Consequently, as human visitation is on the increase, concerns about cumulative effects and about the ability of the most frequented sites to recover after human disturbance are also increasing.

Antarctic soils generally lack structural development and coherence, and the loose material is covered by a thin protective layer of gravel and coarse sand known as desert pavement. Desert pavements play an important role in the desert system, acting as protective armour to stabilise both the slope and the soil (McFadden et al. 1987; Bockheim 2010). Once the desert pavement is disturbed, underlying finer, loose material is susceptible to wind erosion. The subsurface material beneath the desert pavement includes the active layer and permafrost. The active layer is the layer of soil material (above the permafrost) that is subject to annual or diurnal cycles of freezing and thawing (Campbell et al. 1994). Permafrost is the material beneath the soil active layer that remains perennially frozen for at least two consecutive years (Grosse et al. 2011). The presence of permafrost is an important soil property with implications for landscape stability if disturbance leads to melting.

The prevailing low temperatures, low humidity, freeze-thaw cycles, and salinity of Antarctic soils combine to create a harsh environment for plant and animal life. Although few animals and plants have managed to colonise and survive in the soil, bacteria are distributed throughout.

15.2 History of Human Activity

15.2.1 Early Explorers

Impacts of human activities on the Antarctic environment date back to the arrival of the first explorers. The early explorers, and onset of whaling, brought the construction of the first permanent structures, and sustained human presence on the continent. The Heroic Era (1895–1917) comprised at least eight expeditions in the Ross Sea region, and many others elsewhere in Antarctica. As a consequence, the Heroic Era teams, with leaders such as Borchgrevink, Scott, Shackleton, Mawson, and Amundsen, left relics, including huts (Fig. 15.1), relating to human discovery of the continent. They carried out geographic and scientific exploration, collecting plant, animal and rock specimens, mapping previously undiscovered areas. Also, with them, came the first legacies of environmental impacts.

15.2.2 National Programmes and Scientific Visitors

The upsurge in scientific activity of the early 1900s was reignited in the International Geophysical Year (IGY), of 1957/58, and the intensity and diversity of human activities in Antarctica have increased, along with the risk of disturbance to Antarctic flora, fauna and landscapes. Three

T.A. O'Neill (✉) · J. Aislabie
Landcare Research, Hamilton, New Zealand
e-mail: oneilltanya@hotmail.com

J. Aislabie
e-mail: aislabiej@landcareresearch.co.nz

M.R. Balks
School of Science, Faculty of Science & Engineering, University of Waikato, Hamilton, New Zealand
e-mail: m.balks@waikato.ac.nz

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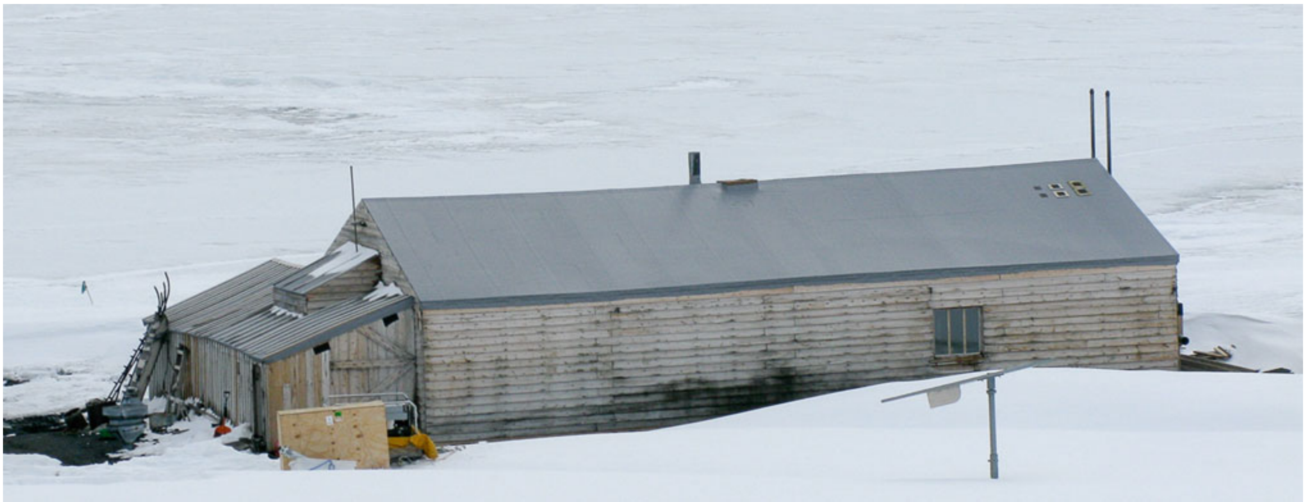

Fig. 15.1 Shackleton's Nimrod Hut at Cape Royds (*Photo* Taken January 2010 by Megan Balks)

year-round scientific bases were established as a result of IGY, McMurdo Station (U.S.A) and Scott Base (New Zealand), and they are examples of two of the larger permanent stations, with combined summer populations of approximately 1,700 individuals (Waterhouse 2001). Many other national research stations have been established since the 1950s, scattered around the continental margins, but concentrated on the Antarctic Peninsula with increasing personnel involved. It is estimated that from 1957 until 2001, approximately 70,000 people have been involved in scientific research and logistic support in the Ross Sea region (Waterhouse 2001); an estimate likely to be approaching 90,000 in 2013. Many scientists visit the Antarctic Peninsula; however, tourists make up a larger proportion of the visitors in the relatively accessible Antarctic Peninsula region.

Land-based research activities are diverse and have included solid earth geophysics, biological sciences, drilling projects, climatology and environmental sciences. Terrestrial scientific research continues to occur and can involve soil pit digging, rock and soil sampling and equipment installation. Legacies of the last 60 years of scientific investigation and human occupation are scattered at isolated sites across Antarctica, particularly in areas close to the major research stations and semi-permanent field camps (Campbell et al. 1993; Tin et al. 2009; Kennicutt et al. 2010).

15.2.3 Tourist Visitors

Tourism on the Antarctic continent dates back to 1891, when the first tourists were passengers on resupply ships to the sub-Antarctic islands. Antarctic tourism, as it is practised today—expeditions in large vessels that enable many small groups to land using small boats, such as "zodiacs"—was initiated in 1966 when passengers were ferried around the Antarctic Peninsula. Tourist activities in Antarctica are based largely around visiting historic huts, research stations, and seal and penguin breeding sites. Some sites, such as Whalers Bay on Deception Island (Fig. 15.2), experience up to 14,000 visitors over a short summer tourist season (International Association of Antarctic Tour Operators 2013). Antarctic-wide visitor numbers peaked in the 2007/2008 season with 46,265 tourists (and approximately 32,000 landings), and have since dropped to 25,284 tourists for the 2012/2013 season (International Association of Antarctic Tour Operators 2013).

The first Ross Sea region tourist ship carried 24 passengers to Scott Base and McMurdo Station in January 1968. The nature of tourism in the Ross Sea region—long journeys on board icebreaker vessels, high expense, inaccessibility of some sites due to sea ice, and lesser abundance of wildlife compared with the Antarctic Peninsula—keep Ross Sea region tourist numbers to an average of 400 landing passengers per season (International Association of Antarctic Tour Operators 2013). Ross Sea region tourism accounts for approximately 2 % of annual Antarctic tourism.

15.3 Types of Human Impacts

There are many human impacts visible in the Antarctic terrestrial environment. Such impacts have included landscape modification as a result of construction activities, geotechnical studies, and roading (Campbell et al. 1993, 1994; Harris 1998; Kiernan and McConnell 2001; Kennicutt et al. 2010); disturbance to soil communities (Naveen 1996; Harris 1998; Tejedo et al. 2005, 2009; Tin et al. 2009 and

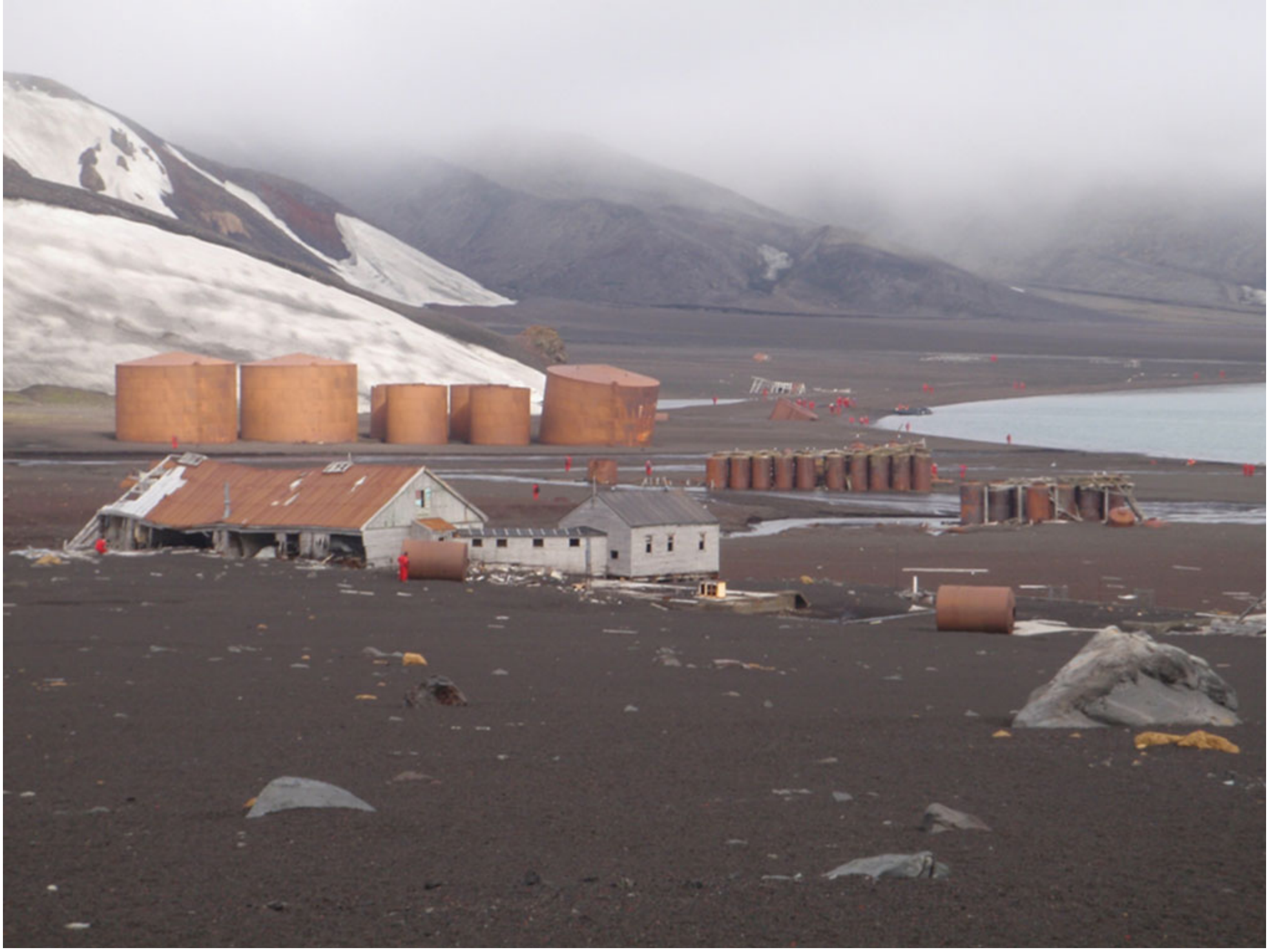

Fig. 15.2 Historic structures at Whaler's Bay on Deception Island (*Photo* Taken January 2013 by Tanya O'Neill)

references therein); local pollution from hydrocarbon spills (Aislabie et al. 2004 and references therein; Kim et al. 2006; Klein et al. 2012); waste disposal (Claridge et al. 1995; Sheppard et al. 2000; Snape et al. 2001; Santos et al. 2005); and the introduction of alien species (Frenot et al. 2005; Cowan et al. 2011; Chown et al. 2012).

All activities in Antarctica are regulated through the national administrative and legal structures of the countries active in the region, underpinned by the international legal obligations resulting from the Antarctic Treaty System.

15.4 The Antarctic Treaty System

15.4.1 Overview

The Antarctic Treaty was signed in Washington DC on 1 December 1959 by the 12 nations active in Antarctica during the International Geophysical Year (1957/58). The Treaty established the guiding principles for all activity in Antarctica. In response to increasing concern over rapidly rising tourism in the late 1980s and early 1990s, and the need to harmonise and adopt a more comprehensive Antarctic-wide environmental protection framework, the Protocol on Environmental Protection to the Antarctic Treaty (hereafter referred to as the Madrid Protocol) was formulated and adopted for signature in Madrid in October 1991. The Madrid Protocol designates Antarctica as "a natural reserve devoted to peace and science".

The Madrid Protocol brings together existing environmental recommendations adopted through the Antarctic Treaty system through a series of technical annexes which outline specific rules for the protection of the Antarctic environment. Annex I of the Madrid Protocol requires that before any activity is conducted the possible environmental impacts need to be assessed. The other four annexes deal with conservation of flora and fauna, waste disposal, prevention of marine pollution and protected areas. The Madrid Protocol also mandates the protection of the wilderness and aesthetic values of Antarctica.

By ratifying the Madrid Protocol, countries signalled their commitment to ensuring Antarctic activities comply with its standards. Independent environmental audits of national programme activities are undertaken to assess the level of compliance with the Protocol and identify areas which could be improved.

15.4.2 Environmental Impact Assessment

Environmental Impact Assessment (EIA) was introduced in Article 8 of the Madrid Protocol and requires persons responsible for an activity in Antarctica to predict its significance and likely environmental impacts (Committee for Environmental Protection 2005). The EIA process is undertaken at one of three levels, depending on the nature and scale of the activity (from Antarctica New Zealand undated):

(1) **Preliminary Environmental Evaluations (PEE)** are processed at the national level and required where impacts are likely to be less than minor or transitory;
(2) **Initial Environmental Evaluations (IEE)** are notified to the Antarctic Treaty Parties and required where impacts are likely to be minor or transitory; and
(3) **Comprehensive Environmental Evaluations (CEE)** are considered by the Antarctic Treaty Parties and required where impacts are likely to be more than minor or transitory.

Project leaders must assemble and analyse information on the potential environmental effects the proposed activity may have and how the potential impacts can be best prevented or mitigated. For activities where a CEE is necessary, such as the multinational Cape Roberts Drilling Project (1997–1999) in the Ross Sea region of Antarctica, the draft CEE was made publically available and considered by the Committee for Environmental Protection (established to advise parties on implementation of the Protocol). A key aspect of the Madrid Protocol, and mandatory for any activity requiring a CEE, is the requirement to regularly monitor impacts caused during a project (Hughes 2010; Kennicutt et al. 2010). Ideally, monitoring should include ongoing assessment of the levels of physical disturbance to terrestrial environments, record levels of pollutants (noise, dust, chemical spills, etc.) and the impacts of pollutants to local ecosystems. Biodiversity studies should also be undertaken so introduced non-native species can be identified and eradicated (Hughes and Convey 2010).

The International Association of Antarctic Tourism Operators was founded to "advocate, promote, and practise safe and environmentally responsible private-sector travel to the Antarctic", and over the course of the last few decades has worked alongside specialists to establish extensive guidelines for tourism including: site inventories in the Antarctic Peninsula (Naveen 1996); regulations and restrictions on the number of tourists ashore; safe staff-to-passenger ratios; and contingency and emergency evacuation plans (International Association of Antarctic Tour Operators 2012).

15.4.3 Wilderness and Aesthetic Values

The Madrid Protocol mandates the protection of wilderness and aesthetic values. Wilderness values are conventionally thought of as relating to large natural areas undisturbed by human activity. Aesthetic values relate to a person's perception of scenic beauty (Summerson and Bishop 2012). The wilderness and aesthetic values of a landscape are clearly influenced by human activity and in particular whether the activity is permanent, such as a station, or minor transitory activity, such as small field camps. Article 3 of the Madrid Protocol, Environmental Principles, states the following:

> 1. The protection of the Antarctic environment and dependant and associated ecosystems…including wilderness and aesthetic values,… shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area.
> 2. To this end:
> (a) activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependant and associated ecosystems;
> (b)… so as to avoid: … (iv) degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance (Secretariat of the Antarctic Treaty 1991).

Despite the inclusion of wilderness and aesthetic values under the protocol, there is no formal definition in the Antarctic Treaty System of how these values should be defined in the context of Antarctica (Summerson and Bishop 2011).

15.5 Landscape Modification

15.5.1 Sources of Disturbance

Disturbance to Antarctic desert pavement surfaces has historically occurred from a number of sources. Vehicles and bulldozers (Broadbent 1994; Campbell et al. 1994) undertake earthmoving, the overturning of large cobbles, and indentation and compression of sub-pavement soils (Fig. 15.3). Disturbances also result from activities such as telecommunications antennae and pipeline installation; active layer removal for road or fill material (Balks et al. 1995, 2002); scientific investigation (Campbell et al. 1993; Kiernan and McConnell 2001); and lower level disturbance

Fig. 15.3 Earth moving equipment preparing a building site adjacent to Scott Base is an example of the most intense scale of disturbance that occurs near permanent bases (*Photo* Taken January 2004 by Megan Balks)

from camping and pedestrian traffic (Campbell et al. 1993, 1998a; Tejedo et al. 2005, 2009). Antarctic desert pavement surfaces are easily disturbed and disturbance can have long-lasting visible impacts on the Antarctic landscape (Campbell and Claridge 1987; Campbell et al. 1993, 1998a, b; Kiernan and McConnell 2001).

15.5.2 Impacts on Soil Physical and Chemical Properties

At Marble Point, in the Ross Sea region of Antarctica, earthworks were conducted in the late 1950s and early 1960s, after which the site was abandoned. Removal of the seasonally thawed (active) layer resulted in retreat of the permafrost table and consequent thawing of the ice contained in the upper part of the permafrost (as a new equilibrium was established forming a new active layer). Lowering of the ground surface, slumping and release of salts that were contained within the permafrost were observed (Campbell and Claridge 1987; Campbell et al. 1994; Balks et al. 1995). Forty years after disturbance, patterned ground cracks were seen to extend through cut or scraped materials, such as bulldozer cut tracks, whereas most fill material showed little sign of new patterned ground formation. The lack of patterned ground cracks in fill material was attributed to lower ice content in the fill material, which became the upper, newly formed, permafrost layer (Campbell et al. 1994, 1998b). In the Ross Sea Region at many "cut" sites, where permafrost melting occurs, salt accumulated on the new ground surface (Fig. 15.4).

Physical disturbance in the landscape from lower impact activities, such as walking, is greatest where there is a pebble surface pavement and the soils have a low proportion of coarse materials (Campbell et al. 1993, 1998a). During a treading trial undertaken on two contrasting parent materials in the Wright Valley of the McMurdo Dry Valleys, Campbell et al. (1998a) observed no disturbance where the surface was bedrock. On the softer till material, after as few as 20 passes, a clear walking track formed. The 1993 treading trial tracks were revisited in 2011 by O'Neill et al. (2013a) and the walking track on the softer till material was still obvious 17 years after it was formed. The colour difference associated with disturbance had disappeared (likely to be a result of wind removing the finer material exposed at the surface); however, displacement of coarser particles to the margins of the track and the recontouring with raised edges and lower centre of the track remained visible (Fig. 15.5).

Fig. 15.4 Surface slumping and salt accumulation is evident on a track formed by a bulldozer that removed the active layer leading to melting and subsequent evaporation of salt-rich permafrost ice; the white material that is visible is salt, not snow (*Photo* Taken January 2009 by Megan Balks)

Disturbances on active surfaces, such as gravel beach deposits, aeolian sand dunes, and areas where meltwater flows occur, recover (visually) relatively quickly (Roura 2004; McLeod 2012; O'Neill et al. 2012a, b, 2013a). Roura (2004) reported the relatively quick recovery of the active sandy beach gravels at the former Greenpeace World Park Base site at Cape Evans. On revisiting the site, O'Neill et al. (2013a) reported natural-looking beach gravel deposit over the entire site with no obvious visible evidence of the previous habitation. The beach-worked loose gravel at the site had been readily resorted by surface wind, water, freeze-thaw and snowmelt and run-off processes.

Campbell and Claridge (1975, 1987) recognised that older, more weathered, desert pavements and associated underlying soils, were the most vulnerable to physical human disturbance. McLeod (2012) produced a 1:50,000-scale soil vulnerability map for ice-free areas in the Wright Valley of the McMurdo Dry Valleys, based on a rapid method to assess the impact of foot trampling. McLeod based his assessment on the impact score (occurrence of boot prints) from 10 footsteps, and identified areas of high, medium, and low, classes of soil vulnerability within the Wright Valley. Strongly weathered soils, as well as material with a high silt content in the layer below the desert pavement, were deemed highly vulnerable, whereas aeolian sand dunes, while readily disturbed (Fig. 15.6), quickly recover and were thus considered of low vulnerability (McLeod 2012).

15.5.3 Factors Influencing Desert Pavement Recovery

Wind action, through the processes of deflation (wind gusts and air turbulence detaching and lifting loose particles from the soil surface), transportation (surface creep, saltation or suspension), and finally deposition (Hillel 1998), is likely to be the primary driver of desert pavement recovery

(Campbell and Claridge 1987; Campbell et al. 1998a, b). The midday heating of a dry soil surface and the microtopography are known to influence wind strength (Hillel 1998) and therefore the inputs of energy available to regenerate disturbed surfaces. The intermittent supply of water, and freeze-thaw action also contribute to surface sorting and, therefore, recovery following disturbance (McFadden et al. 1987; Campbell and Claridge 1987; Haff and Werner 1996). The rate and extent of desert pavement recovery can be attributed to the active surface processes in combination with factors including the intensity of the initial disturbance, properties of the soil material, and also the restoration and remediation efforts undertaken at the site.

At most sites wind is likely to be the instigator in the first stages of formation of an incipient desert pavement and thus the rehabilitation of disturbed desert pavement. In instances of low level disturbance, such as impacts from tent sites, wind action is likely to result in natural infilling of footprints and sorting of surface materials to recreate the surface armouring of coarser material, and thus recovery of randomly trampled areas. Wind action, however, was not sufficient to redistribute larger clasts that lined the margins of foot tracks, formed by repeatedly walking the same route, or vehicle tracks in the Dry Valleys dating back to the 1970s (Fig. 15.7) (O'Neill et al. 2013a).

The intermittent supply of moisture from snowmelt may assist desert pavement recovery at sites in moist coastal climatic zones. Repetitive freeze-thaw action may also aid recovery, and, over time, jostle surface clasts into a more embedded position in the desert pavement surface and infill impressions of removed clasts (O'Neill et al. 2013a). In drier zones, such as in the McMurdo Dry Valleys, further from the coast, moisture available for soil surface processes is less, and visible surface recovery is generally not as advanced as equivalent intensity disturbances in moister areas (Campbell et al. 1998a; O'Neill et al. 2013a).

Campbell et al. (1993) developed a means of rapidly assessing sites that had been impacted by human activity which was called a *visual site assessment* (VSA). A VSA rates the extent of surface disturbance against 11 impact assessment criteria, such as extent of disturbed surface stones, evidence of boot imprints, and evidence of foreign objects, as a means of comparing disturbance severity across different sites. The cumulative impact of a disturbed site is also rated and is described as the "total visual cumulative impact from the various individual impact assessment criteria" (Campbell et al. 1993). Campbell et al. (1998a) showed that the unconsolidated nature of many Antarctic surface materials means visible tracks form quickly, but increased usage of the formed tracks does not add greatly to impacts, and most visible impacts occur quickly and at low

Fig. 15.5 An experimental treading trial on a fan near Lake Vanda in the Wright Valley illustrates the longevity of a walking track formed on gravelly sand fan materials. *Top* Site immediately after 200 walking passes in 1993. *Bottom* Same site revisited 17 years later in 2011. The pale coloured material visible on the track in photo b is fine sediment deposited by a recent fan-building event (*Photos* Megan Balks)

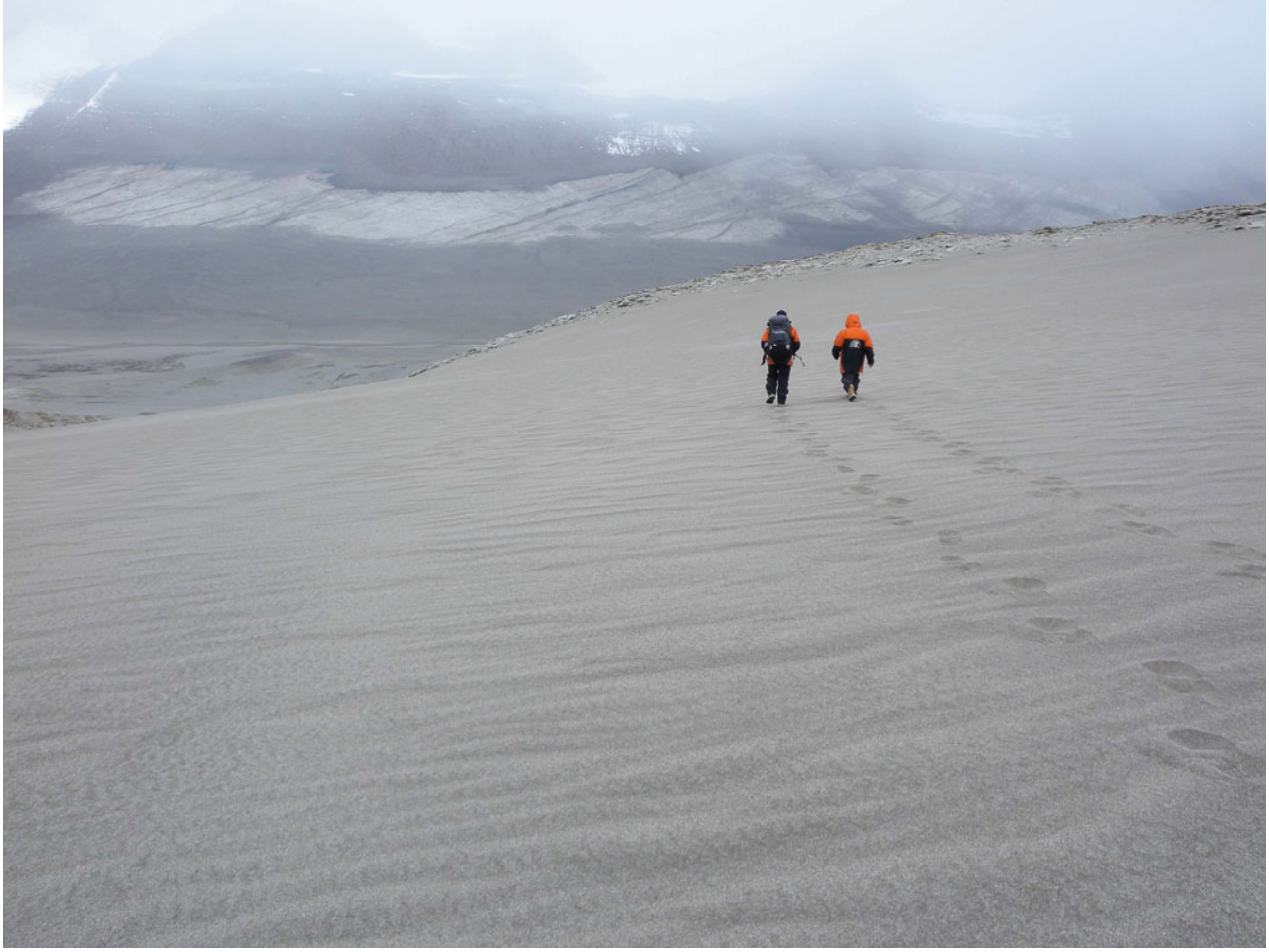

Fig. 15.6 Foot prints on a sand dune will be quickly obliterated as wind moves sand across the ground surface (January 2010) (*Photo* Taken January 2010 by Jeronimo López-Martínez)

levels of use (O'Neill 2013; O'Neill et al. 2013a). Thus, where repeated use is likely over a long period, from this study it is expected that the overall impact will be less if a track is allowed to form and then used repeatedly. However, without rehabilitation, any track formed will remain visible for many decades.

15.6 Disturbance to Fauna and Flora

Soil ecosystems in the Antarctic terrestrial environment are characterised by low and fluctuating temperatures, high aridity, low precipitation, low moisture availability, desiccating winds, high exposure to UV radiation, and often low levels of organic matter (Campbell and Claridge 1987; Wynn-Williams 1990). Mean annual soil temperatures can range from –15 to –40 °C; however, during the continuous daylight of the summer months, surface soils are subject to large daily temperature fluctuations and near-surface soil temperatures can reach 20 °C (Balks et al. 2002). The lack of plant roots and limited available water in some areas mean that carbon and nutrients are not translocated easily down the soil profile and, as a result, the dominant food web, including bacteria, is limited to the near-surface environment (Wall and Virginia 1999). Despite the hostile environment, Antarctic mineral soils can harbour bacterial numbers of up to 10^9 cells g^{-1} dry soil (Aislabie et al. 2008; Cannone et al. 2008; Ganzert et al. 2011).

In polar climates high spatial variability in soil abiotic factors can exist, and the structure of bacterial communities has been observed to be controlled predominantly by soil pH (Yergeau et al. 2007; Aislabie et al. 2008, 2011; Chong et al. 2012), soil salinity (Aislabie et al. 2006; O'Neill et al. 2013b), soil moisture (Aislabie et al. 2006; Barrett et al. 2006; Cary et al. 2010; Ganzert et al. 2011), and nutrient availability (Barrett et al. 2006; Hopkins et al. 2006; Sparrow et al. 2011). Microbes are sensitive to the concentration of soluble salts in soils and past studies have shown that high

Fig. 15.7 Vehicle wheel marks are still evident in the Wright Valley (*left* at ground level and *righ*t from the air) over 40 years after the last vehicle travelled in the area (*Photos* Taken December 2009 by Megan Balks)

salinity reduces microbial biomass (Wichern et al. 2006), amino acid uptake and protein synthesis (Norbek and Blomberg 1998), and reduces soil respiration (Gennari et al. 2007). Ross Sea region soils contain high levels of soluble salts, and small pulses of water from a snowfall event (Ball et al. 2011; Ball and Virginia 2012), or an influx resulting from human disturbance to underlying permafrost (such as the removal of the permafrost-insulating soil active layer and consequent thawing of the salt-rich ice contained in the upper part of the permafrost), can create unfavourable habitats for soil biota, releasing salts into the soil profile or accumulating salts at the ground surface (Campbell et al. 1993, 1998a; Balks et al. 1995).

In all soil communities, disturbances or environmental changes that indirectly affect soil physical and chemical properties can have a detrimental impact on the soil biota (Wall and Virginia 1999). The impacts of human activities can adversely affect different levels of biological organisation, from larger scale localised habitats to community structure, to the individual species themselves through physiological stress. Few scientific reports (apart from those describing impacts of hydrocarbon spills—see Sect. 15.7.3.3) have described the effects of human disturbance on biota, particularly microbial communities, in Antarctica.

Tejedo et al. (2005, 2009) conducted a series of trampling experiments on vegetation-free soils in the South Shetland Islands in the Antarctic Peninsula and documented increases in soil compaction and decreases in the abundance of soil arthropods under different trampling regimes.

One of the most widespread terrestrial fauna in the Ross Sea region are nematodes, with specimens found in 56 % of soil sampled in the McMurdo Dry Valleys and Ross Island (Freckman and Virginia 1997). The influence of soil salinity on population dominance was recognised in soil nematode studies in the McMurdo Dry Valleys (Wall and Virginia 1999). Nematode *Scottnema lindsayae* exhibited the greatest salinity tolerance of three species found in the Dry Valleys, with drier, more saline, and disturbed sites, being dominated by or solely occupied by *S. lindsayae* (Wall and Virginia 1999). Ayres et al. (2008) compared nematode populations (abundance, ratio of living to dead individuals and dominant species) in tracks used continuously for 10 years during summer months with those used for 2 years. Ayres et al. (2008) showed increased nematode mortality, lower abundances and a greater level of physical disturbance to the surface of tracks, which were used at higher intensities and at longer durations, compared with newer tracks and control areas.

Few reports have described the effects of human activity on Antarctic flora; however, it is evident that where high concentrations of scientific bases and infrastructure occur, such as the Fildes Peninsula on King George Island, there are many areas of damaged vegetation (Antarctic and Southern Ocean Coalition 2004). Evidence from sub-Antarctic islands has shown that trampling has impacted on plant species and soils. Impacts include track widening, vegetation degradation, species replacement and soil compaction (Scott and Kirkpatrick 1994; Gremmen et al. 2003; Hughes 2006).

No investigation into the effect of human activity on lichen or moss distribution has been reported in the Ross Sea region; however, it is assumed that past and present day activities around major stations, such as Scott Base, including use of bulldozers and vehicles will have influenced the spatial distribution of local populations.

Algae and cyanobacteria are probably the major primary producers in many parts of Antarctica and occur in any wet area on, under and beside stones, and in endolithic communities. The 'lithic' environment (in, around, under stones) can provide some protection for microbial communities, particularly from wind scouring (Wynn-Williams 1990), UV exposure (Cockell et al. 2008), thermal extremes (Wynn-Williams 1990) and desiccation (Broady 1981; Chan et al. 2013). Human activity, such as vehicle and bulldozer use, resulting in the overturning of large cobbles, can inevitably disturb lithic habitats and adversely affect the communities within. Campbell et al. (1998a) noted impacts from vehicle use to cyanobacterial mats and microbial cryptobiotic soil crusts in the McMurdo Dry Valleys and Marble Point areas. Surface salt accumulations, often associated with surface disturbances, are unlikely to be readily colonised by organisms (Campbell et al. 1998a). However, in areas where available water is plentiful, for instance wetland areas at Marble Point, bulldozed during the late 1950s, algae and mosses have become re-established (Campbell et al. 1994; O'Neill 2013).

Little is known about the impact of human activities on microbes. Surface trampling could dislodge surface particles that protect the soil interface thus exposing underlying soil to changes in soil temperature, moisture and freeze-thaw patterns, which would effectively modify the habitat for microbes (Wall 2007). Moderate-scale disturbances, such as vehicle movement, have the potential to impact on soil physical properties such as bulk density, and thus on soil macro- and microporosity. Through the loss of aggregate stability and the reduction of pore space, compaction has been shown to affect soil microbial communities in temperate localities by impacting on soil water-holding capacity and aeration (Schimel and Parton 1986; Zabinski and Gannon 1997). Changes to soil respiration, decomposition rates and the availability of nutrients may result, thereby affecting functioning of the entire soil ecosystem.

Drivers of Antarctic soil bacterial community structure are predominantly soil EC, soil pH, soil moisture and nutrient availability (Barrett et al. 2006; Yergeau et al. 2007; Aislabie et al. 2008, 2011; Arenz et al. 2011; Ganzert et al. 2011; Chong et al. 2012), which, if disturbed, may cause a shift in bacterial community structure. Soil disturbance that would affect ecosystem functioning near the soil surface (for example Ayres et al. (2008) reported declines in nematode abundance with increased surface compaction from human trampling) could also have an indirect effect on ecosystem functioning at greater depths. Declines in nematode abundance could be due to shifts in bacterial diversity and abundance. O'Neill et al. (2013b) investigated the short-term effects of human disturbance on soil bacterial community structure at an experimental site near Scott Base. They found that the simulated disturbance (removal of the top 2 cm of soil) did not cause any major shifts in the structure of the bacterial communities over the 35 day sampling period. The distinct bacterial communities across the study site reflected differences in spatial variability in soil EC, soil pH and soil moisture content. However, the authors noted that they would expect a disturbance of sufficient intensity to affect the properties mentioned above, could cause a shift in bacterial community structure, over and above the time frame measured in their experiment. There are many unanswered questions relating to the impacts of human disturbances on soil biota, and investigations incorporating DNA–RNA-based analyses and CO_2 efflux studies may lead to greater understanding.

15.7 Chemical Contamination

15.7.1 Sources of Chemical Contaminants

Chemical contamination of Antarctic soils from abandoned waste disposal sites and past fuels spills is a legacy from when environmental management was less stringent before the ratification of the Madrid Protocol in 1991 (Bargagli 2008). The Madrid Protocol provides guidelines for comprehensive environmental management and protection and established the obligation to remediate abandoned sites. Subsequently, many countries that maintain research stations in Antarctica have improved management practices and developed strategies to reduce environmental disturbances, including mitigating past impacts. There is no detailed inventory of contamination in Antarctica; however, the amount of contaminated soil and waste has been estimated at 1–10 million m^3 (Snape et al. 2001). Contaminants most often reported in Antarctic soils are heavy metals and hydrocarbons (Tin et al. 2009). Fuel spills are the most common incidents and have the potential to cause the greatest environmental harm in and around the continent (Aislabie et al. 2004). The presence of persistent organochlorine pollutants in Antarctica has been attributed to long-range atmospheric transport from lower latitudes (Bargagli 2008).

15.7.2 Heavy Metals

Human activities can contaminate soils with heavy metals, but as heavy metals also occur naturally, it can be difficult to distinguish between natural and anthropogenic sources. Elevated levels of metal concentrations have been reported at sites of current or former scientific research stations, especially those areas used for waste disposal or affected by scattered rubbish (Fig. 15.8) or emissions from incinerators or fuel spills (Claridge et al. 1995; Sheppard et al. 2000; Webster et al. 2003; Santos et al. 2005; Stark et al. 2008; Guerra et al. 2011). The highest reported concentrations of metals were detected in soils collected near the site of the former British Base (Trinity House) at Hope Bay on the Antarctic Peninsula (Guerra et al. 2011). For the most impacted site, concentrations of copper (Cu) reached 2,082 mg kg^{-1}, lead (Pb) reached 19,381 mg kg^{-1} and zinc (Zn) was up to 5,225 mg kg^{-1}. Similarly, high levels were reported for waste soil from the Thala Valley landfill at Casey Station, East Antarctica (Stark et al. 2008). At the Thala Valley site, concentrations of total and leachable metals in excavated soil were used to classify the waste for treatment and disposal before transportation to Australia. At other sites, reported levels of heavy metal contamination are considerably lower. For example, Claridge et al. (1995) detected elevated levels of Pb (28.5 mg kg^{-1}) in soil near a crushed battery and Cu (10.6 mg kg^{-1}) in soil sampled from beneath copper wire, at Marble Point, the site of a former USA research station. A detailed investigation of soils at New Zealand's Scott Base has revealed areas contaminated with silver (Ag), cadmium (Cd), Pb, Zn and arsenic (As) (Sheppard et al. 2000). Silver contamination was attributed to disposal of photographic chemicals, whereas As contamination, particularly in surface soils, was attributed to emissions from the incinerator that was operational at Scott Base and has since been decommissioned. Pb in soil could also derive from emissions from the incinerator and spillage of leaded fuel. Elevated levels of methyl lead have been detected in soil from a former fuel storage site at Scott Base (Aislabie et al. 2004 and reference therein).

Fig. 15.8 Metallic rubbish (since removed) from a 1960s era camp at Marble Point, Antarctica was a source of contamination of underlying soil materials (*Photo* Taken January 1990 by Megan Balks)

Once deposited on soil, heavy metals may be mobilised by snowmelt. Claridge et al. (1999) investigated the capacity for soluble contaminants to move through Antarctic soils. Lithium chloride was irrigated into plots of contrasting climate and parent material and soils were subsequently sampled over several years at varying depths to detect movement of the contaminant through the soil. Claridge et al. (1999) showed meltwater facilitated the movement of soluble contaminants down-profile and laterally across the permafrost surface. Webster et al. (2003) investigated the behaviour of heavy metal contaminants at the site of former Vanda Station on the shores of Lake Vanda in the McMurdo Dry Valleys. Some contaminants were susceptible to leaching (e.g. Zn, Cu, Cd and Ni). However, as the area of contamination was small and the concentration of contaminants was low the authors considered the risk to water quality in the lake to be negligible.

15.7.3 Hydrocarbon Spills

15.7.3.1 Occurrence and Characterisation of Hydrocarbon Spills

Hydrocarbon spills on Antarctic soils occur mainly near the scientific research stations where fuel is transported and stored in large quantities and where aircraft and vehicles are refuelled (Aislabie et al. 2004 and references therein; Klein et al. 2012).

Characterisation of the hydrocarbon contaminants in Antarctic soil has revealed that *n*-alkanes predominate with lesser concentrations of the more toxic aromatic and polyaromatic compounds. Naphthalene and methylnaphthalenes are the dominant aromatic compounds detected (Aislabie et al. 2004; Kim et al. 2006) reflecting the chemistry of the fuels, such as JP-8 and JP-5, used and hence spilled in Antarctica (Klein et al. 2012). JP-8 has about 80 % *n*-alkanes in the range of C_6–C_{18}, with a maximum at C_{12}, and 18 % aromatics with <0.5 % PAHs having three or more rings (Ritchie 2003).

At some spill sites, residual hydrocarbons are detected predominantly as an unresolved complex mixture (UCM) (Aislabie et al. 2004 and references therein; Klein et al. 2012). UCM can derive from a number of sources including lubricating oils, motor oils or from severely biodegraded or weathered oils (Frysinger et al. 2003). When spilled on Antarctic soils, hydrocarbons can undergo a number of fates including dispersion, evaporation and biodegradation (Aislabie et al. 2004). The observed persistence of hydrocarbons over decades, however, indicates that biodegradation rates must be low under in situ conditions.

15.7.3.2 Impacts of Hydrocarbon Spills on Soil Properties

Hydrocarbon spills impact on soil chemical, physical and biological properties. Antarctic mineral soils are generally low in carbon and nutrients and therefore, hydrocarbon spills can increase soil carbon concentrations but can further deplete nitrogen and phosphorus when they are assimilated during biodegradation. Hence, soil C:N ratios of >70 have been measured in contaminated sites, whereas those in control sites were <17 (Aislabie et al. 2012).

Monitoring of soil temperature in hydrocarbon-contaminated and control sites at Scott Base and Marble Point in the Ross Sea region indicate that during summer fine weather, when the soils are snow free, the daily maximum surface temperature of the hydrocarbon-contaminated sites may be up to 10 °C warmer than adjacent control sites (Balks et al. 2002). The higher temperatures were attributed to decreased soil albedo from surface darkening by hydrocarbon contamination (Fig. 15.9). There is also evidence that fuel spills impact on soil moisture regimes through increased hydrophobicity (Balks et al. 2002).

15.7.3.3 Impact of Hydrocarbons on the Soil Microbial Community

Introduction

Most investigations of the impacts of hydrocarbon spills on soil biological properties have focused on bacteria. There has been little consideration of the impacts of hydrocarbons on fungi, archaea, photosynthetic microbes, and invertebrates in Antarctic soils. Filamentous fungi and to a lesser

Fig. 15.9 Measurement of albedo on a surface darkened as a result of an oil spill about 40 years prior to the photo being taken (*Photo* Taken January 2001 by Megan Balks)

extent yeasts from the Ascomycota phylum are commonly associated with petroleum contamination in Antarctic soils (Hughes et al. 2007). However, there is limited understanding of those Antarctic species that are not just tolerant to, but are capable of degrading, hydrocarbons.

Soil Bacterial Community Structure

Hydrocarbon spills on Antarctic soils can enrich hydrocarbon-degrading bacteria within the indigenous microbial community (Delille 2000; Aislabie et al. 2004). Cultured hydrocarbon degraders can reach $>10^5$ colony forming units (CFUs) g^{-1} contaminated soils; in contrast, numbers of hydrocarbon degraders are often low or below detection limits in pristine soils. The detection of hydrocarbon mineralisation activity in Antarctic soil, albeit in the laboratory, indicates that the hydrocarbon degraders can be active in situ, conditions permitting (Aislabie et al. 2012; Okere et al. 2012).

Both culture-dependent and -independent methods have been employed to determine the impacts of hydrocarbon contamination on the diversity of bacterial communities in Antarctic soils. Total community DNA extracted from control and hydrocarbon-contaminated mineral soil from near Scott Base on Ross Island (Saul et al. 2005) and ornithogenic soil from Cape Hallett (Aislabie et al. 2009) have been used to prepare 16S rRNA gene clone libraries. In the mineral soil, members of the phyla Acidobacteria, Bacteroidetes, Deinococcus/Thermus, Firmicutes and Candidate TM7 dominated control soils, whereas the contaminated soils were dominated by Proteobacteria only. Similarly, Proteobacteria were dominant in hydrocarbon-contaminated soil from King George Island (Foong et al. 2010). In contrast, both control (abandoned) and contaminated ornithogenic soil was dominated by Proteobacteria (Aislabie et al. 2009). Hydrocarbon spills on mineral soil can lead to a decrease in overall soil bacterial diversity (Saul et al. 2005; Chong et al. 2009; Foong et al. 2010), whereas, for ornithogenic soil, an increase in bacterial diversity was detected in the surface organic soil layer but a decrease in the subsurface mineral layer (Aislabie et al. 2009). Proteobacteria prevalent in hydrocarbon-contaminated mineral soils were assigned to Alpha-, Beta- and Gammaproteobacteria, specifically members of the genera *Sphingomonas*, *Sphingobium* (formerly included in *Sphingomonas*), *Pseudomonas* or *Variovorax* (Saul et al. 2005). Members of the Actinobacteria were found in both hydrocarbon-contaminated and control soils. However, whereas *Rubrobacter* were most prevalent in the control soil from Scott Base, *Rhodococcus* spp. were prevalent in the hydrocarbon-contaminated soil (Saul et al. 2005). In ornithogenic soil, Gammaproteobacteria dominated the control (abandoned) and contaminated soil (Aislabie et al. 2009), with those dominating the control soil most closely related to *Rhodanobacter* or *Dokdonella*, and those in the contaminated soils related to *Alkanindiges* and *Psychrobacter*.

Culturing hydrocarbon degraders from Antarctic soils has resulted in the isolation of members of the phyla Proteobacteria (e.g. *Acinetobacter*, *Sphingomonas*, *Sphingobium, Alkanindiges* and *Pseudomonas*) and Actinobacteria (e.g. *Rhodococcus* and *Gordonia*). Alkane degraders assigned to *Rhodococcus* are frequently isolated from Antarctic soil (Aislabie et al. 2006). *Rhodococcus* spp. strains 7/1, 5/1 and 5/14 grew on a range of alkanes from hexane (C_6) to eicosane (C_{20}) and the methylated compound pristane (2,6,10,14-tetramethyl-pentadecane) (Bej et al. 2000). In contrast, *Sphingobium* sp. Ant 17, degraded numerous compounds in the aromatic fraction of crude oil, jet fuel and diesel fuel (Baraniecki et al. 2002), and utilised many aromatic compounds for growth, including *m*-xylene, naphthalene and its methyl derivatives, and the PAHs fluorene and phenanthrene.

Hydrocarbon-degrading bacteria isolated from Antarctic soils are commonly cold tolerant rather than psychrophilic. They grow at low temperatures (<10 °C) but have an optimum growth temperature > 15 °C. Some of the isolates (e.g. *Rhodococcus* spp.) produce biosurfactants to enhance hydrocarbon degradation (Aislabie et al. 2006 and references therein).

Investigations of Hydrocarbon-Degradative Genes in Bacteria

Functional genes encoding enzymes for hydrocarbon degradation from bacterial isolates have been used to design probes for the presence of microbes with genetic potential to degrade hydrocarbon contaminants in Antarctic soils (Whyte et al. 2002; Luz et al. 2004; Flocco et al. 2009; Jurelevicus et al. 2012a, b). Total DNA extracted from soils near the Brazilian Station Comandante Ferraz on King George Island and cultured bacteria were screened for alkane degradation potential using primers or probes for four alkane monooxygenase genotypes from *Pseudomonas putida* (Pp *alkB*), *Rhodococcus* spp. (Rh *alkB1* and Rh *alkB2*) and *Acinetobacter calcoaceticus* (Ac *alkM*). These analyses revealed that Rh *alkB1* and Rh *alkB2* homologues are common in both contaminated and control soils, and Rh *alkB1* was more prevalent in culturable psychrotolerant bacteria. Pp *alkB* homologues were commonly detected in contaminated soil but Ac *alkM* homologues were rare (Whyte et al. 2002). Based on their results, Whyte et al. (2002) proposed that *Rhodococcus* is the predominant alkane degrader in both control and contaminated Antarctic soils, while *Pseudomonas* may become enriched by the presence of contaminant hydrocarbons, and *Acinetobacter* is rare.

With respect to the genes for aromatic degradation, Ma et al. (2006) found that catabolic genes from several aromatic-degrading psychrotolerant *Pseudomonas* isolates from contaminated Antarctic soils were close matches to those described in mesophilic bacteria. The aromatic degradation genes were either plasmid or chromosomally located. Various PAH degrading isolates carried the *ndo* gene encoding naphthalene dioxygenase on a large self-transmissible plasmid that could be transferred to mesophilic strains (Ma et al. 2006). This indicates that horizontal gene transfer might play a role in transfer of hydrocarbon degradation genes from outside Antarctica to indigenous species. Probing soil DNA extracts have revealed the presence of the archetypal catabolic genotypes *ndoB* and/or *xylE* (encoding 2,3-catechol dioxygenase) in various contaminated soils (Luz et al. 2004; Flocco et al. 2009). Examination of the diversity of the *ndoA* genes in the soil indicated they were most closely related to those from *Pseudomonas* (Flocco et al. 2009). Recently, the alpha-subunit of the PAH ring hydroxylating diooxygenases from Gram-positive and Gram-negative bacteria were characterised in control and oil-contaminated soils from King George Island (Jurelevicus et al. 2012b). The PAH diooxygenases detected in the soil were diverse and included those most closely related to diooxygenases described in *Proteobacteria* (e.g. *Sphingomonas*, *Burkholderia*, *Pseudomonas*) *Actinobacteria* (e.g. *Mycobacterium*, *Nocardioides*, *Rhodococcus*) and *Firmicutes* (e.g. *Bacillus*). Clearly, based on what we know from culturing bacteria from Antarctic soils, there is still much to learn about the catabolic potential of hydrocarbon-degrading bacteria in the Antarctic environment.

15.8 Introduction of Foreign Organisms

15.8.1 Introduction

The geographic, oceanic and atmospheric isolation of the Antarctica terrestrial environment, combined with harsh environmental conditions, provides a barrier to colonisation by terrestrial biota. However, this barrier can be overcome through both scientific and tourist activities in the Antarctic, as well as through the actions of vectors such as wind or migrating birds. With warming potentially leading to changes in habitat in some areas, and increased visitor numbers, the Antarctic is increasingly recognised as being vulnerable to the establishment of alien species.

The likelihood of invasions depends on the numbers of propagules of non-indigenous alien species entering the region, their probability of establishment, and the extent to which they able to spread and alter local ecosystems (Chown et al. 2012).

15.8.2 Plants and Invertebrates

There is evidence that alien plants and other taxa can successfully colonise Antarctic soil ecosystems and once established can spread (Frenot et al. 2005). The alien species, annual bluegrass *Poa annua* was initially recorded in 1985/1986 in the vicinity of the Polish Antarctic station Arctowski on King George Island. *Poa annua* has recently colonised moraines of the retreating Ecology Glacier (Olech and Chwedorzewska 2011), and has since also been reported at three different locations near scientific research stations on the Antarctic Peninsula (Molina-Montenegro et al. 2012). A laboratory experiment was conducted to investigate the effect of *P. annua* on the native pearlwort and hairgrass. It was revealed that the presence of *P. annua* reduced both the biomass and photosynthetic performance of the native species (Molina-Montenegro et al. 2012). In contrast to *P. annua*, *Poa pratensis* introduced to Cierva Point, Antarctic Peninsula, during 1954/1955 has increased in size, but has not yet spread (Pertierra et al. 2013).

Two flowering plants *Nassauvia magellanica* and *Gamochaeta nivalis* have been discovered near a ruined whaling station on Deception Island (Smith and Richardson 2011). As the plants were found near areas of high visitor frequency, and are both wind-dispersed and cold temperature species, it is difficult to determine if the colonisation was natural or a direct result of human activity. Six non-indigenous species of springtails have been recorded at Deception Island and only one elsewhere in maritime or continental Antarctica (Greenslade and Convey 2012). Greenslade and Convey (2012) suggested that high numbers of visitors combined with relatively benign terrestrial habitats, associated with areas of geothermal activity, promote invasion of alien species on Deception Island.

A flightless midge (*Eretmoptera murphyi*) and an enchytraeid worm (*Christensensenidrilus blocki*) were accidentally introduced to Signy Island with plant and soil material from South Georgia in the 1960s (Frenot et al. 2005). Although the midge has only spread slowly, following growth rate and microhabitat climatic modelling, Hughes et al. (2013) report that it could be dispersed to other locations in Antarctica by human activity.

Chown et al. (2012) carried out an Antarctic-wide evaluation of the risks of invasion by vascular plants. They sampled, identified and mapped vascular plant propagules carried by visitors to Antarctica during the field season 2007/2008 and assessed the risk of their establishment based on the identity and origin of the propagules and spatial variation in the Antarctic climate. Visitors carrying seeds averaged about 9.5 seeds per person, with scientists carrying a greater load than tourists. Their analyses revealed that the alien species establishment is currently most likely for the Western Antarctic peninsula. Should marked warming occur, the risk will increase in the Antarctic Peninsula, Ross Sea and East Antarctic coastal regions.

15.8.3 Microbes

The significance of microbial introduction and establishment in Antarctic soils is of increasing concern but there are few data available (Cowan et al. 2011 and references therein). Furthermore, although the application of molecular tools is revealing the extent of microbial diversity in Antarctic soils, it currently remains difficult to differentiate between microbes that might have been introduced to the soils with human activities from those that are naturally occurring.

The potential for introduction of non-indigenous microbes into Antarctic terrestrial ecosystems is high. Microbes are continually dispersed into and around Antarctica by wind and birdlife (Hughes and Convey 2010). Humans visiting Antarctica also release microbes by shedding skin, sneezing, coughing and hair loss. Similarly, the food and equipment used to support human activities on the continent also serve as a source of microbial contamination. Once released into the environment it is usually assumed that microbes of human origin, being mesophiles with a temperature optimum of ca 37 °C, are unlikely to survive, let alone become established, under in situ conditions. DNA, however, can survive in polar soils (Ah Low and Cowan 2005) and may be transferred to indigenous organisms by lateral gene transfer as suggested by Ma et al. (2006).

Of particular concern is the risk of introducing pathogens to wildlife, such as penguins, which can then spread (Kerry and Riddle 2009). It is difficult, however, to prove human activities as the source of infection when birds or mammals may travel between continents and pick up infections as they go (Frenot et al. 2005).

Blanchette, Farrell and colleagues have investigated the role of non-indigenous fungi in the biodeterioration of historic huts, and described the fungi that colonised the huts, artefacts and surrounding areas (Arenz et al. 2006; Duncan et al. 2008; Blanchette et al. 2010; Farrell et al. 2011). The material brought to Antarctic to support construction of the huts and activities of the early explorers was undoubtedly contaminated with fungi. Investigations of the fungi involved in biodeterioration has revealed that while some of the fungi may have established themselves in the soils (Arenz et al. 2006) others are likely to be indigenous, such as *Cadophora* spp. (Blanchette et al. 2004, 2010).

More recently concerns have been raised about the possibility of transferring microbes within the continent (Tin et al. 2009). Such transfers have the potential to contaminate unique ecosystems and pose a serious threat to the validity of molecular ecology studies (Cowan et al. 2011).

15.9 Cumulative Impacts

Cumulative impacts refer to individual and often minor impacts that may be significant when repeated over time (Harris 1998). With expansion of scientific expeditions and their supporting logistics, as well as the increase in tourism and non-governmental activities, there is concern about the cumulative impacts of smaller scale human activities. At vulnerable sites even short duration visits by small numbers of people can cause negative environmental impacts. When individually assessed, each activity may have little impact; however, together such impacts may amount to a substantial cumulative impact. Cumulative environmental impacts are difficult to address under the current environmental management systems in Antarctica, as single-event-based methods of EIA do not address activities that have happened previously in the same area.

Experimental treading trials (Campbell et al. 1998a) have shown that once a track has formed (within 20 or so passes) the cumulative impacts of larger numbers of people following the same track (20 passes, vs. 200 passes, vs. 2000 passes) are minimal. The width of the formed track, number of surface boulders and cobbles, and % area of pale colour exposed, were all impacted most in the first 20 passes of the track (Campbell et al. 1998a). Cumulative impacts on biota are unknown but are likely to affect biodiversity and ecosystem functioning (Wall 2007).

Researchers from the largest scientific station in Antarctica, McMurdo Station (Fig. 15.10), have documented the evolution of the aerial extent of the area impacted by the station, since base construction, through aerial photographs and satellite imagery (Kennicutt et al. 2010). The cumulative impacts of station activities expand rapidly in spatial extent over the first decade of occupancy, after which the station continued to expand at a slower rate (Kennicutt et al. 2010). The spatial extent of physical disturbance at McMurdo Station has been stable for more than 30 years. A similar evolution of environmental footprint is evident at the nearby Scott Base.

15.10 Management of Impacts

15.10.1 Introduction

The ice-free areas visited by humans are small, relative to the Antarctic continent as a whole, and impacts occur as isolated pockets among largely pristine Antarctic wilderness. The most intense and long-lasting visible impacts occur around the current and former research bases, and are remnants of

Fig. 15.10 The footprint of McMurdo Station, the largest Antarctic Base, while relatively large, has not increased markedly since the 1980s. The footprint extends beyond the buildings with hillsides repeatedly scraped and the active layer removed to provide fill material for base building activities (*Photo* Taken January 2010 by Megan Balks)

late 1950s through to the 1970s activity (Campbell and Claridge 1987; Webster et al. 2003; Kennicutt et al. 2010; O'Neill 2013). Since the 1980s when environmental accountability, enhanced environmental management, and environmental awareness increased the environmental footprint of stations such as Scott Base and McMurdo Station on Ross Island, these impacts have remained static or decreased (Kennicutt et al. 2010). Since the ratification of the Madrid Protocol in 1991, environmental awareness has increased and the standard of prevention of human impacts undertaken by many Antarctic programmes is high.

Contemporary occurrences of chemical contamination from waste disposal and fuel spills are few and far between due to the stringent management practices national programmes and tourist operators now have in place to prevent harm to the environment. Antarctic Treaty parties have introduced additional guidelines to avoid and minimise human impacts. As a consequence, visitors take responsibility for their footprint on the environment, and there is a high level of consistency between predicted impacts and actual impacts on the ground (O'Neill et al. 2012a).

Jabour (2009) states that it is often misleading to compare the relative environmental pressure exerted by the Antarctic national programmes and tourist sectors as a function of simple statistics (number of visitors in each sector). In the 2007/2008 season, over 73,000 people visited Antarctica as part of a tourism operation (tourists, staff and ship crew), whereas about 4,000 people visited as part of national programmes. However, the numbers do not represent the relative environmental pressure of the two sectors, as the number of person days ashore for the national programme personnel equates to approximately 675,000 days, while tourists in the 2007/2008 season accounted for about 32,000 person days ashore (Jabour 2009). The majority of Antarctic tourism is ship-based, with no permanent infrastructure. Short shore day trips are facilitated using small boats. In contrast, most people visiting as part of national programmes live in a permanent onshore structure, can spend several months ashore, some camping in remote, previously unvisited places. It is not just the scale of the presence or number of people involved that influence the risk of impacts to the terrestrial environment, but also the types of activities and where they occur. For example operations that involve many flights between low latitudes and Antarctica can create opportunities for the introduction of non-native species (Jabour 2009).

15.10.2 Managing Impacts from Landscape Modification

The longer lasting "worst case scenarios" of past physical disturbances are what we see left in the landscape today and are the subject of recent studies. There are many instances where the intensity of disturbance was low, such as widespread trampling around a tent site, and natural recovery has been such that there is no remaining visible evidence of previous impacts (O'Neill et al. 2013a).

O'Neill et al. (2012a) undertook five case studies of past EIA reporting in the Ross Sea region of Antarctica, ranging from former research stations to field campsites, to compare the impacts predicted in the EIA with observed impacts after the event. In all cases there was a high level of consistency between predicted and observed impacts. It was apparent that the environmental impact assessment process raised the environmental awareness of visitors, motivating them to avoid, remedy or mitigate, their environmental impacts.

Recent research (e.g. Campbell et al. 1993; McLeod 2012; O'Neill et al. 2013a) into the ability of different parent materials, and varying degrees of active surface processes, to recover from impacts has contributed to better informed decisions on site selection, and impact mitigation. For example opting to concentrate activity on active and readily recoverable surfaces or on resilient bedrock is likely to lead to less long-term visible impacts. In some instances, such as one-off campsites, medium-term visual impacts may be minimised by avoiding formation of walking tracks by walking in a random widespread fashion (O'Neill et al. 2013a). In other areas, where slopes are steep and repetitive use over long periods will occur, or where extensive moss and lichen communities are present, use of pre-existing tracks, or concentration of activity to form just one track, will cause less cumulative impact (O'Neill et al. 2013a; Pertierra et al. 2013).

Site remediation (raking and smoothing of disturbed surfaces to free up compacted soil, and redistribute out of place stones) can be effective and led to accelerated *visual* recovery of desert pavement surfaces (O'Neill et al. 2013a). By redistributing larger stones and raking the margins of walking tracks that result from field camps the visual aesthetic of a site is restored by eliminating unnatural surface irregularities. Larger stones, such as those used to pin down tents should be replaced in original orientations with salt-coated surfaces down and polished or weathered surfaces up, preferably in the indentations from which they were removed. Site rehabilitation needs to be undertaken with an understanding of the rock material's natural position in the environment. While the natural stratigraphy of a site cannot be restored, it is possible to mimic the natural geomorphology, and thus reduce visual impacts and longer term changes to geomorphic processes (Kiernan and McConnell 2001).

Although raking will enhance the visual aesthetics of a site there is a question of whether by the activity of raking we are further damaging the remaining microbial communities living in the surface material. The impacts of remedial measures on residing biota have yet to be investigated, so caution must be used as we also have an obligation under Annex II [Article 1(d) and 1(h)] of the Madrid Protocol to protect soil biota. Value judgments must be considered, particularly whether potential adverse impacts to biota outweigh the longer term positive visual effects of site restoration. Where moderate to high-intensity disturbances have changed the contour of the land and the disturbance is likely to change drainage patterns and other geomorphic processes in the longer term, raking the disturbed area may be the best option to ensure ecosystems down-slope of the disturbance are not adversely affected.

The Antarctic Site Inventory (ASI) commenced in 1994 to collect baseline information necessary to detect possible changes in the physical and biological variables. Regular monitoring of selected variables is undertaken to determine how best to minimise or avoid possible environmental impacts of tourism and non-governmental activities in the Antarctic Peninsula area (Naveen 1996). Over the first 17 seasons the ASI made 1,156 site visits and collected census and descriptive data at 142 Antarctic Peninsula locations, including repeated visits to the most heavily visited sites in the Antarctic Peninsula.

Information collected by ASI includes descriptions of key physical and topographical characteristics of the site, distribution of flora, and discrete groups of breeding penguins and flying birds. Variable site information includes weather and other environmental conditions biological variables (number of occupied nests, number of chicks per occupied nest, ages of chicks), and the nature and extent of any observed visitor impacts (footprints or paths, cigarette butts, film canisters, and litter). Photo documentation is carried out and used to compare between visits.

Currently there are no ASI sites in the Ross Sea region of Antarctica; however, Antarctica New Zealand administers a visitor site assessment scheme (VISTA), which aims to support the EIA process and address the shortfall of information on the cumulative impacts of visitor activity through a site monitoring programme. Assessors use a series of booklets, maps, and photographs to help orientate themselves at a site, and GPS waypoints to locate photo and ground disturbance monitoring sites. Annual replication of fixed photo points allows changes such as site recovery, or cumulative disturbance, over time to be monitored. Ground disturbance or "terrestrial impact visual assessments" are also carried out at all landings on ice-free areas using the visual site assessment method of Campbell et al. (1993). Where possible the assessment is carried out before the visitors land and repeated after their visit has been completed. Information on wildlife, vegetation, evidence of previous ground tracking, and other observations are also collected to give an overview of the environmental sensitivities of the site. Currently, 20 sites in the Ross Sea region are part of the VISTA monitoring programme (Antarctica New Zealand 2009), including the frequently visited sites at Cape Evans, Cape Royds, and the Taylor Valley Visitor Zone in the McMurdo Dry Valleys.

The Fildes Peninsula region, on the south-western part of King George Island, South Shetland Islands, on the Antarctic Peninsula, has six permanent Antarctic stations. It is a special case in Antarctica where different interests, from scientific research, station operations, transport logistics, and tourism, regularly overlap in space and time (Braun et al. 2012). Conflicts of interest between multiple users sometimes occur, as well as breaches in the environmental obligations outlined in the Madrid Protocol. There have been recent cases where the level of EIA undertaken by some national programmes has not always been appropriate for the likely level of impact, and in one instance an IEE indicating "minor and transitory" impacts was prepared for the expansion of a station, but the work resulted in destruction of beach ridges (Braun et al. 2012).

Tourists visit the Fildes Peninsula on flights operated by a Chilean air company. However, the tourists strictly follow the ASI site guidelines, and the local environmental impact of tourism was considered to be lower than the impact of national programme personnel (Braun et al. 2012). A potential solution for increasing coordinated environmental management and reducing the conflict of interests between national programmes is the designation of the Fildes Peninsula region as an Antarctic Specially Managed Area (ASMA). An ASMA, much like the McMurdo Dry Valleys ASMA (No. 2) (Antarctic Treaty Consultative Meeting 2011), is the best way to minimise the negative effects of human activities in the area, and provide stakeholders with effective management tools, such as an integrated management plan, codes of conduct for each facility zone and scientific research, and a management group to coordinate activities in the ASMA.

15.10.3 Managing Impacts to Flora and Fauna

Annex II of the Madrid Protocol on conservation of flora and fauna controls interference with native animals or plants and prohibits the introduction of any non-native species to Antarctica.

> Article 1(h) of Annex II prohibits any "harmful interference" to flora and fauna, which refers to:
>
> (i) flying or landing helicopters or other aircraft in a manner that disturbs concentrations of birds and seals;
> (ii) using vehicles or vessels, including hovercraft and small boats, in a manner that disturbs concentrations of birds and seals;
> (iii) using explosives or firearms in a manner that disturbs concentrations of birds and seals;
> (iv) wilfully disturbing breeding or moulting birds or concentrations of birds and seals by persons on foot;
> (v) significantly damaging concentrations of native terrestrial plants by landing aircraft, driving vehicles, or walking on them, or by other means; and
> (vi) any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant or invertebrate.

IAATO (International Association of Antarctic Tour Operators) members have adopted sets of guidelines to comply with Annex II of the Protocol and provide visitors with codes of conduct to help reduce potential disturbance to terrestrial and marine environments. To minimise disturbance to vegetation and wildlife IAATO also utilises the Antarctic Site Inventory site guidelines when taking visitors to specific locations on the Antarctic Peninsula.

15.10.4 Managing Impacts from Fuel Spills

International guidelines relating to fuel oil handling at research stations, spill prevention, containment of fuel spills, and contingency planning, were put in place at an Antarctic Treaty Consultative Meeting in 1998. Since then considerable improvements in fuel management have been seen across national programmes, as well as upgrades to fuel transport, transfer, and storage systems. Although fuel spills still occur, one might expect their frequency and size to decrease with infrastructure and procedural improvements (Aislabie et al. 2004).

It has been common practice to remove as much fuel-contaminated soil as possible, including contaminated ice and snow, and ship it back to the home country for disposal (Roura 2004; Aislabie et al. 2004). Depending on the situation, this "dig it up and ship it out" approach could potentially cause adverse impacts to the local environment, including permafrost melt out, which in turn could lead to environmental impacts such as altered stream flows, surface slumping, salinization, and mobilisation of contaminants (Campbell et al. 1994; Snape et al. 2001). In some cases, such as where a small fuel spill has occurred in an environment conducive to evaporative processes (such as the McMurdo Dry Valleys), or where the environmental impacts of a large clean-up operation are greater than the effects of the spill, “doing nothing” may be the most effective option. Alternative remediation technologies include use of permeable reactive barriers to intercept and facilitate removal of mobile contaminants (Snape et al. 2001) and bioremediation (Aislabie et al. 2006).

Bioremediation is increasingly viewed as an appropriate remediation technology for hydrocarbon contamination of Antarctic soils, whereby microorganisms are used to remediate oil spills (Aislabie et al. 2006 and references therein). There is an optimum temperate, nutrient level, and moisture level at which degradation occurs most effectively, and a number of options have been studied to increase rates of bioremediation. Strategies include hydration (addition of liquid water to facilitate increased microbial metabolic activity), biostimulation (addition of fertilisers to increase the assimilation and mineralisation of oil-derived organic carbon by microorganisms), and bioaugmentation (addition of specifically isolated hydrocarbon-degrading bacteria). Bioremediation technologies can either be carried out in situ (on site without soil removal) or ex situ (removal and transportation of contaminated material to a different location to be treated biologically) (Aislabie et al. 2006). The Antarctic Treaty precludes importation of foreign organisms into Antarctica, so indigenous microbes are required for in situ bioremediation.

15.10.5 Managing Impacts from Introduction of Alien Species

Understanding the initial phases of dispersal and establishment is important for managing the risks posed by invasive alien species. Mitigation measures that reduce the risk of introductions to Antarctica must focus on reducing propagule loads on humans, their food and cargo and transportation (Frenot et al. 2005).

Hughes et al. (2011) report that soil, mould, and invertebrates can all enter Antarctica with fresh fruit and vegetables. A number of measures are proposed for reducing the risk of non-native species introduction. They include limiting importation of fresh foods, likely to have high propagule loads, to those areas where non-native species are more likely to establish, and ensuring food waste and packaging is disposed of in a way that prevents release of associated alien species.

Once established, alien species such as plants or invertebrates can be removed before they spread. Removal is more difficult, if not impossible, for management of microbial contaminants. Hence Cowan et al. (2011) advocate the establishment of “a new tier of Antarctic Specially Protected Areas, essentially no-go, no-fly zones where access would be permitted only under the strictest of conditions of biological protection, designed to provide rigorous protection of the environment from human dissemination of non-indigenous organisms”.

15.11 Summary

Antarctic soils are vulnerable to disturbance due to their physical properties and naturally slow recovery rates due to low temperatures and, in some regions, low moisture contents. The most intense human activities in Antarctica, such as establishment of bases or research stations, are concentrated in ice-free areas.

The first recorded human interactions with Antarctica were sightings from three ships in 1820. Human activity in Antarctica became sustained during the nineteenth century when whaling stations were established and in the “heroic era” (1895–1917) with exploratory expeditions such as those of Scott and Amundsen. The early visitors left structures and other equipment behind, thus establishing the first legacies of environmental impacts. Since the International Geophysical Year of 1957/58 there has been a sustained increase in human activity. In recent years there has been increased ship-based Antarctic tourism, with 46,000 tourists reported in the 2007/08 summer and 25,000 in the 2012/13 season.

The Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) was signed in 1991 and designates Antarctica as “a natural reserve devoted to peace and science”. The Madrid Protocol mandates the protection of Antarctic wilderness and aesthetic values and requires that before any activity is undertaken the possible environmental impacts are assessed.

Human impacts on the Antarctic terrestrial environment include physical disturbance, spillage of foreign substances, and introduction of foreign organisms. Physical disturbances range from land disturbance during construction activities for roads and bases, through to formation of foot tracks and individual footprints in areas where humans have never previously walked. Accidental spills of hydrocarbon fuels and wastewaters have occurred and human waste was sometimes disposed of by discharge onto land. There is now evidence that alien vascular plants and other taxa can successfully colonise Antarctic soil ecosystems and there is increasing concern about the potential for human activities to impact on soil microbial populations.

Where physical disturbance includes removal of the protective “active layer”, the underlying permafrost will melt with resulting land surface subsidence and, in drier regions, the accumulation of salt at the soil surface. The concentration of ice that occurs near the top of the permafrost had not re-established 30 years after disturbance near the Ross Sea region coast. Larger scale surface recontouring, such as bulldozing of tracks or formation of vehicle or foot tracks in loose materials, may remain visible in the landscape for well over 50 years. Where surfaces such as sand dunes are active or where liquid water is available seasonally, smaller scale impacts are obliterated within a few seasons. Visible recovery from footprints, scattered across the environment, was often greater than if the same amount of foot traffic was concentrated to form a foot-track.

Hydrocarbon spills have been shown to persist in the environment, with fuel perching on top of ice-cemented permafrost, for decades. Hydrocarbon-degrading microbes are present in the Antarctic environment but, within the Ross Sea region, their effectiveness is limited by moisture and nutrient (N and P) availability.

Little is known about the response of Antarctic soil microbial communities to human disturbance or on what timescale responses can be detected. Studies of the long-term effects of trampling on soil fauna have shown increased mortality, lower abundances, and shifts in the dominant species of collembola with increasing trampling intensity and soil compaction. Current knowledge of the drivers of bacterial ecology suggests that a disturbance of sufficient intensity to affect soil EC, pH, or moisture content is likely to cause a shift in bacterial community structure. More rigorous investigations incorporating DNA–RNA-based analyses and CO_2 efflux studies could lead to a greater understanding of the effects of soil disturbance on biota.

Many of the most intense impacts on the Antarctic soil environment are legacies of past practice, and are concentrated in areas near bases. Visible disturbance collectively impacts only a small proportion of Antarctic terrestrial environment. With increasing environmental awareness, innovations such as ASMA and ASPA (Antarctic Specially Protected Areas) have been implemented. Thus, the standard of prevention of human impacts undertaken by many of the Antarctic programmes, such as those operating in the McMurdo Dry Valleys, is now more stringent than environmental management standards in most, if not all, other regions of the planet.

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References

Ah Low L, Cowan DA (2005) Dissemination and survival of non-indigenous bacterial genomes in pristine Antarctic environments. Extremophiles 9:385–389

Aislabie JM, Balks MR, Foght JM, Waterhouse EJ (2004) Hydrocarbon spills on Antarctic soils: effects and management. Environ Sci Technol 38(5):1265–1274

Aislabie JM, Saul DJ, Foght JM (2006) Bioremediation of hydrocarbon-contaminated polar soils. Extremophiles 10:171–179

Aislabie J, Jordan S, Barker GM (2008) Relation between soil classification and bacterial diversity in soils of the Ross Sea region, Antarctica. Geoderma 144:9–20

Aislabie J, Jordan S, Ayton J, Klassen JL, Barker GM, Turner S (2009) Bacterial diversity associated with ornithogenic soil of the Ross Sea region, Antarctica. Can J Microbiol 55:21–36

Aislabie JM, Bockheim J, McLeod M, Hunter D, Stevenson B, Barker GM (2011) Microbial biomass and community structure changes along a soil development chronosequence near Lake Wellman, southern Victoria Land. Antarct Sci 24:154–164

Aislabie JM, Ryburn J, Gutierrez-Zamora M-L, Rhodes P, Hunter D, Sarmah AK, Barker GM, Farrell RL (2012) Hexadecane mineralization activity in hydrocarbon-contaminated soils of Ross Sea region Antarctica may require nutrients and inoculation. Soil Biol Biochem 45:49–60

Antarctic and Southern Ocean Coalition (ASOC) (2004) Environmental reports of Fildes Peninsula, 1988–1997: benchmarks for environmental management. Antarctic and Southern Ocean Coalition report, December 2004, 15 pp

Antarctic Treaty Consultative Meeting (2011) ATCM XXIV, measure 10: management plan for Antarctic specially managed area no 2, McMurdo Dry Valleys, Southern Victoria Land. http://www.mcmurdodryvalleys.aq/images/asma2mpfull.pdf

Antarctica New Zealand (Undated) Environmental Impact Assessment. http://www.antarcticanz.govt.nz/environmentalstewardship/environmental-impact-assessment. Accessed 4 Nov 2013

Antarctica New Zealand (2009) VISTA update and review: visitor site monitoring in the Ross Sea region. Antarctica New Zealand, Christchurch

Arenz BE, Held BW, Jurgens JA, Farrell RL, Blanchette RA (2006) Fungal diversity in soils and historic wood from the Ross Sea region of Antarctica. Soil Biol Biochem 38:3057–3064

Arenz BE, Held BW, Jurgens JA, Blanchette RA (2011) Fungal colonization of exotic substrates in Antarctica. Fungal Divers 49:13–22

Ayres E, Nkem JN, Wall DH, Adams BJ, Barnett JE, Broos EJ, Parsons AN, Powers LE, Simmons BL, Virginia RA (2008) Effects on human trampling on populations of soil fauna in the McMurdo Dry Valleys, Antarctica. Conserv Biol 22(6):1544–1551

Balks MR, Campbell DI, Campbell IB, Claridge GGC (1995) Interim results of 1993–94 soil climate, active layer and permafrost investigations at Scott Base, Vanda and Beacon Heights, Antarctica. Antarct Res Unit Spec Rep 1:64

Balks MR, Paetzold R, Kimble JM, Aislabie J, Campbell IB (2002) Effect of hydrocarbon spills on temperature and moisture regimes of Cryosols in the Ross Sea region. Antarct Sci 14(4):319–326

Ball BA, Barrett JE, Gooseff MN, Virginia RA, Wall DH (2011) Implications for meltwater pulse events for soil biology and biogeochemical cycling in a polar desert. Polar Res 30:14555. doi:10.3402/polar.v30i0.14555

Ball BA, Virginia RA (2012) Meltwater seep patches increase heterogeneity of soil geochemistry and therefore habitat suitability. Geoderma 189–190:652–660

Baraniecki CA, Aislabie J, Foght JM (2002) Characterisation of *Sphingomonas* sp. Ant 17, an aromatic hydrocarbon-degrading bacterium isolated from Antarctic soil. Microb Ecol 43:44–54

Bargagli R (2008) Environmental contamination in Antarctic ecosystems. Sci Total Environ 400(1–3):212–226

Barrett JE, Virginia RA, Hopkins DW, Aislabie J, Bargagli R, Bockheim JG, Campbell IB, Lyons WB, Moorhead DL, Nkem JN, Sletten RS, Steltzer H, Wall DH, Wallenstein MD (2006) Terrestrial ecosystem processes of Victoria Land, Antarctica. Soil Biol Biochem 38:3019–3034

Bej AK, Saul DJ, Aislabie J (2000) Cold tolerance of alkane-degrading bacteria isolated from soil near Scott Base, Antarctica. Polar Biol 23:100–105

Blanchette RA, Held BW, Jurgens JA, McNew DL, Harrington TC, Duncan SM, Farrell RL (2004) Wood destroying soft rot fungi in the historic expeditions huts of Antarctica. Appl Environ Microbiol 70:1328–1335

Blanchette RA, Held BW, Arenz BE, Jurgens JA, Bates NJ, Duncan SM, Farrell RL (2010) An Antarctic hotspot for fungi at Shackleton's historic hut on Cape Royds. Microb Ecol 60:29–38

Bockheim JG (2010) Evolution of desert pavements and the vesicular layer in soils of the Transantarctic Mountains. Geomorphology 118:433–443

Braun C, Mustafa O, Nordt A, Pfeiffer S, Peter HU (2012) Environmental monitoring and management proposals for the Fildes Region, King George Island, Antarctica. Polar Res 31:18206. doi:10.3402/polar.v31i0.18206

Broadbent ND (1994) An archaeological survey of Marble Point, Antarctica. Antarct J 19:3–6

Broady PA (1981) The ecology of sublithic terrestrial algae at the Vestfold Hills, Antarctica. Br Phycol J 16(3):231–240

Campbell IB, Claridge GGC (1975) Morphology and age relationships of Antarctic soils. In: Suggate RP, Cresswell MM (eds) Quaternary studies. R Soc N Z Bull 13:87–88

Campbell IB, Claridge GGC (1987) Antarctica, soils, weathering processes and environment. Elsevier, New York, 368 pp

Campbell IB, Balks MR, Claridge GGC (1993) A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. Polar Rec 29(171):321–328

Campbell IB, Claridge GGC, Balks MR (1994) The effects of human activities on moisture content of soils and underlying permafrost from the McMurdo Sound region, Antarctica. Antarct Sci 6(3):307–314

Campbell IB, Claridge GGC, Balks MR (1998a) Short- and long-term impacts of human disturbances on snow-free surfaces in Antarctica. Polar Rec 34(188):15–24

Campbell IB, Claridge GGC, Campbell DI, Balks MR (1998b) Soil temperature and moisture properties of Cryosols of the Antarctic Cold Desert. Eurasian Soil Sci 31(5):600–604

Cannone N, Wagner D, Hubberten HW, Guglielmin M (2008) Biotic and abiotic factors influencing soil properties across a latitudinal gradient in Victoria Land, Antarctica. Geoderma 144:50–65

Cary SC, McDonald IR, Barrett JE, Cowan DA (2010) On the rocks: the microbiology of Antarctic Dry Valley soils. Nat Rev Microbiol 8(2):129–138

Chan Y, Van Nostrand JD, Zhou J, Pointing SB, Farrell RL (2013) Functional ecology of an Antarctic Dry Valleys landscape. Proc Natl Acad Sci (USA) 110:8990–8995

Chong CW, Pearce DA, Convey P, Tan IKP (2012) The identification of environmental parameters which could influence soil bacterial community composition on the Antarctic Peninsula—a statistical approach. Antarct Sci 24:249–258

Chong CW, Tan GYA, Wong RCS, Riddle MJ, Tan IKP (2009) DGGE fingerprinting of bacteria in soils from eight ecologically different sites around Casey Station, Antarctica. Polar Biol 32:853–860

Chown SL, Huiskes AHL, Gremmen NJM, Lee JE, Terauds A, Crosbie K, Frenot Y, Hughes KA, Imura S, Kiefer K, Lebouvier M, Raymond B, Tsujimoto M, Ware C, Van de Vijver B, Bergstron DM (2012) Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. Proc Natl Acad Sci 109 (13):4938–4943

Claridge GGC, Campbell IB, Powell HKJ, Amin ZH, Balks MR (1995) Heavy metal contamination in some soils of the McMurdo Sound region, Antarctica. Antarct Sci 7:9–14

Claridge GGC, Campbell IB, Balks MR (1999) Movement of salts in Antarctic soils: experiments using lithium chloride. Permafrost Periglac Process 10:223–233

Cockell CS, Mckay CP, Warren-Rhodes K, Horneck G (2008) Ultraviolet radiation-induced limitation to epilithic microbial growth in and deserts – Dosimetric experiments in the hyperarid core of the Atacama Desert. J Photochem Photobiol B-Biol 90 (2):79–87

Committee for Environmental Protection (2005) Guidelines for environmental impact assessment in Antarctica, resolution 4. CEP Handbook, 2007

Cowan DA, Chown SL, Convey P, Tuffin M, Hughes K, Pointing S, Vincent WF (2011) Non-indigenous microorganisms in the Antarctic: assessing the risks. Trends Microbiol 19:540–548

Delille D (2000) Response of Antarctic soil bacterial assemblages to contamination by diesel fuel and crude oil. Microb Ecol 40:159–168

Duncan SM, Minasaki R, Farrell RL, Thwaites JM, Held BW, Arenz BE, Jurgens JA, Blanchette RA (2008) Screening fungi isolated from historic Discovery Hut on Ross Island, Antarctica for cellulose degradation. Antarct Sci 21:1–8

Farrell RL, Arenz BE, Duncan SM, Held BW, Jurgens JA, Blanchette RA (2011) Introduced and indigenous fungi of the Ross Island historic huts and pristine areas of Antarctica. Polar Biol 34:1669–1677

Flocco CG, Gomes NCM, Mac Cormack W, Smalla K (2009) Occurrence and diversity of naphthalene dioxygenase genes in soil microbial communities from the maritime Antarctic. Environ Microbiol 11:700–714

Foong CP, Ling CMWV, Gonález M (2010) Metagenomic analyses of the dominant bacterial community in the Fildes Peninsula, King George Island (South Shetland Islands). Polar Sci 4:263–273

Freckman DW, Virginia RA (1997) Low diversity Antarctic soil nematode communities: distribution and response to disturbance. Ecology 78:363–369

Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotnicki M, Bergstrom DM (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80:45–72

Frysinger GS, Gaines RB, Xu L, Reddy CM (2003) Resolving the unresolved complex mixture in petroleum-contaminated sediments. Environ Sci Technol 37:1653–1662

Ganzert L, Lipski A, Hubberten HW, Wagner D (2011) The impact of different soil parameters on the community structure of dominant bacteria from nine different soils located on Livingston Island, South Shetland Archipelago, Antarctica. Microbiol Ecol 76:476–491

Gennari M, Abbate C, La Porta V, Baglieri A (2007) Microbial response to Na_2SO_4 additions in a volcanic soil. Arid Land Res Manag 21:211–227

Gremmen NJM, Smith VR, van Tongeren OFR (2003) Impact of trampling on the vegetation of subantarctic Marion Island. Arct Antarct Alp Res 35(4):42–446

Greenslade P, Convey P (2012) Exotic Collembola on subantarctic islands: pathways, origins and Biology. Biol Invasions 14:405–417

Grosse G, Romanovsky VE, Jorgenson T, Walter AK, Brown J, Overduin PP (2011) Vulnerability and feedbacks of permafrost to climate change. EOS Trans Am Geophys Union 92(9):73–74

Guerra MBB, Schaefer CEGR, de Freitas Rosa P, Simas FNB, Pereira TTC, Pereira-Filho ER (2011) Heavy metal contamination in century-old manmade technosols of Hope Bay, Antarctic Peninsula. Water Air Soil Pollut 222:91–102

Haff PK, Werner BT (1996) Dynamical processes on desert pavements and the healing of surficial disturbances. Quatern Res 45:38–46

Harris CM (1998) Science and environmental management in the McMurdo Dry Valleys, Antarctica. In: Priscu J (eds) Ecosystem processes in a polar desert: the McMurdo Dry Valleys, Antarctica. Antarctic Research Series 72, American Geophysical Union, Washington

Hillel D (1998) Environmental soil physics. Academic Press, San Diego

Hopkins DW, Sparrow AD, Novis PM, Gregorich EG, Elberling B, Greenfield LG (2006) Controls on the distribution of productivity and organic resources in Antarctic dry valley soils. Proc R Soc Lond Ser B 273:2687–2695

Hughes KA (2006) Bird Island path survey. British Antarctic Survey, Internal report, Cambridge, 53 pp

Hughes KA, Bridge P, Clark MS (2007) Tolerance of Antarctic soil fungi to hydrocarbons. Sci Total Environ 372:539–548

Hughes KA (2010) How committed are we to monitoring human impacts in Antarctica? Environ Res Lett 5(4):3

Hughes KA, Convey P (2010) The protection of Antarctic terrestrial ecosystems from inter- and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. Global Environ Change-Human Policy Dimens 20 (1):96–112

Hughes KA, Lee JE, Tsujimoto M, Imura S, Bergstrom DM, Ware C, Lebouvier M, Huiskes AHL, Gremmen NJM, Frenot Y, Bridge PD, Chown SL (2011) Food for thought: risks of non-native species transfer to the Antarctic region with fresh produce. Biol Conserv 144:1682–1689

Hughes KA, Worland RM, Thorne MAS, Convey P (2013) The non-native chrinomid *Eretmoptera murphyi* in Antarctica; erosion of the barriers to invasion. Biol Invasions 15(2):269–281

International Association of Antarctic Tour Operators (IAATO) (2012) Visitor guidelines. http://iaato.org/visitor-guidelines. Accessed 4 Nov 2013

International Association of Antarctic Tour Operators (IAATO) (2013) Tourism statistics. http://iaato.org/tourism-statistics. Accessed 4 Nov 2013

Jabour J (2009) National Antarctic Programs and their impact on the environment. In: Kerry K, Riddle M (eds) Health of Antarctic wildlife. Springer, Berlin, pp 211–229

Jurelevicus D, Cotta SR, Peixoto R, Rosado AS, Seldin L (2012a) Distribution of alkane-degrading bacterial communities in soils from King George Island, Maritime Antarctic. Eur J Soil Biol 51:37–44

Jurelevicus D, Alvarez VM, Peixoto R, Rosado AS, Seldin L (2012b) Bacterial polycyclic aromatic hydrocarbon ring-hydroxylating dioxygenases (PAH-RHD) encoding genes in different soils from King George Bay, Antarctic Peninsula. Appl Soil Ecol 55:1–9

Kennicutt MC, Klein A, Montagna P, Sweet S, Wade T, Palmer T, Denoux G (2010) Temporal and spatial patterns of anthropogenic disturbance at McMurdo Station, Antarctica. Environ Res Lett 5 (3):1–10

Kerry KR, Riddle MJ (2009) Health of Antarctic wildlife. A challenge for science and policy. Springer, New York

Kiernan K, McConnell A (2001) Land surface rehabilitation research in Antarctica. Proc Linnean Soc NSW 123:101–118

Kim M, Kennicutt MC II, Qian Y (2006) Molecular and stable carbon isotopic characterization of PAH contaminants at McMurdo Station, Antarctica. Mar Pollut Bull 52:1585–1590

Klein AG, Sweet ST, Wade TL, Sericano JL, Kennicutt MC II (2012) Spatial patterns of total petroleum hydrocarbons in the terrestrial environment at McMurdo Station, Antarctica. Antarct Sci 24:450–466

Luz AP, Pellizari VH, Whyte LG, Greer CW (2004) A survey of indigenous hydrocarbon degradation genes in soils from Antarctica and Brazil. Can J Microbiol 50:323–333

Ma Y, Wang L, Shao Z (2006) *Pseudomonas*, the dominant polycyclic aromatic hydrocarbon-degrading bacteria isolated from Antarctic soils and the role of large plasmids in horizontal gene transfer. Environ Microbiol 8:455–465

McFadden LD, Wells SG, Jercinovich MJ (1987) Influences of aeolian and pedogenic processes on the origin and evolution of the desert pavement. Geology 15:504–509

McLeod M (2012) Soil and permafrost distribution, soil characterisation and soil vulnerability to human foot trampling, Wright Valley, Antarctica. PhD thesis, University of Waikato, New Zealand, 219 pp

Molina-Montenegro MA, Carrasco-Urra F, Rodrigo C, Convey P, Valladares F, Gianoli E (2012) Occurrence of the non-native bluegrass on the Antarctic mainland and its negative effects on native plants. Conserv Biol 26:717–723

Naveen R (1996) Human activity and disturbance: building an Antarctic site inventory. In: Ross R, Hofman E, Quetin L (eds) Foundations for ecosystem research in the Western Antarctic Peninsula region. American Geophysical Union, Washington, DC, pp 389–400

Norbek KJ, Blomberg A (1998) Amino acid uptake is strongly affected during exponential growth of *Saccharomyces cerevisiae* in 0.7 M NaCl medium. FEMS Microbial Letters 158:121–126

Okere UV, Cabrerizo A, Dachs J, Jones KC, Semple KT (2012) Biodegradation of phenanthrene by indigenous microorganisms in soils from Livingstone Island, Antarctica. FEMS Microbiol Lett 329:69–77

Olech M, Chwedorzewska KJ (2011) The first appearance and establishment of an alien vascular plant in natural habitats on the forefield of a retreating glacier in Antarctica. Antarct Sci 23:153–154

O'Neill TA, Balks MR, López-Martínez J (2012a) The effectiveness of environmental impact assessments on visitor activity in the Ross Sea Region of Antarctica. In: Lundmark L, Lemelin R, Müller D (eds) Issues in polar tourism: communities, environments, politics. Springer, Berlin, pp 87–110

O'Neill TA, Balks MR, López-Martínez J, McWhirter J (2012b) A method for assessing the physical recovery of Antarctic desert pavements following human-induced disturbances: a case study in the Ross Sea region of Antarctica. J Environ Manag 112:415–428

O'Neill TA (2013) Soil physical impacts and recovery rates following human-induced disturbances in the Ross Sea region of Antarctica. PhD thesis, University of Waikato, New Zealand, 369 pp

O'Neill TA, Balks MR, López-Martínez J (2013a) Soil surface recovery from vehicle and foot traffic in the Ross Sea region of Antarctica. Antarct Sci 25(4):514–530

O'Neill TA, Balks MR, Stevenson B, López-Martínez J, Aislabie J, Rhodes P (2013b) The short-term effects of surface soil disturbance on soil bacterial community structure at an experimental site near Scott Base, Antarctica. Polar Biol 36(7):985–996

Pertierra LR, Hughes KA, Benayas J, Justel A, Quesada A (2013) Environmental management of a scientific field camp in Maritime

Antarctica: reconciling research impacts with conservation goals in remote ice-free areas. Antarct Sci 25(2):307–317

Ritchie GD (2003) Biological and health effects of exposure to kerosene-based jet fuels and performance additives. J Toxicol Environ Health, Part B 6:357–451

Roura R (2004) Monitoring and remediation of hydrocarbon contamination at the former site of Greenpeace's World Park Base, Cape Evans, Ross Island, Antarctica. Polar Rec 40(212):51–67

Saul DJ, Aislabie J, Brown CE, Harris L, Foght JM (2005) Hydrocarbon contamination changes the bacterial diversity of soil from around Scott Base, Antarctica. FEMS Microbiol Ecol 53:141–155

Santos IR, Silva EV, Schaefer CE, Albuquerque MR, Campos LS (2005) Heavy metal contamination in coastal sediments and soils near the Brazilian Antarctic Station, King George Island. Mar Pollut Bull 50(2):185–194

Schimel DS, Parton WJ (1986) Microclimatic controls of nitrogen mineralization and nitrification in shortgrass steppe soils. Plant Soil 93(3):347–357

Scott JJ, Kirkpatrick JB (1994) Effects of human trampling on sub-Antarctic vegetation of Macquarie Island. Polar Record 30:207–220

Secretariat of the Antarctic Treaty (SAT) (1991) Protocol on environmental protection to the Antarctic Treaty. http://www.ats.aq/documents/recatt/Att006_e.pdf. Accessed 1 Aug 2013

Sheppard DS, Claridge GGC, Campbell IB (2000) Metal contamination of soils at Scott Base, Antarctica. Appl Geochem 15:513–530

Smith RIL, Richardson M (2011) Fuegian plants in Antarctica-natural or anthropogenically-assisted immigrants? Biol Invasions 13:1–5

Snape I, Morris CE, Cole CM (2001) The use of permeable reactive barriers to control contaminant dispersal during site remediation in Antarctica. Cold Reg Sci Technol 32(2–3):157–174

Sparrow AD, Gregorich EG, Hopkins DW, Novis P, Elberling B, Greenfield LG (2011) Resource limitations on soil microbial activity in an Antarctic dry valley. Soil Biol Biochem 75:2188–2197

Stark SC, Snape I, Graham NJ, Brennan JC, Gore DB (2008) Assessment of metal contamination using X-ray fluorescence spectrometry and the toxicity characteristic leaching procedure (TCLP) during remediation of a waste disposal site in Antarctica. J Environ Monit 10:60–70

Summerson R, Bishop ID (2011) Aesthetic value in Antarctica: beautiful or sublime? Polar J 1:225–250

Summerson R, Bishop ID (2012) The impact of human activities on wilderness and aesthetic values in Antarctica. Polar Res 31:1–21

Tejedo P, Justel A, Rico E, Benayas J, Quesada A (2005) Measuring impacts on soils by human activity in an Antarctic specially protected area. Terra Antart 12:57–62

Tejedo P, Justel A, Benayas J, Rico E, Convey P, Quesada A (2009) Soil trampling in an Antarctic specially protected area: tools to assess levels of human impact. Antarct Sci 21(3):229–236

Tin T, Fleming L, Hughes KA, Ainsley DG, Convey P, Moreno CA, Pfeiffer S, Scott J, Snape I (2009) Review: impacts of local human activities on the Antarctic environment. Antarct Sci 21:3–33

Wall DH, Virginia RA (1999) Controls on soil biodiversity: insights from extreme environments. Appl Soil Ecol 13:137–150

Wall DH (2007) Global change tipping points: above- and below-ground biotic interactions in a low diversity ecosystem. Philos Trans R Soc B Biol Sci 362:2291–2306

Waterhouse EJ (ed) (2001) Ross Sea Region 2001: a state of the environment report for the Ross Sea Region of Antarctica. New Zealand Antarctic Institute, Christchurch

Webster J, Webster K, Nelson P, Waterhouse E (2003) The behaviour of residual contaminants at a former station site, Antarctica. Environ Pollut 123(2):163–179

Whyte LG, Schultz A, van Beilen JB, Luz AP, Pellizari V, Labbe D, Greer CW (2002) Prevalence of alkane monooxygenase genes in Arctic and Antarctic hydrocarbon-contaminated and pristine soils. FEMS Microbiol Ecol 41:41–150

Wichern J, Wichern F, Joergensen RG (2006) Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. Geoderma 137:100–108

Wynn-Williams DD (1990) Ecological aspects of Antarctic microbiology. In: Marshall KC (ed) Advances in microbial ecology, vol 2. Plenum Press, New York, pp 71–146

Yergeau E, Bokhorst S, Huiskes AHL, Boschker HTS, Aerts R, Kowalchuk GA (2007) Size and structure of bacterial, fungal and nematode communities along an Antarctic environmental gradient. FEMS Microbiol Ecol 59:436–451

Zabinski CA, Gannon JE (1997) Effects of recreational impacts on soil microbial communities. Environ Manag 21(2):233–238