16 | Regional Assessment of Soil Change in Antarctica

Contributing author: Megan Balks

16.1 | Antarctic soils and environment

Antarctica has a total area of 13.9 × 106 km^2, of which 44 890 km^2 (0.32 percent) is ice-free (Fox and Cooper, 1994; British Antarctic Survey, 2005) with potential for soil development. Ice free areas are mainly confined to the Antarctic Peninsula, a few places around the perimeter of the continent and along the Transantarctic Mountains. The largest ice-free area (approximately 5 000 km^2) is the McMurdo Dry Valleys in the Ross Sea Region.

Mean annual temperatures vary from near 0°C in the moister, marine influenced Antarctic Peninsula to about -20°C in dry, higher altitude inland areas (Campbell and Claridge, 1987). Many soils are formed on mixed tills with some directly formed on bedrock. Organic matter is minimal (< 0.1 percent) in drier, colder inland areas. However, in areas where free moisture occurs, mosses and, on the Antarctic Peninsula, higher plants, may grow and accumulate to form peat soil materials. Ornithogenic materials dominate soils at many coastal locations (e.g. Hofstee *et al.*, 2006). Surface ages in coastal and Antarctic Peninsula regions tend to be predominantly Holocene, exposed by retreat of the Last Glacial Maximum ice. At higher elevations in the McMurdo Dry Valleys, surfaces as old as Mid-Miocene (14 Ma) have been reported (Sugden, Bentley and Cofaigh, 2006) indicating low erosion rates under a stable polar desert climate. Soil microclimates, driven by strong topographic variability, also influence soil properties (Balks *et al.*, 2013).

A wide variety of soils occur in the ice-free areas (Campbell and Claridge, 1987). Gelisols (Soil Survey Staff, 2014) or Cryosols (IUSS Working Group WRB, 2014) are the predominant soils in Antarctica. Cryosols contain permafrost at depth and are overlain by an active layer that thaws during the summer and is frozen in winter. In moister coastal areas the permafrost is ice-cemented and thus 'frozen solid'. However in some inland areas of the Trans-Antarctic Mountains, including the McMurdo Dry Valleys, there is not enough moisture to form ice-cement so soils with temperatures well below 0°C are loose and easily excavated (Bockheim, 1978; Campbell and Claridge, 1987). The soils range from Gelisols (Cryosols) in the Ross Sea Region, through Gelisols and Entisols in coastal East Antarctica, to a mixture of Gelisols, Entisols, Spodosols and Inceptisols in the warmer northern Antarctic Peninsula Region where permafrost is not ubiquitous (Balks *et al.*, 2013). Due to limited weathering in the cold climate, many Antarctic soils are dominantly gravelly sands. Where vegetation is absent, a protective desert pavement usually forms at the soil surface. The focus for studies on Antarctic soils is not on their potential for food production, but rather on their genesis, diversity, and vulnerability to impacts of human activity.

16.2 | Pressures/threats for the Antarctic soil environment

Most of the human activities in Antarctica, including historic huts, modern research stations, and tourist visits, are concentrated in the relatively accessible, small, ice-free areas, on the coast, particularly in the Ross Sea region and Antarctic Peninsula (O'Neill et al,. in press).

Antarctica was first recorded by three whaling ships in 1820 leading to regular whaling visits and the Ross expedition of 1839-1940. The 'heroic era' of exploration (1895–1917) included expeditions such as those of Borchgrevink, Scott, Shackleton, Mawson and Amundsen. Since the International Geophysical Year (1957-1958), greatly increased human activity has occurred with over 70 scientific research bases established, mainly around the Antarctic coast. Ship-based Antarctic tourism has become popular with 46 000 tourists reported in the 2007/08 summer and 27 700 in the 2013-2014 season (IAATO, 2014).

Legacies of human occupation are scattered at isolated sites across Antarctica, particularly in areas close to the major research stations and semi-permanent field camps (Campbell, Balks and Claridge, 1993; Kennicutt *et al.*, 2010; Tin *et al.*, 2009). Impacts have included physical disturbance as a result of construction activities, geotechnical studies, and roading (Campbell, Balks and Claridge, 1993; Campbell, Claridge and Balks, 1994; Harris, 1998; Kennicutt *et al.*, 2010; Kiernan and McConnell, 2001); local pollution from hydrocarbon spills (Aislabie *et al.*, 2004; Kim, Kennicutt II and Qian, 2006; Klein *et al.*, 2012) and from waste disposal (Claridge *et al.*, 1995, Snape, Morris and Cole, 2001; Santos *et al.*, 2005; Sheppard, Claridge and Campbell, 2000); introduction of alien species (Frenot *et al.*, 2005; Chown *et al.*, 2012; Cowan *et al.*, 2011); and disturbance to soil biological communities (de Villiers, 2008; Harris, 1998; Naveen, 1996; Tin *et al.* 2009 and references therein). The amount of contaminated soil and waste has been estimated at 1–10 million m^3 (Snape, Morris and Cole, 2001). The presence of persistent organochlorine pollutants in Antarctica has been attributed to long-range atmospheric transport from lower latitudes (Bargagli, 2008).

Antarctic soils are easily disturbed and natural recovery rates are slow due to low temperatures and often a lack of liquid moisture (Campbell, Balks and Claridge, 1993, 1998a; Campbell *et al.*, 1998b; Kiernan and McConnell, 2001; Waterhouse, 2001). Where physical disturbance removes the protective 'active layer' the underlying permafrost will melt with resulting land surface subsidence and, in drier regions, accumulation of salt at the soil surface (Campbell, Claridge and Balks, 1994; Waterhouse, 2001). Campbell and Claridge (1975, 1987) recognized that older, more weathered desert pavements and associated soils were the most vulnerable to physical human disturbance. However disturbances on active surfaces, such as gravel beach deposits, aeolian sand dunes and areas where melt-water flows, have the capacity to recover (visually) relatively quickly (McLeod, 2012; O'Neill, Balks and López-Martínez, 2012b, 2013: O'Neill *et al.*, 2012a).

Fuel spills are the most common source of soil contamination and have the potential to cause the greatest environmental harm in and around the continent (Aislabie *et al.*, 2004). Hydrocarbon fuel spills have been shown to persist in the environment for decades, with fuel perching on top of ice-cemented permafrost (Balks *et al.*, 2002). When spilled on Antarctic soils, possible fates of the hydrocarbons include dispersion, evaporation, and biodegradation. 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 (Aislabie *et al.*, 2004, 2012). Hydrocarbon spills on Antarctic soils can enrich hydrocarbon-degrading bacteria within the indigenous microbial community (Aislabie *et al.*, 2004, 2012; Delille *et al.* 2000).

Elevated levels of metal concentrations have been reported at base sites especially in areas used for waste disposal or affected by emissions from incinerators or fuel spills (Claridge *et al.* 1995; Sheppard, Claridge and Campbell, 2000; Webster *et al.*, 2003; Santos *et al.*, 2005; Stark *et al.* 2008; Guerra *et al.*, 2011). Particularly high metal levels have been reported at Hope Bay on the Antarctic Peninsula (Guerra *et al.*, 2011) and at the Thala Valley landfill at Casey Station, East Antarctica (Stark *et al.*, 2008). Elevated levels of methyl lead have been detected in soil from a former fuel storage site at Scott Base (Aislabie *et al.*, 2004).

Surface trampling has been shown to impact on soil nematode abundances in the McMurdo Dry Valleys (Ayres *et al.*, 2008) and on arthropod abundance on the Antarctic Peninsula (Tejedo *et al.* 2005, 2009). Potential for introduction of invasive plant, insect, and microbial biota is gaining attention (Cowan *et al.*, 2011; Chown *et al.*, 2012; Greenslade and Convey, 2012).

16.3 | Response

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. 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. Since the ratification of the Madrid Protocol in 1991 environmental awareness has increased and 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 (O'Neill *et al.*, in press).

The ice-free areas visited by humans are small, relative to the Antarctic continent as a whole, and impacts occur as isolated pockets amongst largely pristine Antarctic wilderness (O'Neill *et al.*, in press). The most intense and long-lasting visible impacts occur around the current and former research bases, and are often remnants of activities in the 1950s-1970s prior to the Madrid Protocol (Campbell and Claridge, 1987; Webster *et al.*, 2003; Bargagli, 2008; Kennicutt *et al.*, 2010; O'Neill, 2013). Since the 1980s environmental accountability, management and awareness have increased, and the environmental footprints of stations such as Scott Base and McMurdo Station on Ross Island have remained static or decreased (Kennicutt *et al.*, 2010). For example, there are mechanisms in place to prevent spills, remove wastes, phase out incineration, limit soil disturbance, and protect sites of particular cultural or environmental significance. These mechanisms are proving effective at preventing further damage to Antarctic soils.

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