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Soil Physical Impacts and Recovery Rates Following Human-Induced Disturbances in the Ross Sea region of Antarctica

A thesis
submitted in fulfilment
of the requirements for the degree
of
Doctor of Science in Earth Science

at
The University of Waikato
by
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THE UNIVERSITY OF
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Te Whare Wānanga o Waikato

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‘Glittering white, shining blue, raven black, in the light of sun the land looks like a fairy tale. Pinnacle after pinnacle, peak after peak – crevassed, wild as any land on our globe, it lies unseen, untrodden’ Roald Amundsen, 1904

‘By three methods we may learn wisdom: First, by reflection, which is noblest; second, by imitation, which is easiest; and third by experience, which is bitterest’
Confucius, 551BC

ABSTRACT

With increasing visitor numbers an understanding of the impacts of human activities on Antarctic soil environments has become an important issue. The overall objective of this thesis was to investigate soil physical impacts, and soil recovery rates, following human disturbance in the Ross Sea region of Antarctica. Visually disturbed and nearby control sites were assessed using a combination of techniques, including field-based visual site assessments, comparative photo-records, a desert pavement recovery assessment method, soil sampling, and soil dry bulk density measurements. An experimental soil disturbance trial was set up near Scott Base and bacterial DNA profiling was used to investigate the response of communities to removal of the top 2 cm of soil. Infra-red track counters were installed on Ross Island walking tracks to record visitor use over a two-year period.

Five case studies, from former research stations to field campsites, were investigated to assess the accuracy of the impacts predicted in environmental impact assessments and the observed impacts. 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 environmental awareness of visitors; motivating them to avoid, remedy, or mitigate, their environmental impacts.

A field-based method was developed to assess desert pavement recovery and tested on 54 sites. Eleven criteria were used: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development. Recovery criteria were assigned a severity rating on a scale from zero to four, and the Mean Recovery Index (MRI) of the site was calculated relative to an equivalent control. Five recovery stages were defined as recently or highly disturbed (MRI of 0-24%), through to indistinguishable from control site (MRI = 100%). Fifty of the 54 sites investigated were in an intermediate or higher stage of desert pavement recovery (MRI > 50%), 30 sites were in an advanced stage of recovery (MRI > 75%), and four sites were indistinguishable from adjacent control sites (MRI = 100%). Active surfaces, such as gravel beach deposits, aeolian sand, and alluvial fan deposits, recovered relatively quickly and had higher MRIs, whereas less active sites of higher intensity disturbances, such as bulldozed tracks at Marble Point, had lower MRIs, with only intermediate recovery up to 50 years after disturbance.

Following physical impacts such as foot and vehicle traffic the surface recovery recorded here was often greater than that predicted by previous researchers. At one-off campsites, footprints from dispersed trampling were undetectable within five years. At some sites walking tracks remained visible in the landscape 17 years after they were formed (due to surface recontouring and larger clasts concentrating along track margins). For steep slopes and sites where repeated visits occur, use of a single track is recommended. At sites where visually obvious impacts were remediated by replacing larger stones back in their original positions, ensuring that surface stones are placed with the weathered side up, and raking of gravel sand-sized displaced materials, visible evidence of former occupation was almost undetectable. Concentrating activity on young, active, and readily recoverable surfaces, or resilient bedrock, is recommended.

There were no significant changes in bacterial community structure in response to experimental removal of the top 2 cm of soil over a 35 day sampling period. Differences in bacterial community structure between samples correlated with differences in soil electricity conductivity ($R^2 = 0.55$) and soil pH ($R^2 = 0.67$), reflecting small scale (< 2 m) soil heterogeneity.

Infrared track counters recorded: 5084 passes on the Scott Base to McMurdo Station walking track, 2842 on the Wind Vane Hill walking track, 3561 on the Round Observation Hill walking track, and 10936 on the Up Observation Hill track between January 2009 and January 2011. On the Crater Hill summit walking track there were 693 passes in 2009. Higher counts were recorded on all tracks in the 2010/2011 summer season, compared with the 2009/2010 summer, and the highest frequency of visitors occurred on Sundays in the summer months. Peak daily counts at the Wind Vane Hill track coincided with the arrival of tourist ships. There was no relationship between the number of passes on the track and the measured impacts, indicating that higher usage of a formed track had little cumulative impact. Track width and track incision were related to the slope of the terrain, with tracks traversing flatter areas generally wider ($R^2 = 0.85$) and less incised ($R^2 = 0.96$) than those traversing steeper hillsides. Soil dry bulk density was higher in the walking tracks compared with the adjacent control areas ($p < 0.05$).

ACKNOWLEDGEMENTS

I wish to thank Landcare Research and the Murray Jessen Memorial Doctoral Scholarship for the financial means and support to undertake this doctoral research.

To Dr Megan Balks for your supervision and unwavering support during this journey. I still remember the first time we met and you gave me your laptop and a room in your house to get to work writing our Foundation of Research and Technology proposal. Many thanks for your time, patience, and camaraderie, both in the field and in the office. To Professor Jerónimo López-Martínez, for your supervision, encouragement, and hospitality while I was in Spain. To Errol Balks for field assistance during our second campaign in the Dry Valleys, and for your support over the last 4 years. To Jerónimo, Errol, and Megan - I will not forget our memorable month at Cape Roberts, Cape Evans, and the Wright and Taylor valleys –And Christmas at Marble Point.

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1 INTRODUCTION

1 INTRODUCTION

1.1 Environmental setting of the Ross Sea region of Antarctica

Antarctica, once known as *Terra Incognita*, the unknown land, is a continent of contrasts. Antarctica is the coldest, driest, windiest, highest and most unforgiving continent on Earth, and also an international focus of science, exploration, and public interest.

The Ross Sea region comprises approximately half (or 23,000 km^2) of the ice-free or soil forming areas of the Antarctic continent (Fox & Cooper, 1994). The physical boundaries of the Ross Sea region, as defined by Waterhouse (2001) are inclusive of the 'Siple, Shirase, and Saunders coasts in Marie Byrd Land, the Ross Ice Shelf, and the Transantarctic Mountains from the Amundsen Coast to the Pennell Coast in Oates Land' (Fig. 1).

The dominant landscape features of the Ross Sea region include the Transantarctic Mountains, the Ross Ice Shelf, areas of ice-free ground including the McMurdo Dry Valleys, a number of active volcanoes, and over 4,000 km of coastline. The largest continuous expanse of ice-free ground in Antarctica occurs in the Ross Sea region, known as the McMurdo Dry Valleys in Southern Victoria Land (Fig. 2). The McMurdo Dry Valleys are dominated by three, generally west-to-east- orientated, glacially carved valleys - the Victoria, Wright, and Taylor valleys, and comprise approximately 6,000 km^2 of ice-free ground (Waterhouse, 2001). The McMurdo Dry Valleys are home to the longest river in Antarctica, the Onyx River, and freshwater lakes such as Lake Vanda, and the hypersaline Don Juan Pond, both in the Wright Valley. Glaciers dot the valley walls and summer runoff and snow-patch melt provide water inputs to the desert environment.

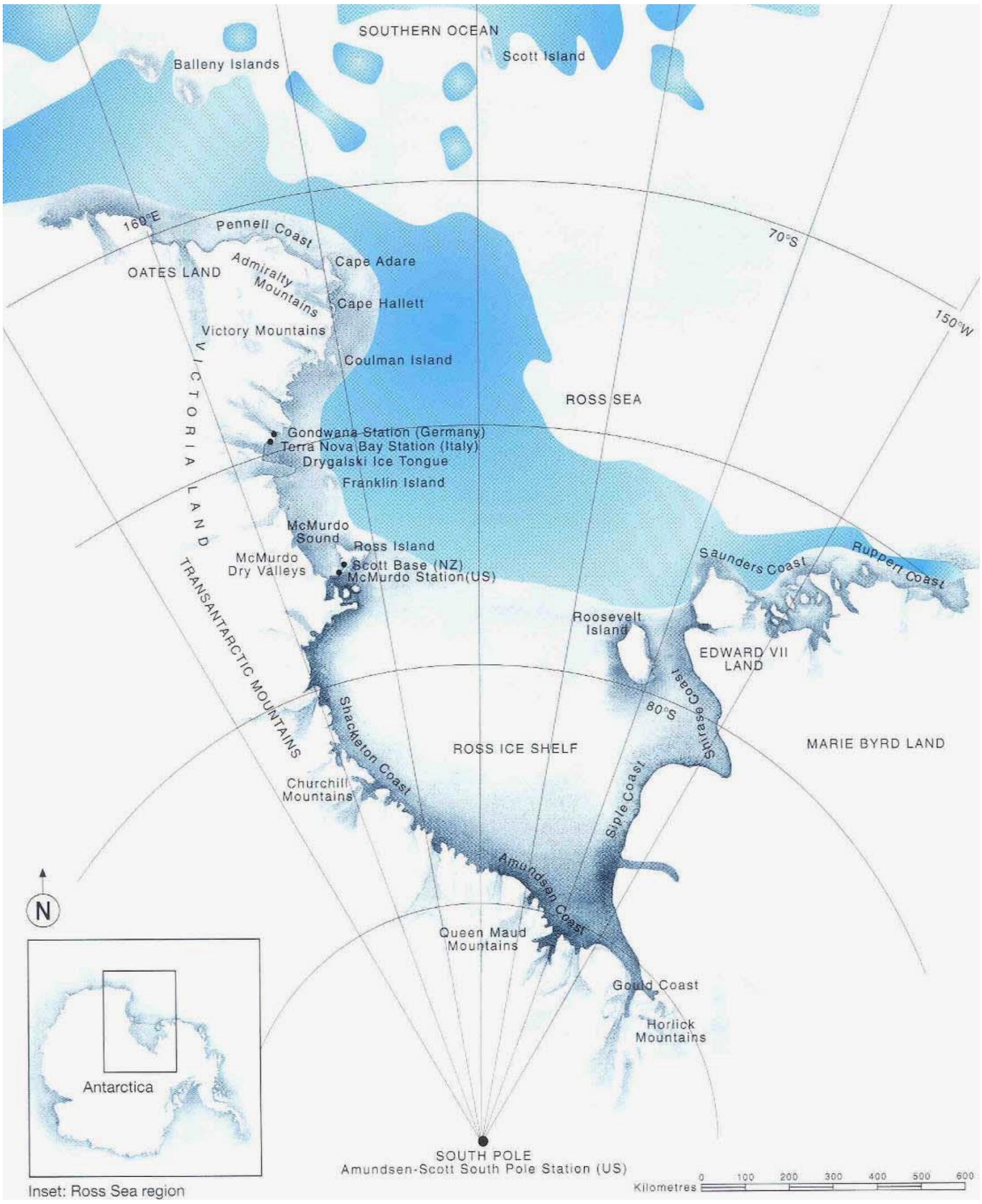

Fig. 1. Map showing the Ross Sea region of Antarctica, *from* Huston & Waterhouse, 2002, p. 2

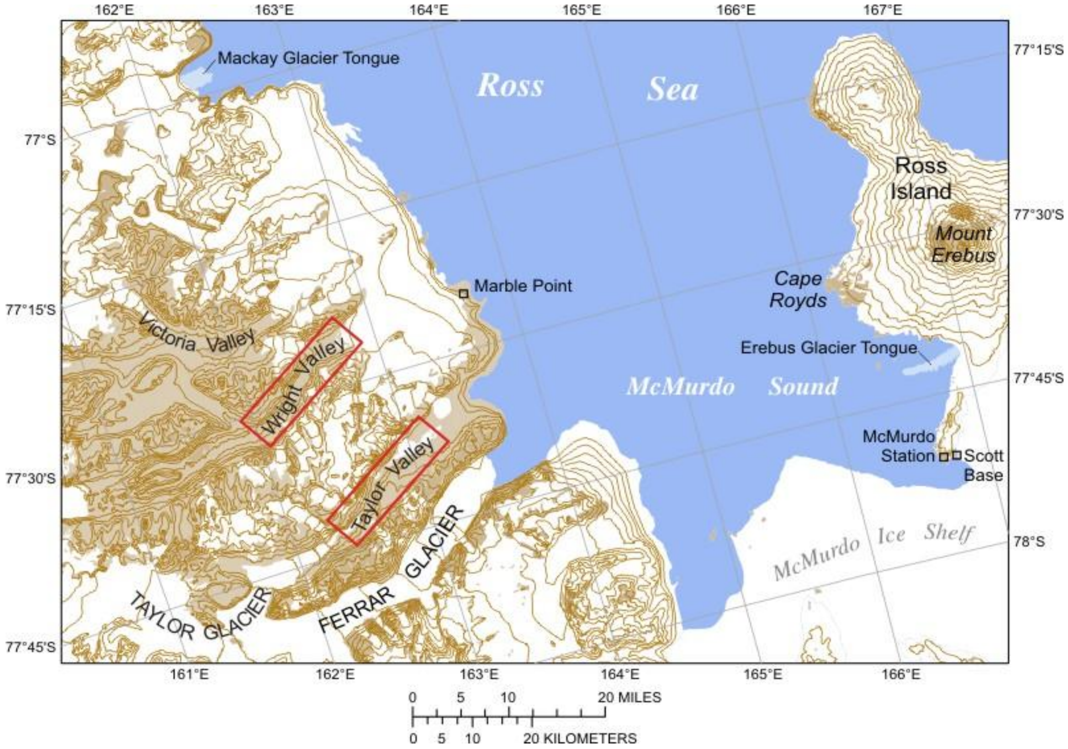

Fig. 2. Map showing the proximity of the McMurdo Dry Valleys (Victoria, Wright, and Taylor valleys) to Ross Island, Scott Base and McMurdo Station, *from* USGS Water Science Center (http://wy.water.usgs.gov/projects/antarctica/htms/map2.htm). Red rectangles show the valleys investigated in this research.

Strong winds, cold temperatures, and storms are synonymous with Antarctica and are a challenge for visitors. Continental coastal Ross Sea region temperatures are comparatively warm compared with the Antarctic interior, with the monthly mean air temperatures at Scott Base ranging from -1 °C in January to -38 °C in May (data *from* Scott Base climate station, USDA, http://soils.usda.gov/survey/smst/antarctica/ScottBase/). The McMurdo Dry Valleys have extremely low annual precipitation (approximately 10-15 mm per annum rainfall equivalent as snow, Campbell and Claridge, 1987), and thus are a desert environment.

The Ross Sea region is a harsh environment for terrestrial biota. There are no land-based vertebrate animals or flowering plants, and so primary producers are cyanobacteria, eukaryotic algae, mosses, and lichens (Wall, 2007). Terrestrial fauna found in the Ross Sea region include collembola, mites, nematodes and protozoa (Wall, 2007).

1.2 Soil environment of the Ross Sea region of Antarctica

Low precipitation, extremes in temperature, and minimal biological activity, characterise the environment from which the soils of the Ross Sea region have evolved. Bare rock is estimated to comprise 10% of the ice-free areas in the Ross Sea region (Waterhouse, 2001) and soil forming materials are diverse. Ross Sea region soils are found on weathered rock surfaces, volcanic scoria, scree and till deposits on the valley walls, floors, and mountain cirques. To a lesser extent, soils can also be found on reworked aeolian and fluvial deposits, coastal beach gravels, and even developed on guano amongst penguin rookeries. The plethora of soil parent materials, including sandstones, basaltic scoriaceous rocks, granites, grano-diorites, and dolerite intrusions, result in a range of soils that fall within the United States Department of Agriculture soil taxonomy Gelisol order (Soil Survey Staff, 2010).

The diversity of soils in the ice-free areas of the Ross Sea region are a function of regional geographical and glacial history (land-surface age), topographic position, local climate variations and associated soil forming processes such as physical and chemical weathering, and soil parent material (Table 1). A common thread through almost all Ross Sea region soils is the occurrence of desert pavement and the presence of permafrost.

Table 1. Geographic location, landforms, parent materials, soil classification, climatic zone, soil moisture regime, weathering, and salt stages at Ross Sea region sites investigated in this thesis.

Geographic location	Landforms	Parent material	Dominant soil classification[1]	Ross Sea region climatic zone[2]	Soil moisture regime[3]	Wxg stage[4]	Salt stage[5]	Depth to permafrost[6]
Ross Island - Hut Point Peninsula	Gently undulating lava flows	Scoriaceous basalt	Typic Haplorthel	Moist coastal mountain	Subxerous	1	1	32 cm
- Capes Evans and Royds	Gently undulating lava flows, beach deposits	Scoriaceous basalt	Typic Haplorthel	Moist coastal mountain	Subxerous	1	1	50 cm
Antarctic Mainland - Cape Roberts	Active beach	Beach gravels and grano-diorite bedrock	Typic Haploturbel Typic, Lithic Haplorthel	Moist coastal mountain	Subxerous	1	0,1	60 cm
- Marble Point	Outwash moraine, wetland	Marble dominated till with granite, dolerite sandstone and gneiss	Typic, Calcic, Lithic Haplorthel	Moist coastal mountain	Subxerous	1,2	1	49 cm
	Raised beach deposits	Gravelly sands	Typic Haploturbel, Typic Haplorthel					
McMurdo Dry Valleys - Wright and Taylor valleys	Glacial moraines, alluvial and colluvial fans, low ridges on valley floors,valley walls	Mixed till of gneiss, grano-diorite origin, fractured grano-diorite, grano-diorite-lamprophytic sands, dolerite, and sandstone	Typic, Lithic, Anhyorthel, Typic Haplorthel, Typic Haplorthel	Central mountain	Xerous	1,2	1	46 cm
		Bedrock outcrops	Lithic Anhyorthel					
		Aeolian sands of granite dominated mixed till origin	Typic Anhyorthel					

Notes: [1]Soil classification *after* Soil Survey Staff (2010); [2]Ross Sea region climatic zones *after* Campbell and Claridge (1987); [3]Soil moisture regime *after* Campbell & Claridge (1969); [4]Soil weathering stage *after* Campbell & Claridge (1975); [5]Soil salt stage *after* Bockheim (1997); [6]Depth to permafrost from Adlam et al. (2010), calculated over eight successive summers from 1999/2000 to 2006/2007 and estimated from knowledge of climate at site and active layer depth in neighbouring similar areas.

Ross Sea region soils generally lack structural development and coherence, and the loose material is covered by a thin protective layer of gravel, or coarse sand, known as a desert pavement Desert pavements play an important role in the desert system, acting as protective armour to stabilize both the slope and the soil (McFadden et al. 1987). 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, by definition, 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 beneath Ross Sea region soils is an important soil property as it has implications for landscape stability and will be discussed further in Chapter 2.

The soil ecosystems of the Ross Sea region are exposed to large variations in temperature and solar radiation (24-hour sunlight in the summer and 24-hour darkness in the winter), steep chemical gradients, and high levels of UVB light. To further accentuate the hostility of the environment, physical and chemical properties associated with soils also impose low levels of soil organic matter, low bioavailability of water, and often high salinity conditions upon soil communities (Cary et al., 2010).

1.3 Human activity in the Ross Sea region of Antarctica

1.3.1 Early explorers

Sir James Clark Ross discovered the Ross Sea in 1842; landings followed and the first winter-over was conducted by the Norwegian-crewed British Antarctic Expedition between 1898 and 1900. The Heroic Era (1895-1917) comprised at least eight expeditions in the Ross Sea region, and as a consequence, leaders such as Borchgrevink, Scott, Shackleton, and Amundsen, left relics, including huts, relating to human discovery of the continent. These first explorers carried out geographic and scientific exploration, collecting plant, animal, and rock specimens, and mapped previously undiscovered areas. Together with the first visitors and their early scientific and construction activities, come the first legacies of environmental impacts.

1.3.2 Contemporary visitors

The upsurge in scientific activity of the early 1900s was reignited in the International Geophysical Year (IGY) in 1957/58, with three year-round scientific bases established. There are currently four stations in the Ross Sea region, two permanent year-round stations (Scott Base, summer population approximately of 320, winter 10-20; and McMurdo Station, summer population of 1350, winter 350) and two permanent summer-only stations (Terra Nova Bay or Mario Zuchelli, Station, Italy, and Gondwana Station, Germany) (Waterhouse, 2001). An airlink between New Zealand and the Ross Sea region services approximately 100 flights between September and March each year.

The New Zealand, United States, and Italian Antarctic programmes constitute the majority of present day human activities in the Ross Sea region. It is estimated that over the last 50 years, up until 2001, approximately 70,000 people have been involved in scientific research and logistic support in the region (Waterhouse, 2001); an estimate likely to be approaching 90,000 in 2012. Land-based research activities are diverse and in the past have included solid earth geophysics, biological sciences, drilling projects, climatology, and environmental sciences. Large-scale land-based and off-shore drilling projects have included the Dry Valley Drilling Project, the Cape Roberts Drilling Project, and most recently ANDRILL (ANtarctic geological DRILLing). Terrestrial scientific research continues to occur, and can involve soil pit digging, soil sampling, and equipment installation.

Legacies of the last 60 years of scientific investigation and human occupation are scattered at isolated sites across the Ross Sea region, particularly in areas close to the major research stations and semi-permanent field camps (Campbell et al. 1993; Tin et al. 2009; Kennicutt II et al. 2010).

1.3.3 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 and small group cruising in zodiac boats - was initiated in 1966 where passengers were ferried around the Antarctic Peninsula. The first Ross Sea region tourist ship carrying 24 passengers visited Scott Base and McMurdo Station in January 1968. Regular annual ship-based tourism commenced in the early 1990s in the Ross Sea region. Voyages are typically 3-to-4 weeks at sea, with itineraries including visits to sub-Antarctic Islands, Cape Adare, Cape Hallett, and Cape Royds and Cape Evans on Ross Island. The nature of tourism in the Ross Sea region, long journeys on board ice-breaker 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 (IAATO, 2011). Ross Sea region tourism accounts for approximately 2% of the annual Antarctic-wide visitor numbers, a total that peaked in the 2007/08 season with 46,265 tourists (approximately 32,000 landings), and has since dropped to 38,824 for the 2010/11 season (IAATO, 2011). Tourist activities in the Ross Sea region are based largely around visiting historic huts, research stations, seal and penguin breeding sites, and sea-ice walks.

1.4 The Antarctic Treaty System

All activities in the Ross Sea region 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 (ATS).

At the heart of the ATS is the Antarctic Treaty (Antarctic Treaty, 2011), which was signed in Washington on 1 December 1959 by the 12 nations that had been active in Antarctica during the International Geophysical Year (1957/58). The Antarctic Treaty established the guiding principles for all activity in the Ross Sea region. In response to an 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 (the Madrid Protocol) was formulated and adopted for signature in Madrid in October 1991 (see Antarctic Treaty, 2011). The Madrid Protocol designates Antarctica as "a natural reserve devoted to peace and science", and to that end, Annex I of the Madrid Protocol requires that before any kind of activity is conducted the possible environmental impacts need to be assessed. The Madrid Protocol also mandates the protection of the wilderness and aesthetic values of Antarctica. The terms Environmental Impact Assessment (EIA) and wilderness and aesthetic values and where they fit into the greater picture of landscape recovery, vulnerability, and resilience, will be further discussed in Chapter 2.

1.5 Impacts of visitors on the terrestrial environment

Antarctic soils are vulnerable to disturbance due to their physical properties and naturally slow recovery rates suppressed by low temperatures, low levels of precipitation and high aridity. As most human activities are concentrated in ice-free areas of the Ross Sea region, 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 the ability of the most frequented sites to recover after human disturbance, are also increasing.

Current information is insufficient to accurately predict how or to what extent the physical features at particular sites may be adversely affected by repeat visits. This knowledge gap will impede our ability to effectively manage sites of value, and may consequently prove detrimental to the natural assets of the ice-free areas of the Ross Sea region.

1.6 Research objectives

My doctoral study aims to bridge the existing knowledge gap by investigating the physical impacts and soil recovery following human activities in the Ross Sea region of Antarctica. There is a common belief that physical impacts to the Ross Sea region terrestrial environment are permanent, causing long-lasting visible scars on the landscape. Little is known about the recovery of desert pavements, the surface processes involved, and the timescales at which recovery occurs. Specific research objectives were to:

1) Investigate the effectiveness of the current Environmental Impact Assessment system with respect to predicting and managing the effects of visitor activity in the Ross Sea region. This objective is addressed in Chapter 3.

2) Develop a method to investigate the recovery of desert pavement following physical disturbance and test the method on a range of previously disturbed sites, across a variety of parent materials, landforms, and climates. This objective is addressed in Chapter 4.

3) To assess the impacts of, and visual surface recovery from, foot and vehicle traffic on varying soil landscape units in the Ross Sea region, including addressing the long-standing question: what has the greatest impact, single file pedestrian movements which form a "track" or footprints being spread randomly over a wider area (Chapter 5).

4) To investigate the short-term effects of human disturbance on soil bacterial community structure at a controlled experiment near Scott Base. This objective is addressed in Chapter 6.

5) To investigate the relationships between the physiochemical properties of walking tracks and the number of track users at five

popular recreational walking tracks on Ross Island. This objective is addressed in Chapter 7.

The objectives were designed to advance current understanding on how the Ross Sea region terrestrial environment might react to future human disturbance and assist environmental managers and decision makers by allowing better predictive and managerial capability.

1.7 Study locations

The study area comprises locations of former and present day human activity in the Ross Sea region of Antarctica (Fig. 3).

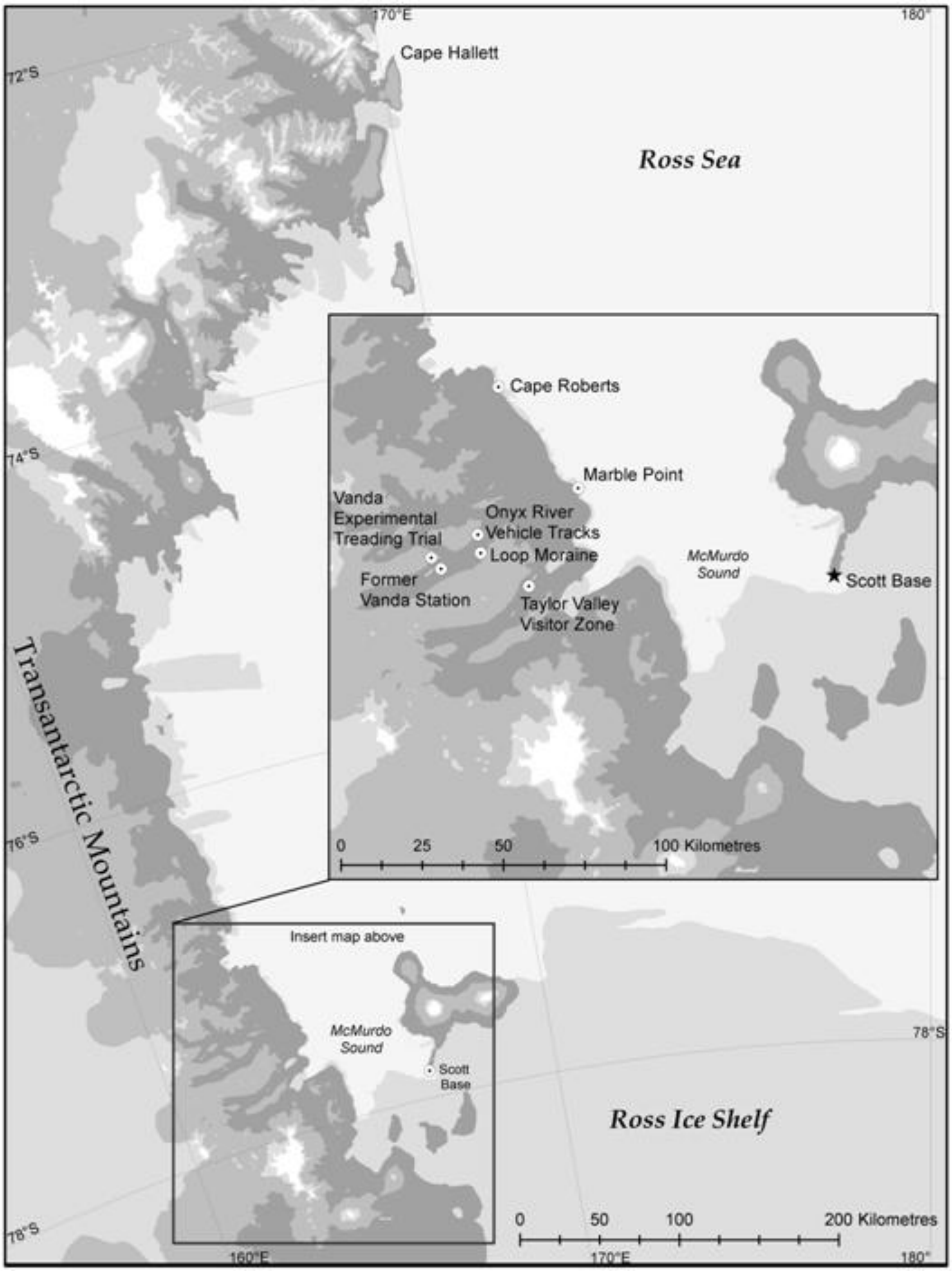

Fig. 3. Map showing the Ross Sea region sites investigated in this thesis.

The following maps illustrate the individual study areas. Study areas included: disturbed sites around the Hut Point peninsula including McMurdo Station and Scott Base (Figs. 3 and 4), Cape Evans, Ross Island (Fig. 5), and on the Antarctic mainland, Cape Roberts (Fig. 3), and Marble Point (Figs. 3 and 6). In the McMurdo Dry Valleys, the Canada Glacier in the Taylor Valley (Figs. 3,6, and 7), and in the Wright Valley, the experimental treading trial sites at Lake Vanda, former Vanda Station, and Loop Moraine campsite (Figs. 3 and 6).

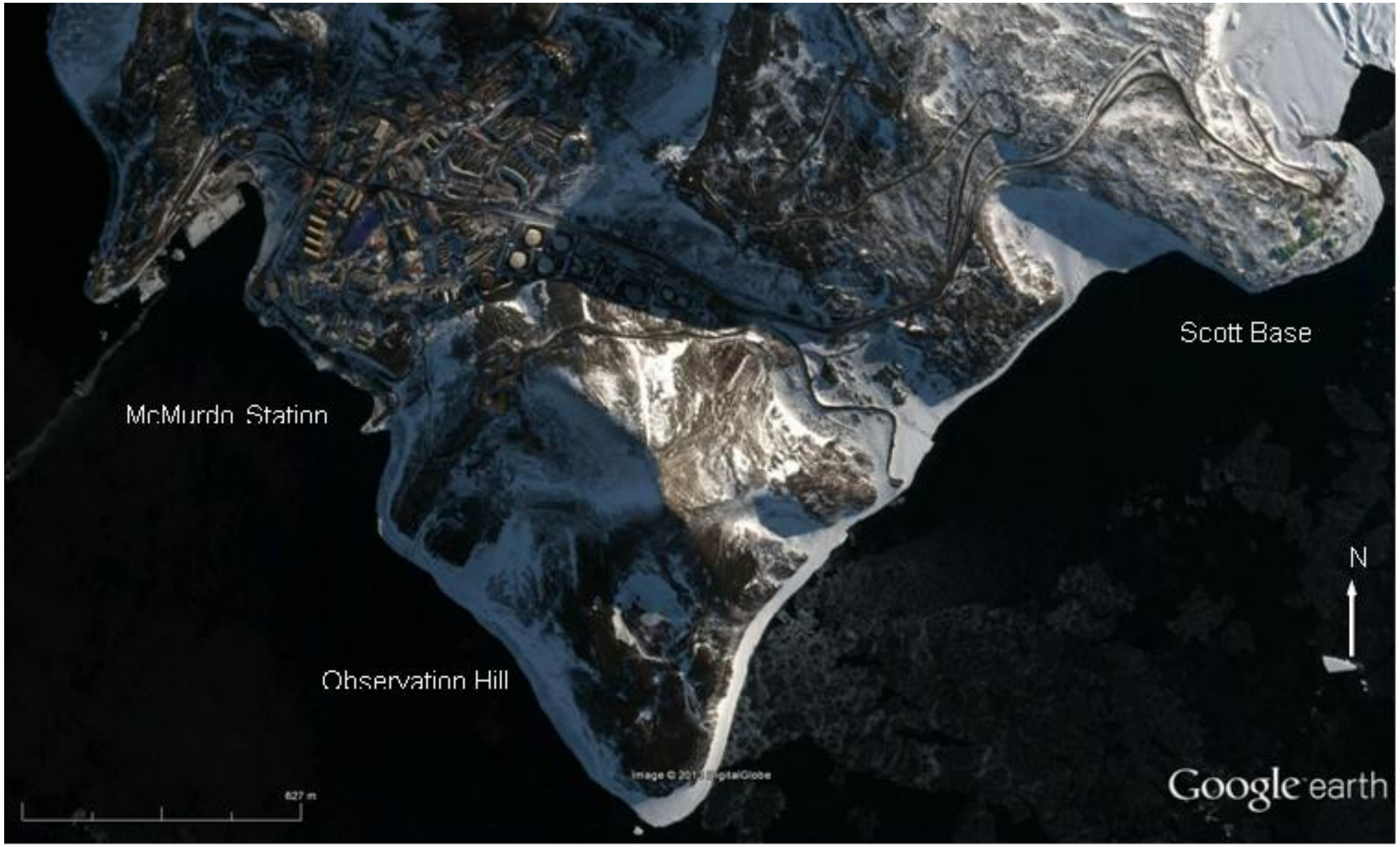

Fig. 4. Satellite image of the southern tip of the Hut Point peninsula, including Scott Base, McMurdo Station, and Observation Hill. Image modified from Google Earth.

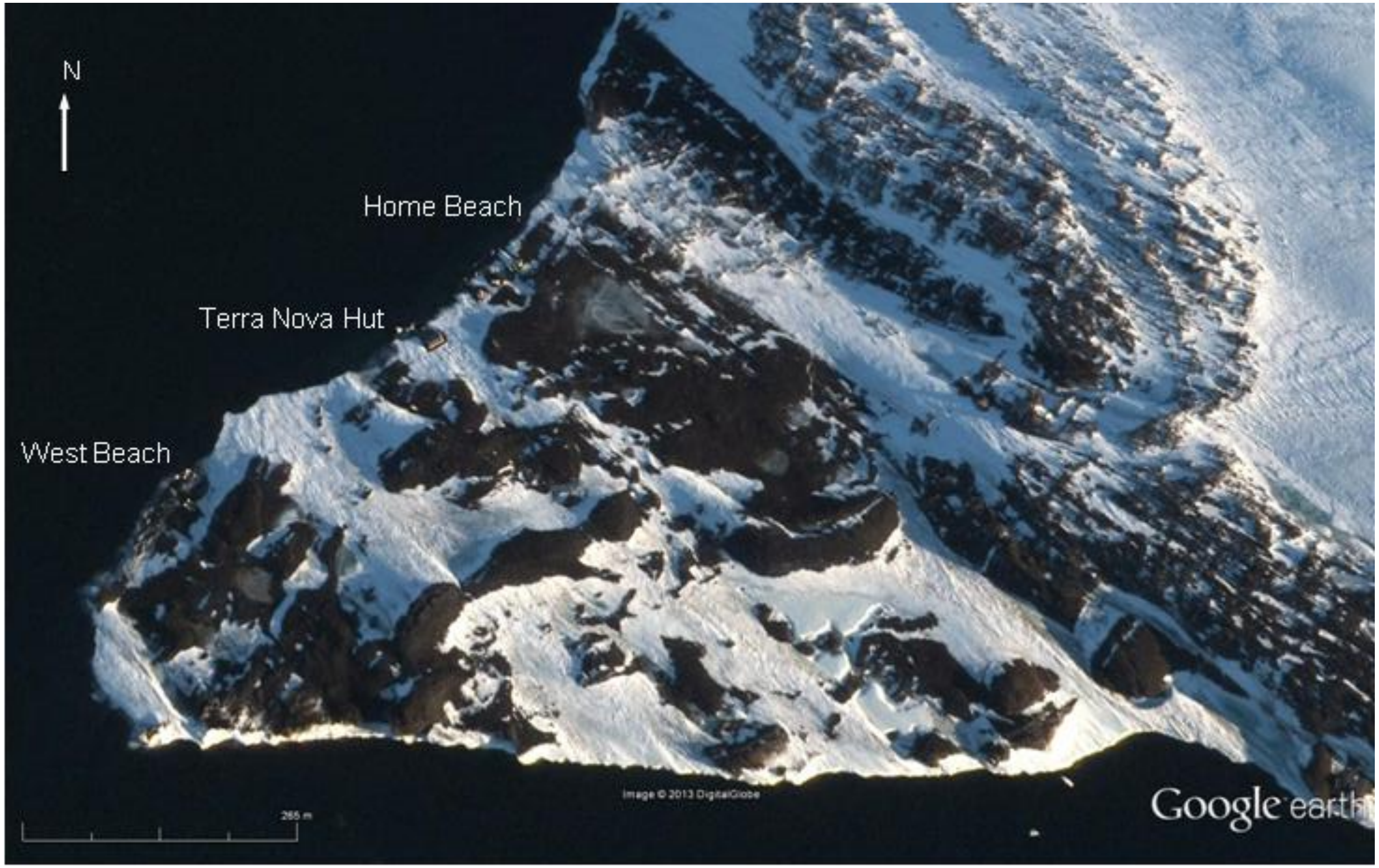

Fig. 5. Satellite image of Cape Evans showing the study sites of Home Beach, West Beach, and Terra Nova Hut. Image modified from Google Earth.

Fig. 6. Satellite image of the McMurdo Dry Valleys, showing the locations of Lake Vanda, the Wright and Taylor valleys, Canada Glacier, and Marble Point. Image modified from Google Earth.

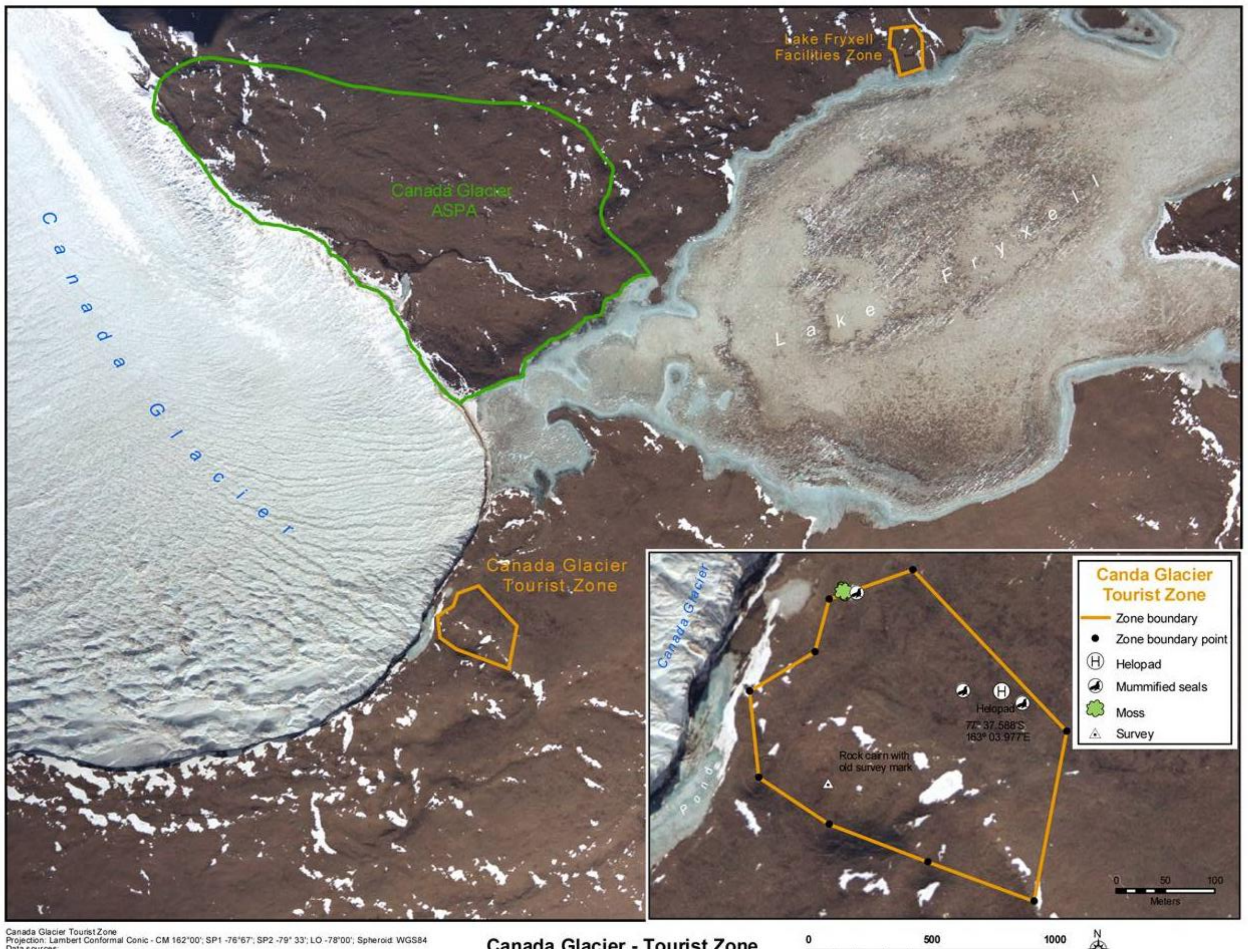

Fig. 7. Satellite image of the Canada Glacier and Tourism Zone, showing zone boundaries and features. Image sourced from Raytheon Polar Services.

1.8 Thesis structure and publications

This thesis is organised into an introductory and literature review chapters, followed by five research papers (three published, and two accepted and waiting final approval). The introduction (Chapter 1) outlines the environmental setting of the Ross Sea region, and also includes dialogue on the soil environment, past and present day human activity, and impacts to the terrestrial environment. The Antarctic Treaty System is also discussed. The literature review chapter (Chapter 2) explores the specific physiochemical and biological characteristics of Ross Sea region soils. A discussion on previous soil disturbance studies is also included, and the environmental protocol to the Antarctic Treaty is discussed in detail. The research papers resulting from this research are as follows:

- Chapter 3, *'The effectiveness of Environmental Impact Assessments on visitor activity in the Ross Sea region of Antarctica'* has been published as a book chapter in a Springer publication entitled: *Issues in Polar Tourism: Communities, Environments, Politics*. Lundmark, L, Lemelin, R,Müller, D. (Eds.) Berlin-Heildelberg-New York: Springer.

- Chapter 4, '*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'* has been published in the *Journal of Environmental Management*.

- Chapter 5, *'Visual recovery of desert pavement surfaces following impacts from vehicle and foot traffic in the Ross Sea region of Antarctica'* is a paper in the *Journal of Antarctic Science*.

- Chapter 6, *'Short-term effects of human disturbances on soil bacterial community structure at an experimental site, Scott Base, Ross Sea region of Antarctica'* has been accepted in the *Journal of Polar Biology*.

- Chapter 7, *'Ross Island recreational walking tracks: relationships between soil physiochemical properties and use'* has been accepted in *Polar Record*, awaiting final proofs and publication.

A discussion and conclusions chapter (Chapter 8) draws on the results of the core papers and closes with a synthesis including on a discussion of the management implications arising from this research, study limitations, and recommendations for further research.

Appendices 1 and 2 comprise supplementary information in the form of two unpublished reports for the environmental management division of Antarctica New Zealand. The first report was prepared in April 2009 and is entitled: *Potential impacts and recovery of soil from camping activities at Cape Evans, Antarctica: Home Beach versus West Beach.* The second report was commissioned for Antarctica New Zealand to assist a mid-2011 review of the Taylor Valley Visitor Zone Management Plan in the McMurdo Dry Valleys, and is entitled: *Canada Glacier Tourism Zone* [now known as the Taylor Valley Visitor Zone] *Antarctica Specially Managed Area Two (ASMA 2): State of the Environment.* Appendix 3 contains soil chemistry data for all Ross Sea region sites. Appendix 4 comprises soil chemistry data for the Scott Base bacterial community structure experiment. Appendix 5 contains soil physiochemical data for the Ross Island walking track sites. Appendix 6 comprises TRF data for the bacterial community structure experiment.

The work presented in this thesis, including fieldwork and laboratory work, data analysis, interpretation and writing, was my own. My PhD supervisors, and paper co-authors, Dr Megan Balks (University of Waikato, New Zealand) and Professor Jerónimo López-Martínez (Universidad Autónoma de Madrid, Spain), accompanied me and assisted in the field and contributed with discussion, advice on all aspects of the work and write-up of the manuscripts, as would be normal for PhD student supervision. Co-authors Bryan Stevenson and Judi McWhirter have helped with advanced statistical analysis.

2 ANTARCTIC SOIL AND HUMAN INTERACTIONS

2 ANTARCTIC SOIL AND HUMAN INTERACTIONS

2.1 Introduction

Impacts of human activities on the Antarctic environment date back to the arrival of the first explorers. The ensuing Heroic-era and development of whaling brought the construction of the first permanent structures, and sustained human presence on the continent. Since the International Geophysical Year in 1957/58, the intensity and diversity of human activities have increased, along with the risk of disturbance to Antarctic flora, fauna, and landscapes. Tin et al. (2009) provides a thorough review of the impacts of local human activities on the Antarctic environment.

The following chapter reviews the current understanding on the physiochemical and biological properties of Ross Sea region soils, and in particular, the properties that influence soil resilience and vulnerability to disturbance. A section follows on previous soil disturbance studies in Antarctica, starting generally, and narrowing down to researcher's works on physical disturbance in the Ross Sea region. Important aspects of the Protocol on the Environmental Protection to the Antarctic Treaty are explored, including Environmental Impact Assessments; and a section on visitor attractions and tourism trends in the Ross Sea region closes the chapter.

2.2 Types of human impacts in Antarctica

Although my focus is directed on the physical disturbance to the Ross Sea region soil environment, past human impact studies have included: chemical contamination from land-based operations (Sheppard et al. 1994, 2000; Claridge et al. 1995, 1999; Campbell et al. 1993) sewage (Edwards et al. 1998; Delille & Delille, 2000; Hughes, 2004; Hughes & Thomspon, 2004;

Santos et al. 2005) and fuel spills (Aislabie, 1997; Aislabie et al. 1998, 2001, 2004, 2006b, 2008; Balks et al. 2002); human impacts to flora and fauna (Harris, 1998; Naveen, 1996; de Villiers, 2008), and in particular wildlife populations (Tin et al. 2009 and references therein).

Studies into the impacts of geoscience and national programme activities on the soil landscape have been undertaken (Campbell et al. 1993; Campbell et al. 1994; Harris, 1998; Kiernan & McConnell, 2001; Kennicutt II et al. 2010). Various studies into the introduction of non-indigenous species to the Antarctic terrestrial environment have also been carried out (e.g. Freckman & Virginia, 1997, Bergstrom & Chown, 1999, Convey, 2006). The bioremediation potential of microbes has been investigated (Aislabie et al. 2006a, Walworth et al. 2008 and references therein).

2.3 Ross Sea region soil characteristics

2.3.1 Desert pavement

Desert pavements, of varying degrees of development, are a feature of Ross Sea region ice-free terrestrial environments. Mature, undisturbed, desert pavements are typically characterised by a closely packed layer of gravel, cobble, and boulder sized rock material, which can be ventifacted, pitted, and coated with desert varnish (Fig. 8a,b) (Campbell and Claridge, 1987).

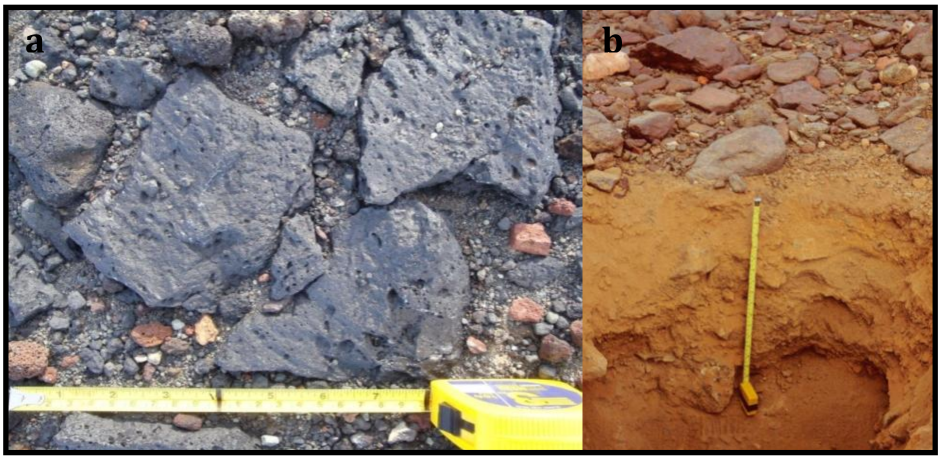

Fig. 8. Typical Antarctic desert pavements. a) Pitted scoriaceous basalt on Crater Hill; b) Beacon Heights sandstone, note polished, lowlying and closely packed nature of pavement surface. Photo: Megan Balks.

Clasts are embedded into a finer matrix, and their undersides are often coated in salts (Claridge, 1965; McCraw, 1967). The clasts are not usually strongly cemented to one another or the substrate beneath. Consequently desert pavements can be vulnerable to disturbance, and once the protective armour of the desert pavement is lost, the underlying fine grained fraction becomes susceptible to wind and water erosion. Desert pavement formation is initiated through the process of winnowing, or deflation by wind (Cooke, 1970), and over time less resistant rocks in the pavement are broken down by weathering processes, while the more resistant rocks become polished, stained and ventifacted (Campbell and Claridge, 1987). As a consequence, soils on the older surfaces can have a desert pavement lithology that is different to the underlying subsoil beneath. Alternative theories of desert pavement evolution include (i) overland flow, (ii) upward migration of clasts (Cooke & Warren, 1973; Ugolini et al. 2008), (iii) *in situ* formation from dust deposition (McFadden et al. 1987), and (iv) physical and/or chemical weathering (Al-Farraj & Harvey, 2000; Al-Farraj, 2008). Theories have evolved from mid-latitude deserts which are comparable in terms of their aridity and low vegetative cover, yet differ from Antarctic desert pavements due to the presence of petrocalcic horizons, and a vesicular layer beneath the desert pavement in mid-latitude settings (Bockheim, 2010). Antarctic desert pavements may also reach greater age compared with their mid-latitude equivalents due to the absence of moist pluvial periods to disrupt pavement formation that occur in the mid-latitudes (Quade, 2001; Bockheim, 2010). Studies by Bockeim (2010) have shown age-related trends in Antarctic desert pavements with clast size decreasing and an increase in clasts showing ventifaction and varnish over time.

2.3.2 Soil parent material and surface characteristics

The lower slopes of Ross Island are dominated by volcanic lava flows (Kyle, 1981), and soils are formed from relatively unweathered (and comparatively young) scoriaceous basalt-dominated till over basalt scoria bedrock (Table 1). Ross Island soils contain considerable amounts of fine material, presumably due to the ease at which scoria breaks up under freeze-thaw processes (Campbell et al. 1998b).

Soils on coastal margins, such as at Cape Evans, are formed on active beach deposited scoriaeous basalt. On the inland valley floors of the Taylor and Wright Valleys, in the McMurdo Dry Valley, soils are formed predominately on till materials of mixed gneiss grano-diorite lithology (Turnbull et al. 1994; Campbell et al. 1998b). Fluvial, fluvio-glacial, colluvial, and aeolian deposits also comprise some of the soils developed on the valley floors. Fluvio-colluvio- and aeolian deposits tend to be weakly developed, and range from bouldery gravel deposits to fine aeolian sands. Bedrock exposures form a significant component of the Wright Valley sites, especially around Lake Vanda. Soils from Marble Point on the Antarctic mainland are formed on marble-dominated tills. Older and more strongly weathered basement material containing veins of micaceous schist outcrop in some areas. Soils at Cape Roberts, located north of Marble Point on the Antarctic mainland, are formed on beach gravels and grano-diorite bedrock (Table 1).

2.3.3 Permafrost

Permafrost is the material beneath the soil active layer (see 2.3.4) that remains perennially frozen for at least two consecutive years (Soil Survey Staff, 2010; Grosse et al. 2011). The interface between the soil active layer and permafrost is not always easy to detect as maximum thaw varies each year, and by location. Near the coast Antarctic permafrost is usually ice-cemented, however in some situations, particularly within the McMurdo Dry Valleys, the water content of the permafrost is less than 5% and insufficient to cement the soil particles together. Soils with low moisture contents may remain loose (dry permafrost) even below freezing point. The depth to ice-cement is used to describe the depth to frozen-hard material at the base of a soil profile, which can be shallower than the depth to permafrost if the site is not sampled at the time of maximum thaw (Campbell & Claridge, 1987; Campbell et al. 1994). Commonly associated with permafrost is a surface feature called patterned ground. Patterned ground is a surface expression of polygonal ground cracks formed through thermal contraction and expansion of the ice-cemented permafrost beneath the ground surface (Campbell & Claridge, 1987). Resulting polygons can be greater than 10 m across (Fig. 9).

Fig. 9. Example of patterned ground in the Taylor Valley, McMurdo Dry Valleys. White arrows show the patterned ground cracks. Photo: Megan Balks.

2.3.4 Soil active layer

Beneath the desert pavement is the active layer, which is the layer of soil material that is frozen in winter and thaws in the summer. The active layer depth in Antarctica has been shown to be spatially variable (Campbell et al. 1998b, Adlam et al. 2010) and is dependent on local climate variations (Campbell et al. 1998b). For example, coastal sites such as Scott Base on the Hut Point Peninsula of Ross Island, has an mean active layer depth of 32 cm (calculated over eight consecutive summers, 1999 until 2007, Adlam et al. 2010; Table 1); whereas inland central mountain climatic zones (Campbell & Claridge, 1987) such as Mt Fleming at 1100 m elevation on the edge of the polar plateau, had a mean active layer depth of 6 cm over the same time period (Adlam et al. 2010).

Ross Sea region soils are generally loose and unconsolidated in nature (Fig. 10a). Soil colour reflects both the parent material and age of the surface (and degree of oxidation) (Campbell & Claridge, 1987). Most Ross Sea region soils lack the distinct horizons commonly seen down a soil profile in temperate regions (Fig. 10b).

Fig. 10. Typical Ross Sea region soil profiles. a) Shallow and unconsolidated soil adjacent to Lake Vanda, Wright Valley, McMurdo Dry Valleys; b) Soil formed in beach gravel deposits at Cape Evans, Ross Island.

2.3.5 Soil moisture

Wide-ranging differences in soil available moisture content across Ross Sea region soils can be attributed largely to climate differences, which in turn influence the physical, chemical, and biological properties of the soils. Campbell & Claridge (1969) defined three soil moisture status regimes for Antarctic soils: ultraxerous, xerous, and subxerous (Table 1). Generally the soils on Ross Island, around Scott Base, McMurdo Station, Cape Royds, and Cape Evans have a subxerous moisture regime (soils may be wet for short periods of each year). For example at Scott Base, summer soil moisture contents are approximately 1-2% at the soil surface and approximately 10% at the active layer base (Campbell et al. 1998b). Coastal regions such as the vicinity of Scott Base, Marble Point, and Cape Roberts have an average of seven snow fall per month during summer (Campbell et al. 1998b). Much of the snowfall sublimates with relatively little soil moistening in many areas. Where snow patches form, and with subsequent melt, soils may become saturated for brief periods. Soils of the drier inland McMurdo Dry Valleys, on the whole, have a xerous moisture regime (some moisture is available for soil processes, but insufficient to cause much movement or leaching of soluble salt). At an experimental site near Lake Vanda in the Wright Valley, summer soil moisture contents were approximately 0.4% at the soil surface and approximately 0.25% at 40 cm depth (Campbell et al. 1998a). Local soil climate and soil moisture variations exist in areas adjacent to thawing snow patches and streams, which when moistened during the warm summer months, may have high soil moisture values (Campbell et al. 1998b; Wall & Virginia, 1999).

2.3.6 Soil salinity

Soluble salts accumulate in Ross Sea region soils via release through rock weathering, where evaporation exceeds precipitation or from atmospheric deposition (Campbell & Claridge, 1987). Salt can manifest as surface efflorescences (Figs. 11a,b), accumulations under clasts within the desert pavement (Fig. 11c) or within the soil profile, or as salt lenses or horizons within the soil profile (Campbell & Claridge, 1987). Under ultraxerous moisture regimes, where soil temperature never reach above freezing point, salts tend to accumulate as single horizons; whereas in xerous moisture regimes, where there is the occasional occurrence of liquid water and occasional snow fall, salts are often dispersed throughout the profile or on the soil surface as surface salt efflorescences.

More than 30 different salt phases occur in the Ross Sea region (Keys & Williams, 1981) but the most common salts are chlorides, nitrates and sulphates of sodium, magnesium, calcium and potassium (Campbell & Claridge, 1987). Keys and Williams (1981) reported that the spatial distribution of salt is a function of soil parent material i.e. salts containing magnesium ions occur mainly on substrates derived from igneous rocks; and is also a function of soil proximity to the coast. Soils dominated by chloride and sodium salts become less common away from the coast.

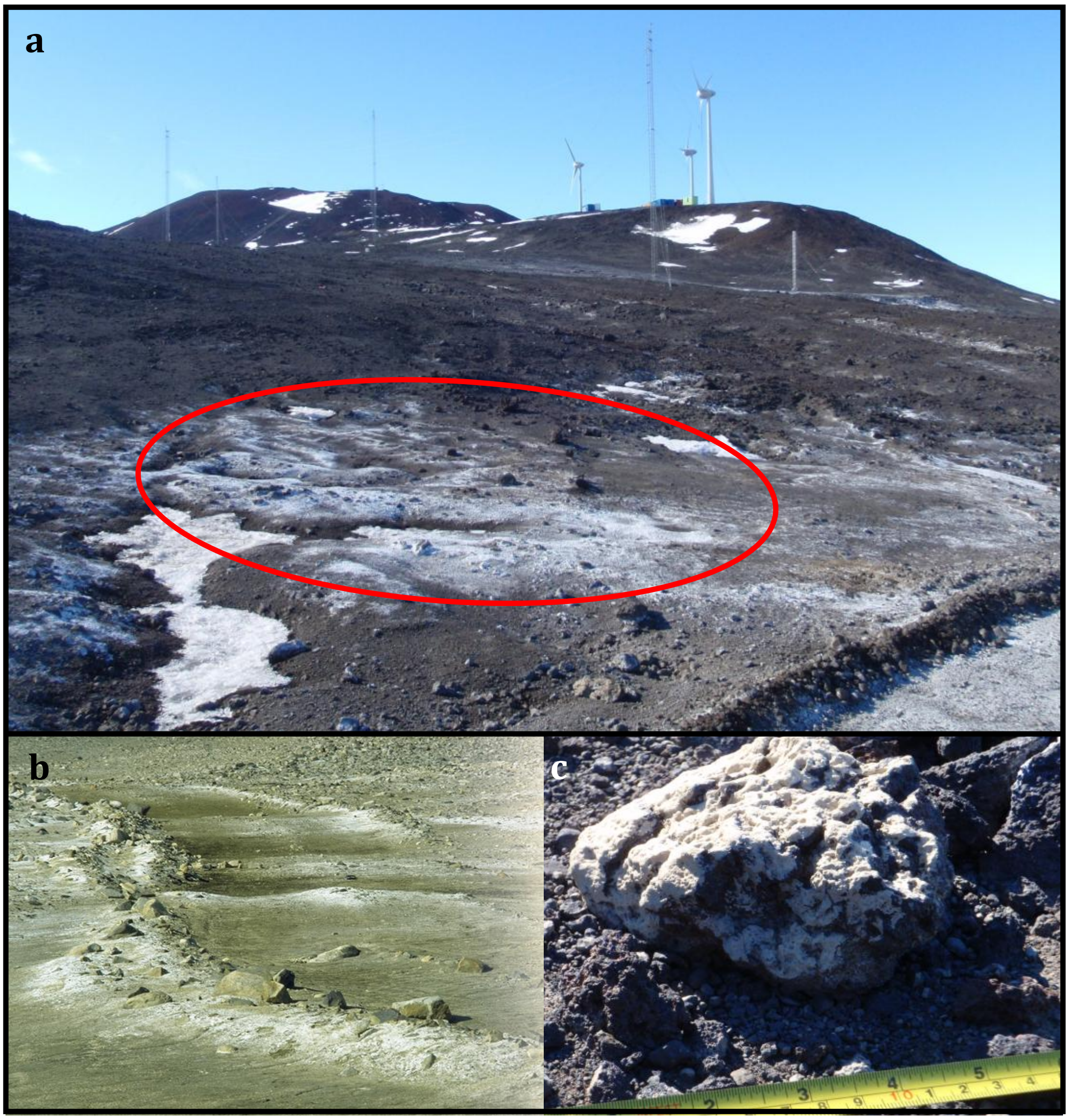

Fig. 11. Examples of salts in the Ross Sea region. a) Red oval marks a surface salt efflorescence resulting from earthworks at the Crater Hill Wind Farm, 3-months prior; b) Surface salt efflorescences forming the margins and hollows of a bulldozed track at Marble Point. Photo taken >30 years after initial disturbance; c) Calcium carbonate salt accumulations under desert pavement clasts.

Common to the Ross Sea region are crusts of calcium carbonate, or calcite, which concentrate on the underside of surface clasts (Fig. 11c). Calcite crusts are related to the weathering of carbonate-containing rocks (Campbell & Claridge, 1987). In marble-rich areas, such as Marble Point, marble is thought to weather and calcium carbonate is formed in the soil, then dissolved and reprecipitated as a crust on the underside of clasts (Haskell et al. 1965). The calcite deposits under clasts in the volcanic Hut Point area of Ross Island are thought to be the result of the solution of carbonates contained in the loess dusts that blow across the McMurdo Sound from the Victoria Land coast (Wellman, 1964).

2.3.7 Soil pH

Soils of the Ross Sea region are generally alkaline (Aislabie et al. 2008) but soil pH can vary widely (Campbell & Claridge, 1987). Soils in areas closer to the coast, such as soils in the Hut Point Peninsula area, where input of marine salts occurs, soil pH can rise to greater than pH 9 (Campbell et al. 1998b). As mentioned previously, Hut Point Peninsula soils are subject to inputs of loessial material, predominantly fine-grained calcium carbonate, which also contribute to high pH. The soils of the McMurdo Dry Valleys are slightly less alkaline than the soils of the coastal region, and pH values are usually below 8.5 in the upper part of the profile, increasing with depth.

2.3.8 Soil biological communities

Soil biological communities in the Ross Sea region include mosses, liverworts, lichens, cyanobacteria, algae, collembola, mites; mesofauna, including rotifers, tardigrades, and nematodes; and microorganisms, bacteria, fungi, and archaea (Waterhouse, 2001). Communities have had to adapt to an extreme environment of high levels of desiccation, high salinity, low nutrient levels, high summer UV radiation levels, and physical instability of the soil surface caused by katabatic winds and freeze-thaw cycles. Mean annual soil temperatures in the Ross Sea region range from -15 °C to -40 °C (Aislabie et al. 2008). However, during the summer months of continuous daylight, soil temperatures can reach up to 20 °C (Balks et al. 2002). As a consequence of the physical and chemical extremes imposed on life in the Ross Sea region, terrestrial ecosystems are predominantly abiotically-driven systems (Hogg et al. 2006).

Microbial populations respond to Antarctic environmental conditions the same way populations respond in more temperate climates – under the most unfavourable conditions, there are no life forms at all, but species diversity and numbers increase towards the more favourable extremes of the environmental gradient (Campbell & Claridge, 1987). Micro-niches exist within the Ross Sea region and extensive biotic communities can occur sporadically where there is light, warmth, moisture, and shelter from the wind (Waterhouse, 2001). Where conditions are favorable, algal crusts, lichen communities (on rock surfaces protected from the wind), and endolithic communities (occurring under rocks or in rock fissures), have been reported. Other unusual environments providing a substrate for biological activity include geothermally heated soils on Mt Erebus (thermophilic bacterial communities); high nutrient and high soil moisture ornithogenic soils at penguin rookeries such as Cape Hallett (Hofstee et al. 2006; Aislabie et al. 2008); and beneath mummified seal carcasses found within the Dry Valleys (where the soil beneath is stabilized from the local environmental conditions) (Cary et al. 2010; Tiao et al. 2012).

Soil pH, salinity, and available water content, can have a major impact on the abundance, community structure, and ecosystem functioning of Antarctic biological systems (Cameron et al. 1970; Kennedy, 1993; Freckman & Virginia, 1997; Billi and Potts, 2002; Saul et al. 2005; Nkem et al. 2006; Smith et al. 2006; Aislabie et al. 2006a, 2006b, 2008; Chong et al. 2009). High spatial variability in abiotic factors, such as water content, can result in high variability in species diversity and community structure (Niederberger et al. 2008; Smith et al. 2010).

A number of investigations into bacterial ecology have been undertaken in the Ross Sea region. When compared with temperate regions Ross Sea region soil bacterial communities have relatively low diversity and are dominated by a few bacterial phylotypes, dominated by: *Acidobacteria*, *Bacterioidetes,* and *Actinobacteria,* as well as *Proteobacteria, Deinococcus-Thermus, Firmicutes* and *Cyanobacteria* (Saul et al. 2005, Smith et al. 2006; Aislabie et al. 2006a; Aislabie et al. 2008); however, recent molecular studies have revealed that Ross Sea region soils harbour higher diversity than originally thought (Barrett et al. 2006a; Yergeau et al. 2007; Niederberger et al. 2008) including as many as 14 different phyla (Cary et al. 2010).

Nkem et al. (2006) showed, in studies carried out in the McMurdo Dry Valleys, that nematode survival, distribution patterns, and abundance, was a function of the ionic composition of the salts in the soil (salt type) as well as the concentration of the salt.

2.4 Previous soil disturbance studies in Antarctica

2.4.1 Introduction

There have been limited previous studies on the ability of the Antarctic soil environment to recover from human disturbance. Soil disturbance-related studies in Antarctica - physical, chemical, and biological - and in chronological order, have included:

- Recognition that a key attribute of Antarctic landscapes was the "weathering stage" which defined the age and stability of the landscape based on the degree of surface boulder weathering and soil morphology (Campbell & Claridge, 1975). It was also recognised that the older, weathering stage 4, 5, and 6, desert pavements and underlying soils, were the most vulnerable to physical human disturbance (Campbell and Claridge, 1987).
- Observations that salt and water is released upon disturbance and accumulates on recently disturbed surfaces (Campbell & Claridge, 1987; Balks et al. 1995).
- Development of a visual site assessment (VSA) by Campbell et al. (1993), including a set of criteria for rapid visual evaluation of present day terrestrial environmental impacts. 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).
- The effects of earth moving activities on patterned ground were investigated on 1959-era cut surfaces at Marble Point (Campbell et al. 1994).
- Investigation of the impact of physical removal of the soil active layer at Scott Base and Marble Point, where it was noted that salt efflorescence's precipitate on the surfaces of recently disturbed sites as the exposed underlying material equilibrated with the environment (Balks et al.

1995). Changes to soil surface albedo, soil moisture, and the soil surface (slumping) were also noted as a consequence of removal of the soil active layer (Balks et al. 1995).

- A treading trial experiment was undertaken at Scott Base, and at sites of contrasting soil materials near Vanda Station, where the rate of track formation was investigated (Campbell et al. 1998a). Campbell et al. (1998a) showed that on some unconsolidated parent materials it takes less than 20 passes for a track to form.
- The capacity for soluble contaminants to move through Ross Sea region soils was investigated by Claridge et al. (1999). 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) revealed the significance of liquid water to facilitate the movement of contaminants down-profile and laterally across the permafrost surface.
- Investigation into the impacts of hydrocarbon spills on Antarctic soil physical, biological, and chemical properties has been carried out by many researchers (Aislabie et al. 1999, 2001, 2004; Deprez et al. 1999; Kennicutt II et al. 2010; Snape et al. 2001; Balks et al. 2002; Webster et al. 2003; Blanchette et al. 2004). Evidence that fuel spills affect soil temperature (by altering surface albedo, Balks et al. 2002); soil moisture (through increased hydrophobicity, Balks et al. 2002); increased soil carbon, decreased soil nitrate and phosphorus (Aislabie et al. 1998; Ferguson et al. 2003), and thereby influenced soil biota through the enrichment of hydrocarbon-degrading microbes (Aislabie et al. 2000, 2001; Delille & Delille, 2000; Delille et al. 2007a,b; Powell et al. 2006; Ferguson et al. 2008), resulting in an overall decrease in microbial community diversity (Aislabie et al. 2001; Saul et al. 2005); were all investigated.
- The use of bioremediation and “assisted bioremediation” (through amelioration of the factors limiting biodegradation by indigenous microbes) has been investigated as a means of ‘cleaning up’ fuel-contaminated soils (Kerry, 1993; Ferguson et al. 2003; Aislabie et al. 2004, 2011; Ruberto et al. 2003, 2005; Stallwood et al. 2005).

- Estimation of the speed of physical recovery at the active beach site of the former Greenpeace World Park Base at Cape Evans (Roura, 2004).
- Investigation into the impacts of human trampling on soils and arthropod populations in the Byers Peninsula of the Antarctic Peninsula (Tejedo et al. 2005, 2009).
- Investigation into the direct effects of foot traffic on soil nematode populations in the Taylor Valley, McMurdo Dry Valleys (Ayres et al. 2008).
- Identification of differences in soil vulnerability across a variety of landforms and parent materials in the Wright Valley of the McMurdo Dry Valleys (McLeod, 2012).

The important aspects of the previous soil disturbance work, specially, how soil physical attributes of Ross Sea region soils relate to soil resilience, vulnerability, and landscape recovery, will be discussed in the following section.

2.4.2 Soil physical disturbance from human activities in the Ross Sea region

Desert pavement disturbances have been considered by Campbell et al. (1998b) to occur at three scales: major, such as base construction, moderate, resulting from vehicle traffic and soil sampling, and low-level disturbance, resulting from foot traffic (Fig. 12a-c).

Fig. 12. Scales of human impacts in the Ross Sea region. a) Major impacts: Scott Base, Ross Island; b) Moderate impacts: camping activities. Photo: Fiona Shanhun; c) Minor impacts: foot traffic. Photo: Megan Balks.

Disturbance to Ross Sea region desert pavements has historically occurred from a number of sources; from vehicles and bulldozers (Campbell et al. 1994; Broadbent, 1994), resulting in the overturning of large cobbles, indentation and compression of sub-pavement soils; through to disturbance resulting from telecommunications antenna and pipeline installation; active layer removal for road or fill material (Balks et al. 1995, 2002); scientific investigation (Campbell et al. 1993; Kiernan & McConnell, 2001); and lower level disturbance from camping and pedestrian traffic (Campbell et al. 1993, 1998a). Previous researchers have noted that Antarctic desert pavement surfaces are easily disturbed and disturbance may have long-lasting visible impacts on the Antarctic landscape (Campbell & Claridge, 1987, Campbell et al. 1993, 1998a,b; Kiernan & McConnell, 2001).

Studies by Campbell et al. (1994) at Marble Point, where major earthworks had been carried out in the 1958/59 summer then abandoned, showed that the areas of patterned ground which had been cut and others that had been covered by fill material, displayed differences in the occurrence of patterned ground and stability of the ground surface. Removal of the upper active layer of the soil resulted in the retreat of the permafrost table and consequent thawing of the ice contained in the upper part of the permafrost (as a new equilibrium is established forming a new active layer). Ensuing lowering of the ground surface, slumping, and release of salts that were contained within the permafrost, which accumulate as surface salt efflorescences when salt-rich water is evaporated, was observed (Campbell et al. 1994). 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).

Previous studies have shown that initial physical disturbance in the landscape is greatest where there was a pebble pavement and the soils had 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 by Campbell et al. (1998a), the least disturbance was observed where the desert pavement was predominately bedrock boulders and cobbles. On the softer till material, after as few as 20 passes, a clear walking track had formed; the finer grained and lighter in colour sediment below was uncovered at the surface of the track (Fig. 13a). In contrast at the rockier site track development was slower and only occurred in the fine-grained sections of the trial surface. The track formed on the rocky, more resilient parent material was much less visible in the landscape (Fig. 13b).

Fig. 13. Vanda Treading Trial Experiment, Wright Valley, McMurdo Dry Valleys. a) Vanda Fan site after 200 passes, 1993/94; b) Vanda Rocky site after 192 passes (last pass, 8 people), 1993/94. Photos: Megan Balks.

The importance of utilising young active surfaces was evident in the commissioning and decommissioning of the Greenpeace World Park Base at Cape Evans. Roura (2004) reported the relatively quick recovery of the active sandy beach gravels of the former Greenpeace World Park Base site. 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 (2012) based his assessment on the impact score of 10 boot prints, and revealed areas of high, medium, and low classes of soil vulnerability within the Wright Valley.

2.4.3 Microbial communities and disturbance in the Ross Sea region

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 & 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 have described the effects of human disturbance on biota, particularly microbial communities, in Antarctica.

On a macro- flora and fauna level there are no land-based vertebrate animals or flowering plants in the Ross Sea region of 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.

On a mesofauna level, 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, 1998). The influence of soil salinity on population dominance was recognised in soil nematode studies in the McMurdo Dry Valleys (Wall & 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 & Virginia, 1999). Ayres et al. (2008) investigated the direct effects of foot traffic on soil nematode populations over a 10 year period in the Taylor Valley, McMurdo Dry Valleys. The authors noted decreased abundances of the dominant nematode *S. lindsayae* in the walking tracks that received high levels of human foot traffic, compared with lower level tracks; the ratio of living to dead nematodes also declined with higher track usage, indicating increased mortality; and higher levels of trampling also reduced soil respiration at one site.

Lichens and mosses have been documented in the McMurdo Dry Valleys (Hale, 1987; Green et al. 1992) and lichens have also been observed in the vicinity of Scott Base on the Hut Point Peninsula (J. Newman, Environmental

Advisor to Antarctica New Zealand, personal communication, 15 May 2009). No investigations into the effect of human activity on lichen or moss distribution has been undertaken in the Ross Sea region, however, it is assumed that past and present day activities around Scott Base, including use of bulldozers and vehicles will have influenced the spatial distribution of local populations (J. Newman, Environmental Advisor to Antarctica New Zealand, personal communication, 15 May 2009). Algae and cyanobacteria are probably the major primary producers in the Ross Sea region (Waterhouse, 2001) 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). 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. (1998b) 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. 1998b). However, in areas where available water is plentiful, for instance wetland areas at Marble Point bulldozed during the late 1950s, surface salt is able to be redissolved and leached down the profile, allowing algae and mosses to re-establish (Campbell et al. 1994).

Little is known about the impact of human activities on microbes, the primary decomposers, bacteria and fungi. At a local level, trampling could dislodge soil particles and pebbles which protect the soil interface. This could in turn expose deeper soil, change soil temperatures, moisture, and freeze-thaw patterns; effectively modifying the habitat for microbes (Wall, 2007). Furthermore, moderate scale disturbances, such as vehicle movement has the potential to impact soil physical properties such as compression and bulk density, which can impact soil macro and micro porosity. In temperate localities, compaction, through the loss of aggregate stability and reduction of pore space has been shown to affect soil microbial communities through by affecting the water holding capacity and aeration of the soil (Schimel & Parton, 1986; Zabinski & Gannon, 1997). Changes to soil respiration, decomposition rates and the availability of nutrients may result, thereby affecting ecosystem functioning of the entire soil system.

2.4.4 Cumulative impacts from human activities in the Ross Sea region

Cumulative impacts refer to individual and often minor impacts that may be significant when accumulating 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 regarding 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 to have very little impact, may together amount to a substantially greater 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 which have happened previously in that same area. Repetitive disturbance, whether associated with scientists walking to-and from experimental sites, or tourists walking around the walking tracks in the Taylor Valley Visitor Zone, although low in intensity, can have a cumulative effect. Previous experimental treading trial work by Campbell et al. (1998a, Fig. 13) has 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, versus 200 passes, versus 2000 passes, are minimal. Of the three parameters Campbell et al. (1998a) assessed, width of the formed track, number of surface boulders and cobbles, and % area of pale colour exposed, the greatest measurable impact was observed within the first 20 passes of the track. Cumulative impacts on biota are also unknown but likely to affect biodiversity and ecosystem functioning (Wall, 2007).

Researchers from the largest scientific station in Antarctica, McMurdo Station, 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 II et al. 2010). Their results showed the cumulative impacts of station activities expanding rapidly in spatial extent over the first decade of occupancy, after which the station continued to expand at a slower rate (Kennicutt II 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 (J. Newman, Environmental Advisor to Antarctica New Zealand, personal communication, 4 Jan 2010).

2.5 Visitor impacts to the Ross Sea region and the Environmental Protocol

2.5.1 Introduction

The Antarctic Treaty establishes the guiding principles for all human activity in Antarctica. Within the Antarctic Treaty System resides the Protocol on Environmental Protection to the Antarctic Treaty (referred to as the Protocol) which sets out common minimum standards for environmental management by all Antarctic Treaty Parties. On a national level, all of the countries operating national programmes in the Ross Sea region are signatories to the Protocol and have national procedures and domestic legislation in place to ensure that the provisions of the Protocol are implemented. In New Zealand, the Antarctica (Environmental Protection) Act regulates the environmental aspects of all activities organized *in* New Zealand or proceeding to Antarctica *from* New Zealand.

2.5.2 Environmental Impact Assessments

The term Environmental Impact Assessment (EIA) was introduced in Article 8 of the Protocol and is a process whereby persons responsible for an activity in Antarctica predict the 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* http://www.antarcticanewzealand.govt.nz):

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 a proposal may have and how the potential impacts can be best prevented or mitigated. In New Zealand EIAs must be approved by the Antarctic Policy Unit of the New Zealand Ministry of Foreign Affairs and Trade before any activity can commence. Antarctica New Zealand, a crown research institute, advises the Ministry of Foreign Affairs and Trade on environmental issues, including EIAs, and is responsible for managing, and executing New Zealand Government activities in Antarctica.

For activities where a CEE is necessary, such as the multinational Cape Roberts Drilling Project (1997-1999), the draft CEE is made publically available and considered by the Committee for Environmental Protection (which was established to advise parties on implementation of the Protocol). The Antarctic Treaty signatories meet annually to discuss issues relating to Antarctica. At the Antarctic Treaty Consultative Meetings the Committee for Environmental Protection then gives expert advice on the proposed activities, comments are provided by other Treaty signatory representatives, and a decision is made as to whether and how the activity is to be conducted.

A key aspect of the Protocol, and mandatory for any activity requiring a CEE, is the requirement to quantify and regularly monitor impacts caused during the project (Hughes, 2010; Kennicutt II et al. 2010). Ideally, monitoring should include ongoing assessment of the levels of physical disturbance to marine and terrestrial environments, should record levels of pollutants (noise, dust, chemical, 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 & Convey, 2010).

2.5.3 Wilderness and aesthetic values

The Protocol on Environmental Protection to the Antarctic Treaty also mandates the protection of wilderness and aesthetic values. Article 3, Environmental Principles, states the following:

1. The protection of the Antarctic environment and dependant and associated ecosystems and the intrinsic values of Antarctica, including wilderness and aesthetic values and its value as an area for the conduct of scientific research, in particular research essential to understanding the global environment, 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) activities in the Antarctic Treaty area shall be planned and conducted so as to avoid: ….. (iv) degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance (SAT 1991).

Despite the inclusion of wilderness and aesthetic values under the Madrid Protocol there is no formal definition in the Madrid Protocol or elsewhere in the Antarctic Treaty System of how these values should be defined in the context of Antarctica (Summerson and Bishop, 2011). Wilderness values are conventionally thought of as relating to large natural areas undisturbed by human activity (Summerson and Bishop, 2012). Kormos and Locke (2008) refer to wilderness areas as the "most intact, undisturbed, wild, natural areas- those last truly wild places that humans do not control and have not developed with roads and other industrial infrastructure". Aesthetic values relate to a persons perception of scenic beauty. In a recent study by Summerson and Bishop (2011, 2012) a survey comprising 90 images of Antarctic landscapes was established on the internet to investigate people's perceptions of wilderness and aesthetic preference. Summerson and Bishop have shown that the evidence of human activity, especially infrastructure, detracts from aesthetic value (Summerson and Bishop, 2011). Furthermore, it is the presence of infrastructure that defines permanent human presence, and so it is one of the key factors in deciding whether an area can be designated as a wilderness area (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 transitory, ranging from ships and aircraft to minor transitory activity, such as small field camps. When considering site recovery, sufficient weighting should therefore be put on the visual component of surface recovery (site appearance) as it is likely to impact on the aesthetic and wilderness values of the site.

2.5.4 Visitors to the Ross Sea region and Environmental Impact Assessments

The Antarctic Treaty, in its original form, lacked the instruments needed to manage the growing tourism industry. Antarctic tourism and where it fits within the Antarctic Treaty System (ATS) and EIA systems, particularly with respect to the cumulative environmental impacts of tourism, remains a controversial topic (Hemmings & Roura, 2003; Bastmeijer & Roura, 2004). The Protocol on Environmental Protection to the Antarctic Treaty stipulates that cumulative impacts be considered as a component of the EIA process, however, the level of analysis this "consideration" requires is not defined, and not necessarily suitable to the transient, fast-moving, multisite activities that characterize contemporary Antarctic tourism (Bastmeijer & Roura, 2004).

The Antarctic tourism industry is regulated by the Antarctic Treaty system and by the International Association of Antarctic Tourism Operators (IAATO). IAATO was founded in 1991 and currently has more than 100 Antarctic-bound operators as voluntary members of the organisation. IAATO 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, 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 (IAATO, 2012). There is increased environmental awareness amongst visitors to Antarctica, and growing effort to manage and prevent environmental impacts.

At present, tourism operators are required to undertake an EIA, however it is commonplace for tourism EIAs to lack adequate detail about the planned itinerary, potential sites, and activities to be undertaken. It is the nature of the tourism industry in both the Antarctic Peninsula and Ross Sea region, that itineraries need to be flexible in terms of the number of sites, and order of sites visited. When scheduled landings are not possible, due to sea-ice for example, opportunistic landings are commonplace. Cumulative impacts are addressed in Chapters 3, 5, and 8 of this doctoral research.

2.5.5 Visitor attractions and tourism trends in the Ross Sea region

In the years 2005/06 through to 2008/09 twenty sites in the Ross Sea region have been frequently visited by tourists, science personnel and base staff. The 12 most frequented sites and their attractions are summarized in Table 2.

Four of the most frequented sites (excluding ice landings) are Cape Evans, Cape Royds, Hut Point Peninsula, and Cape Adare. Approximately 1100 people (national programme personnel and tourists) visit Scott's Terra Nova Hut at Cape Evans annually; 800 visit Shackleton's Nimod Hut at Cape Royds; and 1000 people visit Scott's Discovery Hut at Hut Point (Table 3) (Antarctica New Zealand, 2012). Tourist visitors comprise the greater proportion of visitors to Cape Royds and Cape Adare each year, whereas, Cape Evans is visited by a large number of United States and New Zealand base personnel (Table 3). McMurdo Station staff also comprises the largest proportion of visitors to Scott's Discovery Hut on the Hut Point Peninsula, due to the close proximity to the station, making it a "must see" attraction amongst staff and science event personnel in the evenings and on their days off. These huts are designated Antarctic Specially Protected Areas (ASPAs) under the Antarctic Treaty and all visitors require permits.

Table 2. The 12 most visited sites in the Ross Sea region, over the summer seasons 2005/06 and 2008/09, and their attractions (data from Newman, 2009).

Site	**Attractions**
Ice landings	Ice bergs, ice tongues, wildlife.
Cape Royds	Historic hut and associated artefacts from British Antarctic (Nimrod) Expedition 1907- (Fig. 14a), led by Sir Ernest Shackleton (ASPA 157). Adelie penguin colony (ASPA 121).
Cape Adare	Historic hut and associated artefacts from British Antarctic (Southern Cross) Expedition 1898-1900, led by Carsten Borchgrevink (ASPA 159). Remains of Scott's Northern Party (Terra Nova Expedition, 1911) hut. Adelie penguin colony.
Cape Evans	Historic hut and associated artefacts from British Antarctic (Terra Nova) Expedition 1910-1913 (Fig. 14b,c), led by Captain Robert Falcon Scott (ASPA 155).
Franklin Island	Adelie penguin colony.
Terra Nova Bay	Italian summer station and Adelie penguin colony.
Inexpressible Island	Historic site where the Northern Party of Scott's Terra Nova Expedition wintered over in a snow cave in 1912. Adelie penguin colony.
Hut Point Peninsula	Includes Scott Base (Fig. 15a), Crater Hill Wind Farm (Fig. 15b) McMurdo Station (Fig. 16a), and Observation Hill (Fig. 16b). Historic hut at Hut Point, from British Antarctic Expedition (Discovery, 1901-1904), led by Captain Robert Falcon Scott (ASPA 158).
Cape Washington	Emperor penguin colony (Fig. 17a).
Coulman Island	Emperor penguin colony.
Cape Hallett	Adelie penguin colony. Protected site (ASPA 107) for avifauna and vegetation.
Canada Glacier	Taylor Valley Visitor Zone (ASMA 2). Canada Glacier views, proglacial lakes, mummified seals, ventifacts, and spectacular McMurdo Dry Valley views (Fig. 17b).

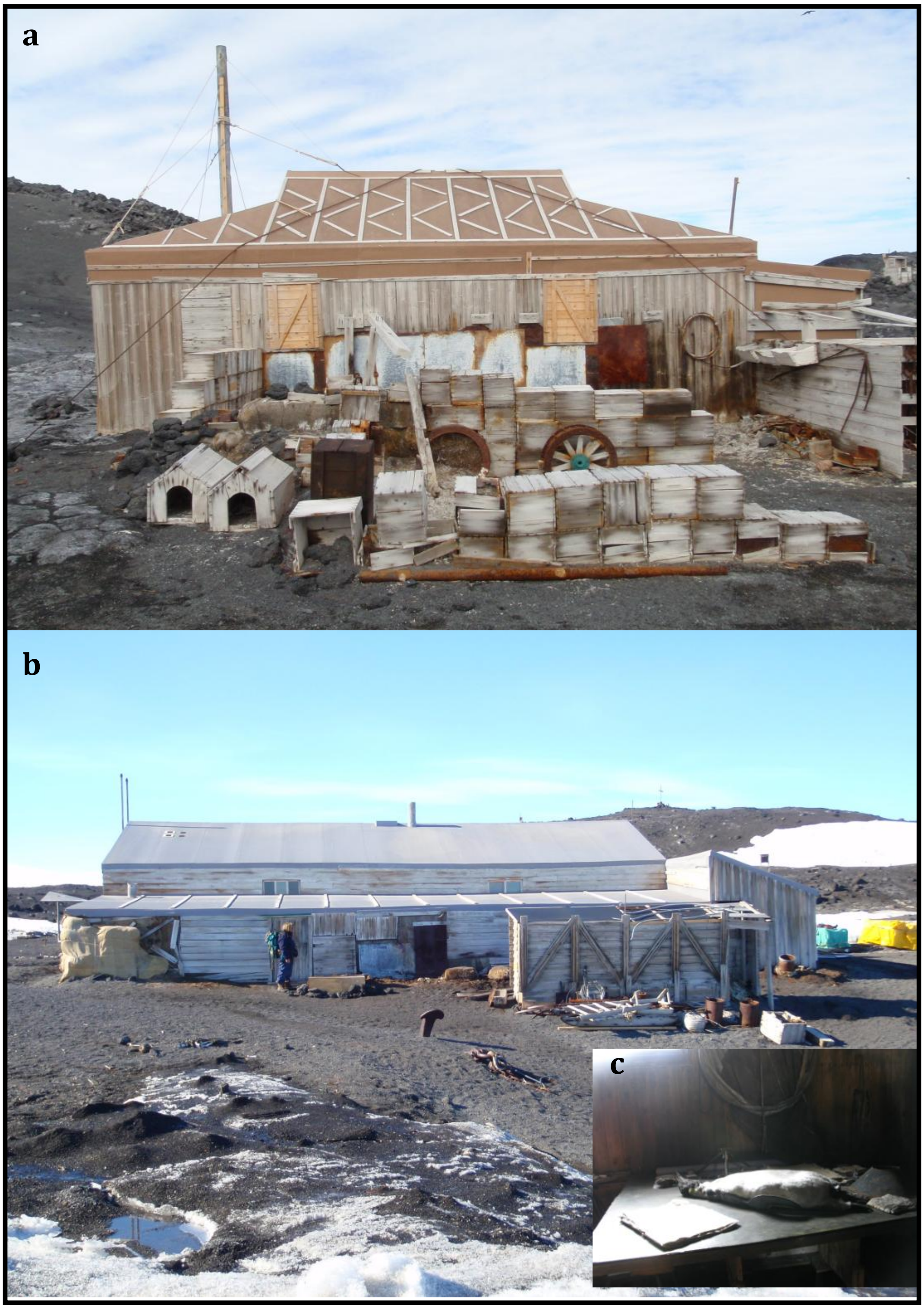

Fig. 14. Visitor attractions in the Ross Sea region. a) Shackleton's Nimrod Hut, Cape Royds; b) Scott's Terra Nova Hut, Cape Evans. Note: Windvane Hill with memorial cross in background; c) Remains of emperor penguin inside Scott's Terra Nova Hut, photo: Megan Balks.

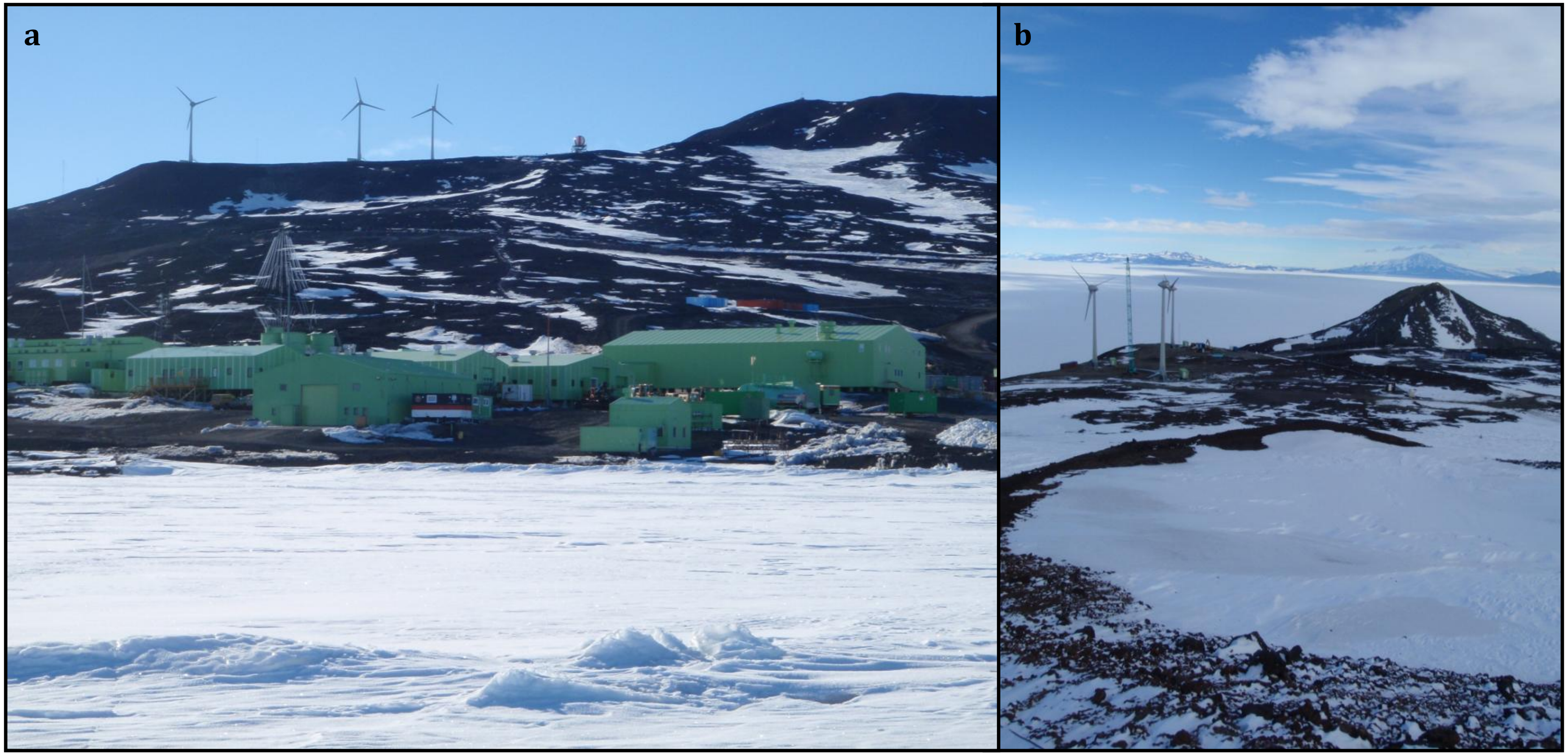

Fig. 15. Visitor attractions in the Ross Sea region. a) New Zealand Antarctic Programme Scott Base with Crater Hill Wind Farm in background; b) Crater Hill Wind Farm during construction, December 2009, Observation Hill to right-hand side of photo.

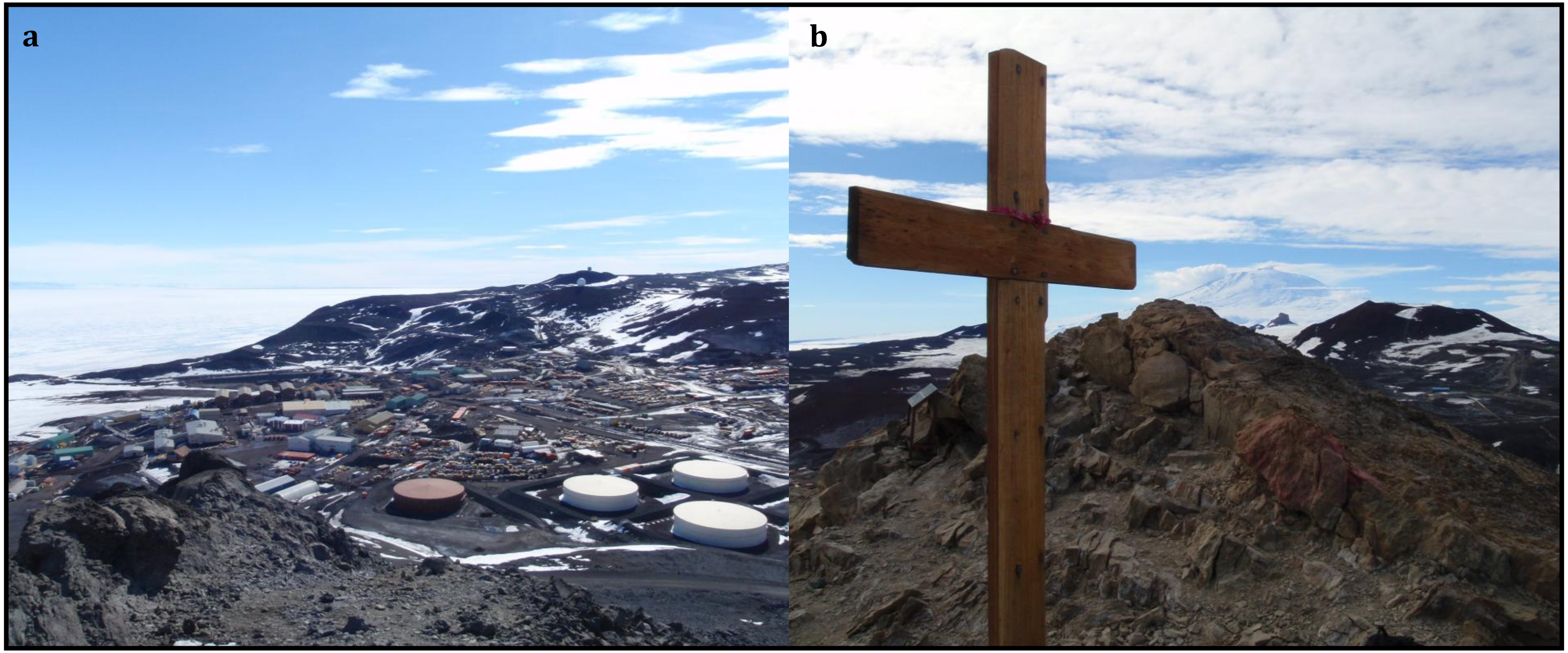

Fig. 16. Visitor attractions in the Ross Sea region. a) United States of America Antarctic Program McMurdo Station, taken from midway up Observation Hill; b) Scott’s Memorial Cross ‘To Strive, to Seek, to Find, and Not to Yield’, Observation Hill, Castle Rock and Mount Erebus in background.

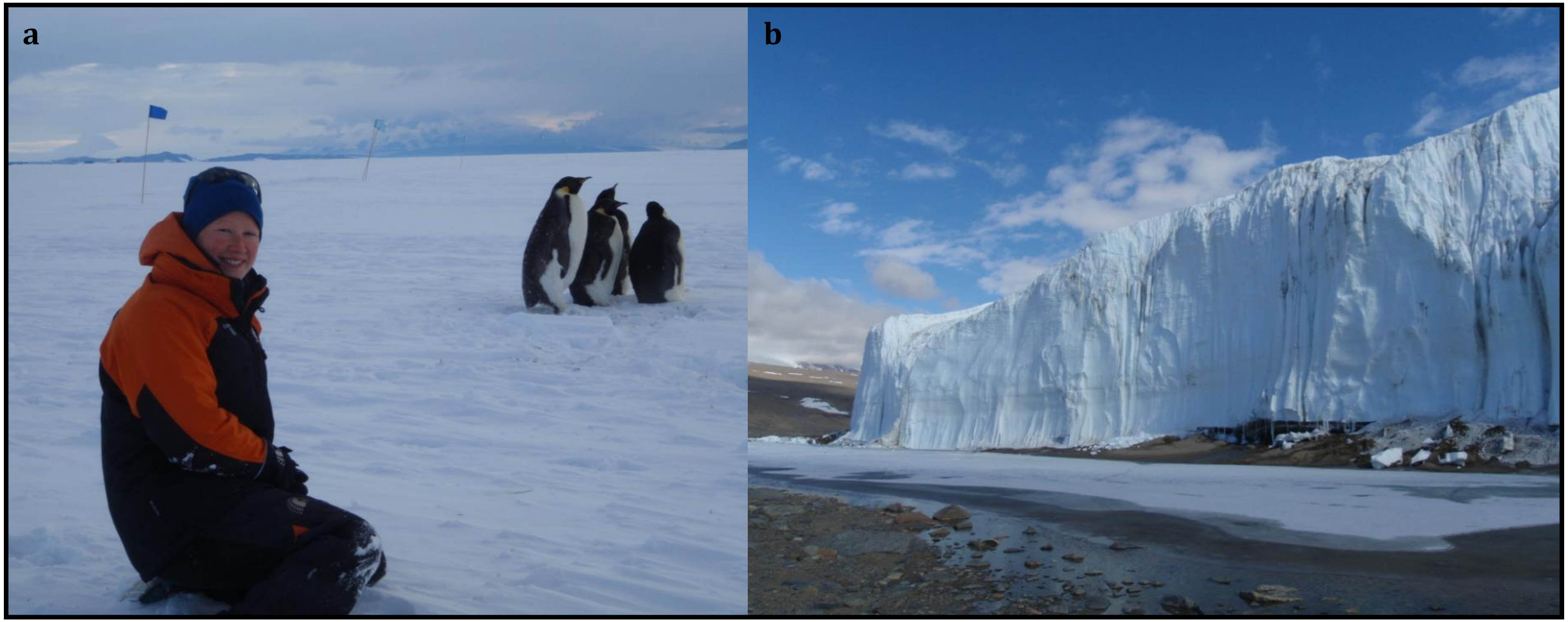

Fig. 17. Visitor attractions in the Ross Sea region. a) Myself with Emperor penguins; b) Canada Glacier and proglacial lakes, Taylor Valley Visitor Zone, Taylor Valley, McMurdo Dry Valleys

Table 3. All visitors to Historic Huts 1998 to 2010 (data from Antarctica New Zealand, 2012).

	1998/99	1999/2000	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Average
ASPA 155 Cape Evans													
USAP	731	974	407	1021	872	417	401	153	557	616	257	329	
Tour Ships	713	854	311	228	228	202	373	278	359	171	272	340	
Antarctica NZ	153	191	322	244	195	185	150	167	131	192	73	105	
	1597	**2019**	**1040**	**1493**	**1295**	**804**	**924**	**598**	**1047**	**979**	**602**	**774**	1098
ASPA 157 Cape Royds													
USAP	975	514	284	522	363	158	200	125	215	162	98	147	
Tour Ships	691	299	351	235	235	307	373	369	454	171	282	314	
Antarctica NZ	137	172	314	211	189	160	79	174	133	167	47	72	
	1803	**985**	**949**	**968**	**787**	**625**	**652**	**668**	**802**	**500**	**427**	**533**	808
ASPA 158 Hut Point													
USAP	712	586	683	618	711	623	688	639	619	627	583	760	
Tour Ships	269	162	263	74	0	321	212	423	19	133	250	172	
Antarctica NZ	158	172	256	205	187	214	138	105	138	89	38	147	
	1139	**920**	**1202**	**897**	**898**	**1158**	**1038**	**1167**	**776**	**849**	**871**	**1079**	1000
ASPA 159 Cape Adare													
USAP	0	0	0	0	0	0	0	0	0	0	0	0	
Tour Ships	72	53	54	146	55	150	442	538	19	119	465	63	
Antarctica NZ	0	0	5	0	5	0	0	2	0	0	0	0	
	72	**53**	**59**	**146**	**60**	**150**	**442**	**540**	**19**	**119**	**465**	**63**	182
Totals													
USAP	2418	2074	1374	2161	1946	1198	1289	917	1391	1405	938	1236	
Tour Ships	1745	1368	979	683	518	980	1400	1608	851	594	1269	889	
Antarctica NZ	448	535	897	660	576	559	367	448	402	448	158	324	
Totals	**4611**	**3977**	**3250**	**3504**	**3040**	**2737**	**3056**	**2973**	**2644**	**2447**	**2365**	**2449**	

2.5.6 Conclusion

Human impacts on the Ross Sea region terrestrial environment have occurred since humans first stepped into the region. Increased scientific research, and increased accessibility for tourists and adventurers, has meant the number of people visiting Antarctica has increased. At the same time there continues to be an increase in environmental awareness amongst visitors to Antarctica and a growing effort by national programmes and IAATO operators to manage and prevent environmental impacts.

This chapter has documented previous studies into the physiochemical and biological characteristics of Ross Sea region soils that are known influence soil resilience and vulnerability to human disturbance. Previous researchers document a reasonable understanding of the materials from which the soils are derived, the characteristics of the desert pavement, permafrost, soil active layer, soil salinity, pH, and the biological communities living in Ross Sea region soils. Previous studies report existing damage to the terrestrial soil environment as a result of past human activities. However, gaps in knowledge are evident from this literature review when attempting to tie influential soil characteristics, impacts, and the ability for soils to recover, both in the Ross Sea region, and in Antarctica on the whole.

This doctoral research endeavours to advance scientific understanding on physical impacts and soil recovery rates in Ross Sea region terrestrial environments.

3 THE EFFECTIVENESS OF ENVIRONMENTAL IMPACT ASSESSMENTS ON VISITOR ACTIVITY IN THE ROSS SEA REGION OF ANTARCTICA

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The effectiveness of Environmental Impact Assessments on visitor activity in the Ross Sea Region of Antarctica

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Introduction

The persistence of cold even during summer; blizzards, severe winds, extreme aridity, and difficulties in accessibility, are but a few of the factors that combine to curtail human activities in Antarctica. Yet we persist. Antarctica was the last continent to be discovered. The historical explorations of Drake, Halley, and Cook in the 1600s and 1700s were followed by the first sealers and whalers in the Scotia Sea in the late 18th and 19th centuries, and discovery of the South Shetlands Islands of the Antarctic Peninsula in the 19th Century. It was not until the late 19th Century where the impetus for scientific exploration of Antarctica was both encouraged and funded (Tin et al. 2009). The upsurge in scientific activity of the early 1900s with the visits of Scott, Amundsen, and Shackleton, culminated in the International Geophysical Year (IGY) in 1957-58. By 2009 there were 40 year-round research stations in Antarctica (http://www.comnap.aq). Tourism in the Antarctic region dates back to 1891, when the first tourists were passengers on resupply ships to the sub-Antarctic islands (Codling 1995). Larger-scale commercial tourism began in 1957-59 with Argentinean and Chilean naval transports, which accommodated tourists to help pay the costs of servicing national naval expeditions (Reich 1980). By 1966 Lars-Eric

Lindblad began expedition cruising to the Antarctic Peninsula and initiated the use of zodiacs to ferry passengers to onshore sites. Antarctic-wide tourist numbers peaked in the 2007/2008 season with 46,265 tourists (approximately 32,000 landings). Due to expense, inaccessibility, and a lesser abundance of wildlife in the Ross Sea region, tourism remained at approximately 400 landing passengers per season from 2005/2006 through to 2009/2010 (IAATO 2010).

The Protocol on Environmental Protection to the Antarctic Treaty, signed in Madrid in 1991 (The Madrid Protocol), designates Antarctica as a "natural reserve devoted to peace and science". The Madrid Protocol gives a comprehensive protection to the Antarctic environment and its ecosystems and maintains the value of the continent as an area for scientific research.

The objective of this chapter is to use five case studies to illustrate the effectiveness of the current Environmental Impact Assessment system with respect to predicting and managing the effects of visitor activity in the Ross Sea region of Antarctica. Investigated Environmental Impact Assessments included:

- the decommissioning of the Greenpeace World Park Base, Cape Evans;
- Taylor Valley Visitor Zone, Taylor Valley;
- the decommissioning of the Vanda Station, Wright Valley;
- occupation of the Loop Moraine campsite, Wright Valley, McMurdo Dry Valleys;
- the occupation and restoration of the ice-free storage area for the Cape Roberts Drilling Project, Cape Roberts.

The similarities and differences between the Antarctic and Arctic Environmental Impact Assessment systems are briefly discussed.

Visitors to the Ross Sea region

Tourism: operators, voyages, and landing sites

IAATO (the International Association of Antarctic Tour Operators), is a member organization founded in 1991 to advocate, promote, and practice safe and environmentally responsible private-sector travel to the Antarctic (http://www.iaato.org). IAATO member parties work within the Antarctic Treaty and Madrid Protocol, promoting *Guidelines for Visitors to the Antarctic* and coordinating member itineraries so that no more than 100 people are ashore in any one place at any one time. IAATO provides members with visitor guidelines, guidelines on wildlife watching, biosecurity, and decontamination guidelines for small boat operations.

Seaborne tourism in the Ross Sea region in the summer of 2009-2010, comprised three operators, who conducted five voyages; each involving helicopter and zodiac landings for a combined 397 passengers (IAATO 2010). A further eight voyages by three operators, and an estimated 500 passengers were predicted to visit the area in the 2010/2011 season. In the last five years 20 sites in the Ross Sea region have been visited by tourists, the 12 most visited sites, and their attractions, are summarized (Table 1).

Table 1. The 12 most visited sites in the Ross Sea region.

	Site and Attraction	Mean annual visitors numbers*
1	***Ice landings*** : includes landings on the Drygalski Ice Tongue, B15K, Ice walks near Cape Hallett, Cape Royds, Beaufort Island, and the Ross Ice Shelf	367
2	***Cape Royds:*** Shackleton's Nimrod Hut. Adélie penguins	318
3	***Cape Adare:*** Borchgrevink's and Scott's Northern Party Huts. Adélie penguins	293
4	***Cape Evans:*** Scott's Terra Nova Hut	291
5	***Franklin Island:*** Adélie penguins	215
6	***Terra Nova Bay:*** Mario Zuchelli Station Tour and vantage point for Inexpressible Island	192
7	***Inexpressible Island:*** Historic site where Scott's Northern Party from the Terra Nova Expedition wintered in a snow cave. Adélie penguins	154
8	***Hut Point Peninsula:*** Scott's Discovery Hut, McMurdo Station, Scott Base and Observation Hill	154
9	***Cape Washington:*** Emperor penguin colony	154
10	***Coulman Island:*** Emperor penguins and historic site	115
11	***Cape Hallett:*** Adélie penguins	110
12	***Canada Glacier (Taylor Valley Visitor Zone):*** Dry Valleys experience: Canada Glacier, mummified seals, ventifacts	109

*Mean annual tourist visitors between 2005/2006 and 2008/2009. *Data from:* Antarctica New Zealand (2009).

National program visitors:

Four of the twelve sites most frequently visited by tourists (Cape Royds, Cape Adare, Cape Evans, and Hut Point Peninsula) are also regularly visited by New Zealand and US National Program personnel and base staff (Table 2). Tourist visitors comprise the greater proportion of visitors to Cape Royds and Cape Adare each year, whereas, Cape Evans is visited by a large number of US National Program personnel, who also comprise the largest proportion of visitors to Scott's Discovery Hut on the Hut Point Peninsula. McMurdo Station's close proximity to Discovery Hut, makes Discovery Hut a "must see" attraction amongst base staff and other US National Program personnel on their off-days.

Table 2. The total number of visitors, US National Program, New Zealand National Program, and tourists, to Cape Royds, Cape Adare, Cape Evans, and the Hut Peninsula, in the Ross Sea region.

Site and Attraction	Annual visitor ratios to most frequented sites				Mean annual
	2005/06	2006/07	2007/08	2008/09	visitor numbers*
Cape Royds: Hut. Adélie penguins					
US National Program	125	215	162	98	150
New Zealand National Program	174	133	167	47	130
Tourists	369	454	171	282	319
Total	**668**	**802**	**500**	**427**	**599**
Cape Adare: Huts. Adélie penguins					
US National Program	0	0	0	0	0
New Zealand National Program	2	0	0	0	1
Tourists	538	19	119	465	285
Total	**540**	**19**	**119**	**465**	**286**
Cape Evans: Hut					
US National Program	153	557	616	257	396
New Zealand National Program	167	131	192	73	141
Tourists	278	359	171	272	270
Total	**598**	**1047**	**979**	**602**	**807**
Hut Point Peninsula: Hut. Stations					
US National Program	639	619	627	583	617
New Zealand National Program	105	138	89	38	93
Tourists	423	19	133	250	206
Total	**1167**	**776**	**849**	**871**	**916**

*Mean annual ratios of National Program and tourist visitors between 2005/2006 and 2008/2009. *Data from:* Antarctica New Zealand (2011).

Environmental Impact Assessment

Annex I of the Madrid Protocol requires that before any kind of activities are conducted the possible environmental impacts need to be assessed. The term *Environmental Impact Assessment* (EIA) was introduced in Article 8 of the Protocol and is a process whereby persons responsible for an activity predict the likely environmental impacts and assess their significance (Committee for Environmental Protection 2005). The EIA process is at one of three levels, depending on the nature and scale of the activity (*from* http://www.antarcticanewzealand.govt.nz):

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 a proposal may have and how they can be best prevented or mitigated. The people responsible for an EIA need to consult as widely as is reasonably necessary and possible in order that the best available information and professional advice contribute to the outcome (Committee for Environmental Protection 2005).

Where a CEE is necessary, such as the multinational Cape Roberts Drilling Project (1997-1999) the draft CEE was made publically available and considered by the Committee for Environmental Protection, which then advises the Antarctic Treaty Consultative Meeting. The Antarctic Treaty Consultative Meeting is a mechanism established by the Antarctic Treaty which over the last decade meets annually; for the purpose of exchanging information, consulting and formulating recommendations on many matters including current CEE applications; and thus ensuring the principles and objectives of the Treaty and Madrid Protocol are fulfilled. During the Antarctic Treaty Consultative Meeting the CEEs for the proposed activities are discussed, comments are provided by other Treaty signatory representatives and a decision is made as to whether and how an activity is conducted.

The main purpose of the EIA is to facilitate the systematic consideration of environmental issues as part of development and decision-making (Abaza et al. 2004).

New Zealand's Visitor Site Assessment Scheme (VISTA)

EIA is based on the premise that activity-related environmental impacts can be predicted. But in reality, our current understanding of cumulative impacts and cause-effect relationships in Antarctica remains limited. Because of this a precautionary approach should be taken where the likely impacts of the proposal are unknown or uncertain.

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 program. Representatives use a series of booklets, maps, and photos to help orientate themselves at a site, and find waypoints for 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 dry ground. Using the visual site assessment method of Campbell et al. (1993) assessing surface disturbance in 5 m x 5 m plots in areas where visitors walk. 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 program (Antarctica New Zealand 2009), including the Taylor Valley Visitor Zone, one of the sites used as a case study in this chapter.

Examples of New Zealand managed Environmental Impact Assessments

Under New Zealand's Antarctica (Environmental Protection) Act 1994 (which implements Annex I (Madrid Protocol) provisions), all activities organized *in New Zealand* or proceeding to Antarctica *from New Zealand* must undertake an EIA. The evaluation must be approved by the Antarctic Policy Unit of the Ministry of Foreign Affairs and Trade (MFAT) before the activity can commence. A Crown Entity established in 1996 under the New Zealand Antarctic Institute Act (1996), known as *Antarctica New Zealand*, is responsible for developing, managing, and executing New Zealand Government activities in Antarctica and the Southern Ocean. Antarctica New Zealand is required to develop, manage and execute New Zealand's activities in the Ross Sea region of Antarctica, conserve the intrinsic value of Antarctica by understanding and managing human impacts on the Antarctic environment, and raise public awareness of the international significance of the continent. The environmental impacts of an "event" managed by Antarctica New Zealand should never outweigh the likely benefits of the scientific research and its outcomes (Antarctica New Zealand, *Statement of Intent* 2011).

The effectiveness of the EIA process was investigated over the 2008/2009 and 2009/2010 field seasons at five Ross Sea region sites of human occupation and activity (Table 3, Figure 1).

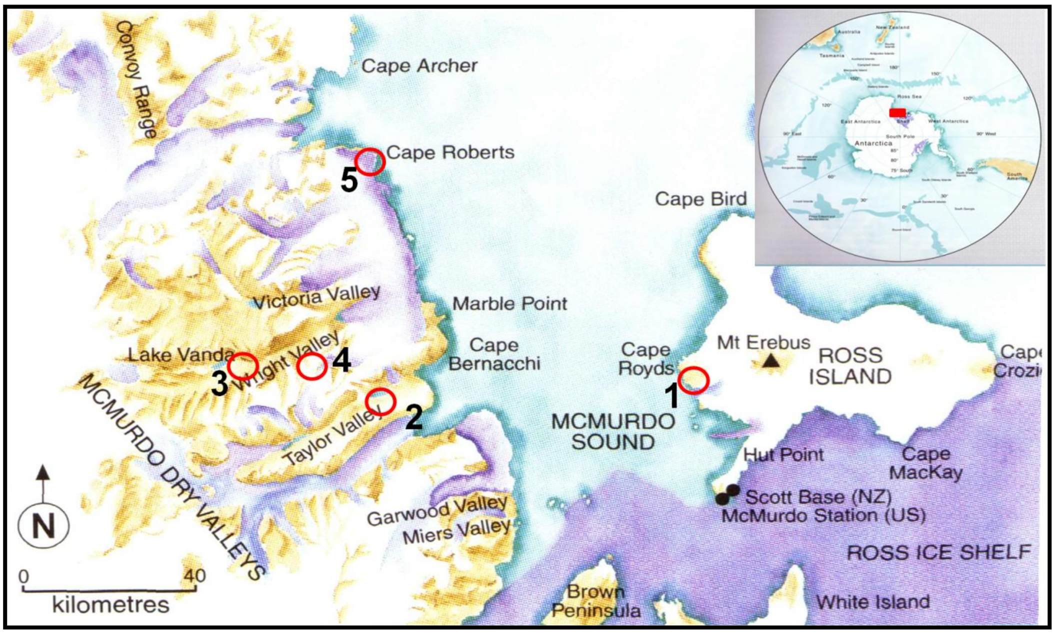

Figure 1: Location of Ross Sea region case study sites: 1. Greenpeace Base, Cape Evans; 2. Taylor Valley Visitor Zone; 3. Vanda Station, Wright Valley; 4. Loop Moraine campsite, Wright Valley; 5. Cape Roberts storage area, Cape Roberts (not drawn to scale).

Table 3: General location, description, history, landform, climate, and estimated annual visitor numbers at the case study sites.

Site description and history	EIA type	Time since last disturbance	Post-EIA monitoring	Estimated visitor #s	Landform	Parent material	Ross Sea region climate zone*
***Former Greenpeace World Park Base* (77° 38' 05.2'' S, 166° 25' 20.6'' E)**: a 4-person base established on a pre-disturbed site in the summer of 1986/87. The station was decommissioned, removed and the former site remediated in the summer of 1991/1992.	IEE	13 years	1991/92 1992/93 1995/96	site currently occupied by Antarctic Heritage Trust. Up to 8 people in the summer	active beach	scoriaceous basalt and locally derived till, alluvium, colluvium, and beach gravels	moist coastal mountain
Taylor Valley Visitor Zone* (77° 37' 35.3'' S, 163° 03' 18.6'' E):* Designated as a Visitor Zone in the McMurdo Dry Valleys ; spectacular landscape for visitors to see the Canada Glacier terminus, mummified seals, ventifacts and patterned ground.	IEE	10 months	yes VISTA	224 (2006/07) 117 (2007/08) 93 (2008/09)	glacial moraine	mixed till	central mountain
***Loop Moraine field site* (77° 29' 10.8'' S, 162° 21' 50.6'' E)**: Campsite for New Zealand Programme K123 during summer 2004/2005; occupied by 4 people for one month. Campsite, and walking track formed from the campsite to toilet facilities, and the stream-side experiment.	PEE	5 years	no	not in last 5 years	glacial moraine-alluvial fan	mixed till and alluvial fan deposits	central mountain
Former Vanda Station site* (77° 31' 41.5'' S, 161° 40' 18.6'' E):* established in the summer of 1968/1969 at Lake Vanda, Wright Valley. The station was occupied predominately during summers until 1990/1991, and decommissioned in 1994/1995 due to rising lake levels at the nearby Lake Vanda (* lake level and contaminants monitoring 1994-2002)	IEE	17 years	yes	< 10 annually	low ridge on the valley floor	surface lag layer of mixed till over granodiorite granodiorite blocks, bedrock, erosion-resistant lamprophyre dykes	central mountain
Former Cape Roberts Project storage area* (77° 02' 07.3'' S, 163° 10' 43.0'' E):* Ice-free storage site for the Cape Roberts Drilling Project from 1997 through 1999. Site remediation began in 1999/2000 and the disturbed site was manually raked in 2000/2001.	CEE	10 years	yes	< 5 annually	active beach-bedrock outcrop	beach deposited gravels and granodiorite bedrock	moist coastal mountain

*Climate zones are those of Campbell and Claridge (1987).

The assessed sites were situated on a variety of landforms, soil parent materials and climates (Table 3). At each site the history of the site was known, the time since last disturbance was well constrained with sufficient background information into the EIA predicted impacts, and, in some cases, photo documentation was available. Assessment of the present state of the sites and accuracy of the EIA predictions compared with the actual impacts were carried out in the summers of 2008/2009 and 2009/2010.

Site of the Greenpeace World Park Base

The ice-free area of Cape Evans, Ross Island, is a site of historical value, with Scott's 1910 Terra Nova Hut and associated artifacts, as well as other monuments such as the Cross erected by Scott's expedition on Wind Vane Hill. In the summer of 1986/87 Greenpeace established a base 400 m along the beach from Scott's Terra Nova Hut, on a raised beach terrace about 5 m above sea-level between low rock outcrops and the present day beach (Figure 2a). The site had been previously occupied on a number of occasions since Scott's arrival in the early 1900s. The occupants prior to Greenpeace had been members from Robert Swans 'Footsteps of Scott' British expedition to South Pole in 1984-86, where the crew set up camp at the site for number of days before recreating Scott's last march to the Pole (Mear and Swan 1987). The Greenpeace four-person winter-over base consisted of a main building of pre-fabricated units constructed in 1987, and then from 1988 to 1990 several structures were added to the base; forming an L-shaped main building, fuel rack, storage shed for food, SATCOM-tower, wind generator and radio-antennas (Greenpeace 1991a).

Environmental Impact Assessments and restoration efforts

The IEE for the commissioning of the base stated that potential impacts during the construction phase could include fuel spills, stress on the immediate surrounds, including disturbance to skuas and the ground, as well as dust and helicopter noise pollution (Greenpeace 1986). During occupation and overwintering of the base the EIA stated that the 'presence of four people in a limited area will put some limited stress on the immediate surroundings' but that the small party would have little impact on the soils, that there was 'no nearby vegetation, and that no vehicles were planned to be used inland'. Greenpeace concluded that the 'foreseeable environmental impacts of the proposed activities of base construction are negligible, and an Environmental Impact Statement [precursor to a CEE] is not needed'. Monitoring during site occupation and at the conclusion and decommissioning phases of the program was promised.

An IEE was prepared for decommissioning of the Greenpeace base, and removal and remediation of the site took place in the 1991/1992 summer. The IEE indicated that 'the proposed base removal will not have more than a minor and transitory effect on any component of the environment, and a CEE is not needed' (Greenpeace 1991a) and that ongoing monitoring of the site would be continued beyond the 1991/1992 decommissioning season. During occupation Greenpeace estimated that a maximum of 30 cubic meters of soil may have been contaminated with fuel. Contaminated soil was removed to a depth of 20 cm in the most contaminated sites and returned to New Zealand during the site remediation process to ensure all practicable mitigative pathways had been followed to prevent contamination via subsurface flow into the Ross Sea (Roura 2004). In total it is estimated that five tonnes of contaminated sediments were removed (Greenpeace 1992, 1994b). All excavations were back-filled and levelled to prevent permafrost degradation. Most of the sediments used as backfill were extracted from the present day beach, where the potential for permafrost degradation was comparatively minor (Roura 2004). Environmental monitoring to evaluate the likelihood of fuel migration and to assess backfill stability was carried out by Greenpeace in 1991/92, 1992/93 and 1995/1996 with the logistic support of Antarctica New Zealand (Greenpeace 1991a, 1991b, 1992, 1993, 1994a, 1994b, 1997).

Observations

Photos and sketches were used as a means of locating the site of the former Greenpeace base. Soil was excavated to the depth of ice-cemented permafrost (approximately 40 cm below the surface in January 2009) around the vicinity of the former fuel rack; and a qualitative “sniff test” conducted to check for evidence of hydrocarbons. The main visible evidence of the former Greenpeace base was the unnatural gravel mounds associated with either the removal of persistent snow drifts from the landward side of the building, or site flattening to accommodate the base (Figure 2b,c). Unnaturally placed boulders on top of the raised beach surface were noted (Figure 2d), as well as an occasional nail or small (<10 cm long) piece of wood (though the litter may be attributable to the Scott era). On an undisturbed surface the rocks would be embedded into the pavement whereas rocks sitting clear on top of the surface appear to have been placed there in an attempt to restore the surface. A trace of a corner of the main building was still visible, though not obvious, where the area was levelled and Greenpeace cut into the ridge (Figure 2c).

Overall there was little remaining evidence of the former base. It took knowledge of the location of past activities and careful observation to identify any evidence of disturbance. A lag gravel deposit had reformed over the entire site. There was no evidence of structures such as the drainage trench, SATCOM tower, or food storage hut. The raised beach surface showed no evidence of permafrost degradation in backfilled areas, no visual expressions of fuel spills, or remnants of walking tracks or drains, or any obvious differences in texture or surface colour when compared with nearby undisturbed beach surfaces. The beach worked loose gravel at the site is readily resorted by surface wind, water, freeze-thaw, and snow melt and run-off processes; making it an active and readily recoverable surface. The site was temporarily reoccupied in 2011 by the Antarctic Heritage Trust whilst they carry out restoration of Scott’s Terra Nova Hut.

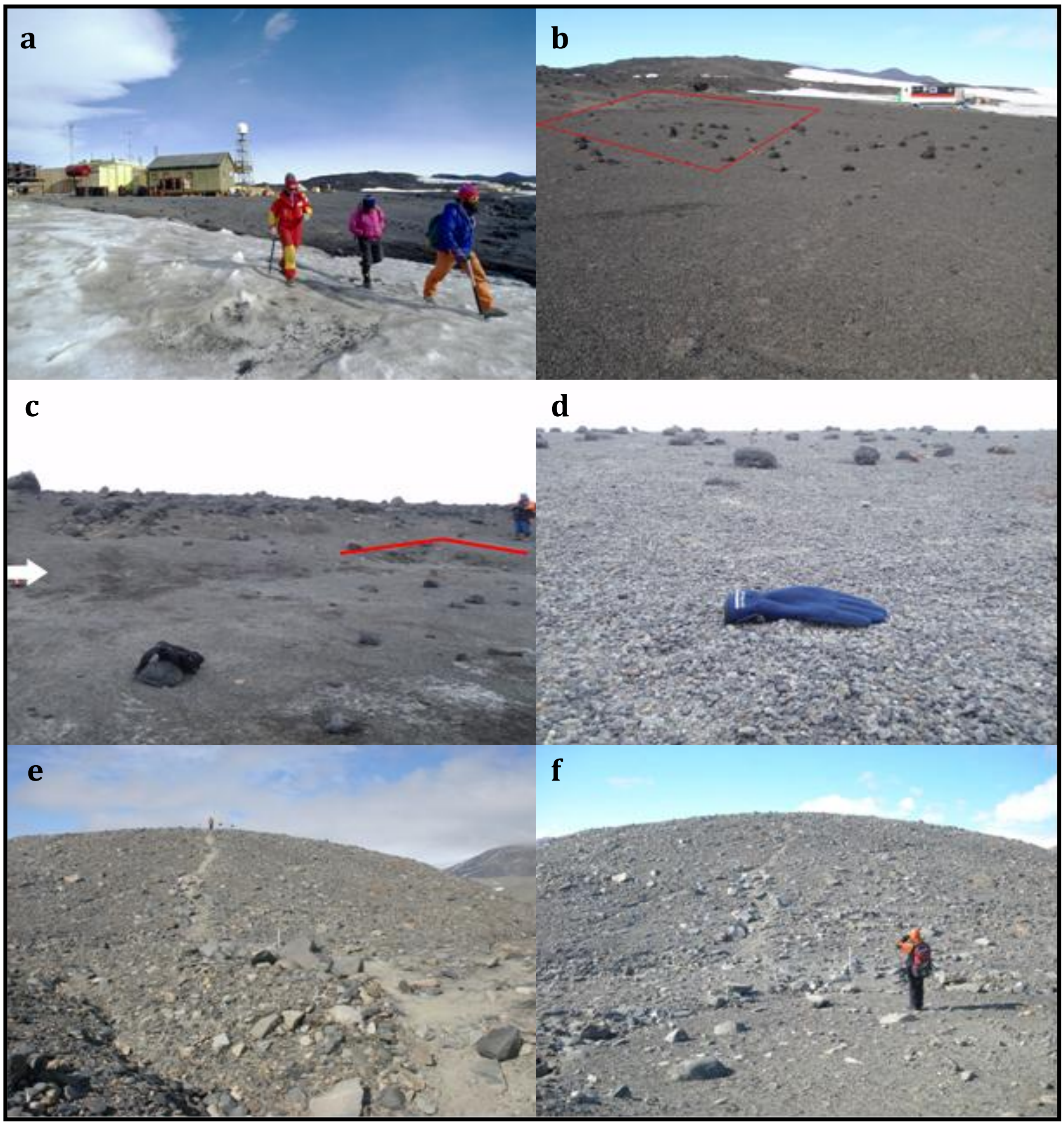

Figure 2: Sites of Greenpeace World Park Base at Cape Evans, and the Taylor Valley Visitor Zone. a) Greenpeace huts and fuel storage racks in January 1992; b) Red rectangle marking the location of the former Greenpeace base; c) Red marks the trace of former corner of main Greenpeace building and unnatural gravel mounds; d) "unnaturally" placed boulders on top of the raised beach surface, with recovered surface in foreground (glove for scale); e) Taylor Valley Visitor Zone steep track to lookout, 06/07 season, post-96 visitors; f) Taylor Valley Visitor Zone steep track to lookout, 09/10 season, before first tourist group of the season.

Tourism at the Taylor Valley Visitor Zone

The Taylor Valley Visitor Zone (TVVZ) is located adjacent to the Canada Glacier, in the Taylor Valley. Designated as a 'Tourism Zone' in 1995, the TVVZ is currently the only area in the McMurdo Dry Valleys where tourists are allowed to visit. It is an attractive site which provides visitors with a spectacular experience of a typical "Dry Valley" site. The visitor zone was selected as a site where "safe and easy access and movement within the area can be reasonably assured with minimal impact to science activities or the environment" (New Zealand, United Kingdom, United States 2006). Access is by helicopter only. The tourism zone is approximately 350 x 300 m, dominated by a low (approximately 30 m high) hill, and is covered in gravely rocky till. There are established walking tracks and small guided groups walk around the site, passing by a pro-glacial lake and the terminus of the Canada Glacier, up a steep track to a lookout point, and also past mummified seals. A total of 434 people have landed between the summers of 2006/2007 and 2008/2009. Average landing times are about 9 hours (entire party) (Antarctica New Zealand 2009). Research program activity also occurs in the vicinity of the site, with substantial United States Antarctic Program camps at nearby Lake Fryxell and Lake Hoare, so total visitor numbers are difficult to quantify.

Environmental Impact Assessment

Inspection of a recent IEE from a tourist operator working in the Ross Sea revealed the sections relating to the assessment of impacts to surfaces traversed and possibilities of cumulative impacts as generic, stating the activities proposed in Antarctica "are likely to have less than minor or transitory impact on the Antarctic environment". Details regarding specific sites to be visited, and precautions required at each site were not included. Perhaps this is typical of a tourist operator IEE and was confirmed by an Antarctic Policy Unit compliance officer from the New Zealand Ministry of Foreign Affairs and Trade (Ane Hunkin, *pers.comm*. June 21, 2011).

Observations

A visual site assessment and Antarctic New Zealand administered Visitor Site Assessment (VISTA) scheme photo-replication revealed that the physical impacts of the tracks within the TVVZ persist between seasons (Figure 2e,f); although distinct foot-prints were not evident prior to tourists arriving in December 2009. An overall contrast in desert pavement colour between the track and adjacent undisturbed mixed till pavement was evident; and, due to the concentration of larger clasts being pushed to the outer margin the formed walking track was clearly evident. However, VISTA photo-replication showed that the colour contrast between track and adjacent control was much less pronounced after the site had a winter to recover; implying that some visual recovery of the desert pavement does occur between tourist seasons. It was also observed that the tracks follow the patterned ground cracks were practicable. The patterned ground cracks are the most active and readily recoverable areas in the landscape, and the most favourable place to concentrate visitor flow.

Site of the former Vanda Station

Vanda Station was established adjacent to Lake Vanda in the 1968/1969 summer to support research in the Wright Valley (Figure 3a). Human occupation left the former Vanda Station site disturbed by trampling, vehicle movement, excavations, occasional oil spills and accumulation of debris (Webster et al. 2003). Urine and grey water was strained and dumped in an adjacent gully until 1993. With rising lake levels the potential for leaching of contaminated ground into the lake system was a concern (Sheppard et al. 1993) so decommissioning of the station took place from the summers of 1992/1993 to 1994/1995 (Hayward et al. 1994).

Environmental Impact Assessment and restoration efforts

An IEE was submitted to carry out the decommissioning and remediation of the site in March 1994. The IEE stated that all physical structures would be removed; all contaminated soil with the potential to adversely impact on lake waters would also be removed. And in addition a monitoring program would be undertaken to ensure that any changes in lake levels could be identified (Hayward et al. 1994). Little information was included in the IEE regarding the impacts from the removal activities. All that was mentioned was that the decommissioning activities would "have the minor and transitory impacts of generating dust and noise", and that "all solid and liquid wastes generated during this period will be removed ..." (Hayward et al. 1994).

Over the summer of 1994/1995 a team of 4-6 people were stationed at the site. Removal of the station, comprising eight buildings able to accommodate 14 people, took over 180 person days and 70 helicopter hours to complete. Buildings and a large amount of contaminated soil and painted rocks were removed (Webster et al. 2003). Effort was also made to restore land surfaces to a “natural” condition including pathways and tracks (Hayward *et al*., 1994). The IEE indicated that a significant environmental concern following station removal was the potential for reactivation of soil contaminants in the immediate vicinity of the former buildings (Hayward et al. 1994). The risk of leaving the structures and contaminated soil in place, however, with rising lake levels causing major contamination into the lake waters, was considered to outweigh the risk (Sheppard et al. 1993).

Following decommissioning of the site Antarctica New Zealand undertook an annual program of water and algae sampling from 1994/1995 until 2001/2002. Samples were taken from Vanda Bay (immediately adjacent to the station site) and a control site to ensure any changes in lake water chemistry could be identified. Analysis of data, including dissolved nutrients, chlorophyll, particulate nutrients, algal species composition and heavy metals, revealed that there was ‘no evidence to date to suggest contamination has occurred in Vanda Bay’ (Sutherland 2002).

Observations

The hardy nature of the bedrock and the thorough cleanup made it difficult to locate the site of the former central court and mess hut (Figure 3a,b), even though a member of our party had stayed at the site on a number of occasions. There were no visible footprints, all building materials had been removed, displaced rocks had been redistributed, and efforts had been made to redistribute boulders concentrated along vehicle and walking track margins. It was noted that black lamprophyre dyke rocks which outcrop in long narrow stripes on the surface, were redistributed somewhat unnaturally amongst the lighter granitic slabs and bedrock.

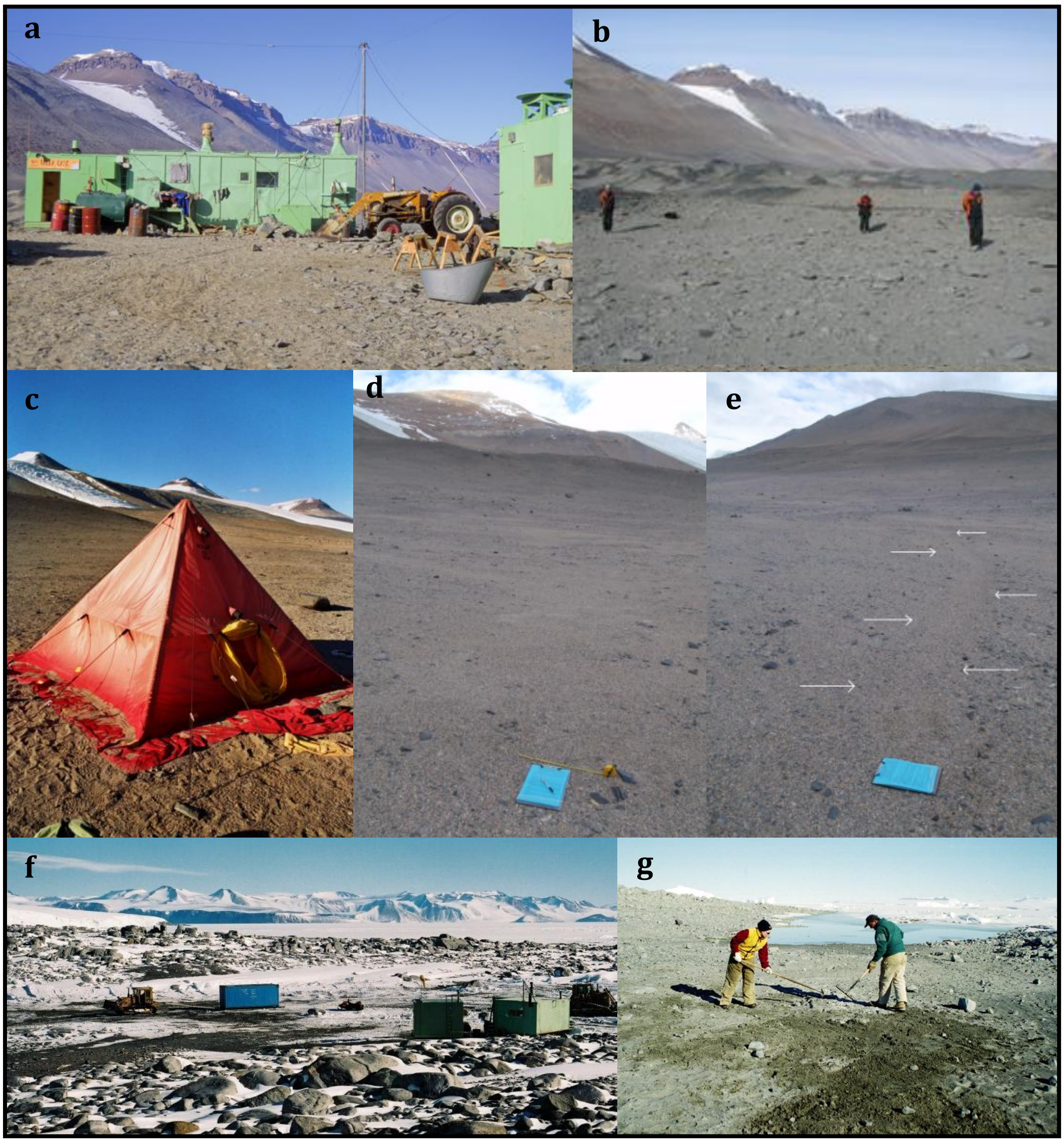

Figure 3: Site of the former Vanda Station, the Loop Moraine campsite, and Cape Roberts ice-free storage area. a) Vanda Station in Jan 1992, immediately prior to removal; b) the site of the main Vanda mess hut. The three people are marking the corners of the buildings ; c) Loop moraine campsite, Dec 2004. Photo: Fiona Shanhun; d) Loop moraine campsite, 5-years later, Dec 2009; e) Loop moraine track to toilet, track margin visible (white arrows), after 5-years recovery, Dec 2009; f) Cape Roberts storage area, c. 1997. Photo: Rebecca Roper-Gee; g) Cape Roberts remediation Jan 2001. Photo: Rebecca Roper-Gee.

Loop Moraine campsite and walking tracks

The New Zealand Antarctic Program K123 Loop Moraine campsite and associated walking tracks were occupied for one month by four people during the summer of 2004/2005 (Figure 3c). The camp consisted of three tents and a nearby site where toilet buckets were placed. Also field equipment was stacked adjacent to the site of three helicopter landings.

Environmental Impact Assessment and restoration efforts

The event IEE indicated that there would be disturbances to ice-free areas, but that 'any soil sampling pits would be backfilled, and desert pavement restored as much as possible, [and that] any stones moved would be replaced'. The IEE detailed that impacts from the visit would be minimal as the environments visited had 'active surfaces from which disturbances are soon obliterated' and stated that their total impact on the environment is likely to be 'less than minor and transitory' (Preliminary Environmental Evaluation K123 2004).

At the end of January 2005 all tents and equipment were removed and any obviously disturbed stones were returned to their original orientation. At the time of departure from the site footprints were widely evident around the area where the tents had been and distinct walking tracks had formed between the campsite and the toilet facilities and the campsite and stream side experiment (Figure 3e)

Observations

At the Loop Moraine widespread trampling around campsites was undetectable within five years (Figure 3c,d), yet evidence of walking tracks remained in the landscape (Figure 3e) even though the desert pavement had visually recovered. The larger clasts which concentrated along the margins of confined tracks remain visible in the landscape (Figure 3e).

Cape Roberts ice-free storage area

Cape Roberts is a small ice-free coastal peninsula situated on the southern side of Granite Harbour on the Antarctic Mainland. Currently the facility zone includes an area of flat ground where two huts, a toilet shelter and a fuel depot are located. The buildings were erected in November 1984 and the site used for winter storage of vehicles, drilling, and camp equipment during the

Cape Roberts Drilling Project; a multinational marine sediment drilling program that operated from 1995 to 2000 (Figure 3f). Site remediation occurred over the summers of 1999/2000 and 2000/2001. The huts were left in place to support ongoing tide gauge measurements (Figure 3g). Since site remediation the numbers of visitors to Cape Roberts have ranged between one (summer of 2003/04) to 20 visitors (summer of 2009/2010) (Antarctica New Zealand 2011).

Environment Impact Assessment and restoration efforts

A baseline survey of the Cape Roberts storage area was carried out over the summer of 1992/1993 to collect environmental data which would enable the impact of the project to be assessed at its conclusion (Campbell and Keys 1993). General soil and vegetation patterns were determined and representative plots established in the areas deemed likely to be subject to the highest impacts. A CEE was required for the Cape Roberts Drilling Project. The CEE predicted that the main impacts at Cape Roberts would be caused by vehicles and storage of materials and human trampling in an area previously disturbed by human activities. Likely impacts would include surface disturbance by compaction, as well as the risk of contamination from fuel spills. Helicopter movement was also predicted to impact the skua populations in the vicinity. The CEE concluded that there would be cumulative impact resulting from the proposed activity, however it would be “small and insignificant in relation to its advantages” (Keys et al. 1994). A decommissioning, spill monitoring, and a cleanup phase took place over the summers of 1999-2001, and rakes were used to redistribute rocky soil disturbed by vehicle tracks and other activities. Full restoration of the storage area to pre-project condition was attempted (Figure 3g).

Observations

The site was visited in January 2010; 10 years after remediation took place. A visual site assessment was repeated on the representative plots first surveyed pre-project in 1992/1993, and evidence of former site occupation was undetectable. It was evident that the use of manual raking in site remediation had been effective.

Discussion

The five case studies showed that overall the standard of landscape recovery was higher than anticipated. The decommissioning and site remediation of the Greenpeace World Park Base at Cape Evans, and Vanda Station, in the McMurdo Dry Valleys, was effective. There was very little evidence of either base, and no evidence of former structures or vehicle tracks. A considerable volume of contaminated soil was removed at both the Greenpeace World Park Base and the Vanda Station during site remediation, and we found no evidence of permafrost degradation, or humps or hollows indicating backfilled areas. The faint trace of the corner of the Greenpeace base, would not be noticeable to the casual observer. It can be assumed that generally the cleanup at Greenpeace World Park Base would have required less effort than that of Vanda Station as the EIA system was in place and precautionary measures, for example, to prevent oil spills, would have been put in place from the commissioning of the station in 1987. Life at Vanda Station, on the other hand, was different in the late 1960s, with few measures in place to mitigate the environmental concerns we have today.

The Taylor Valley Visitor Zone is the only zone in the McMurdo Dry Valleys that is visited by tourists. Tourist operators in the Ross Sea region are careful to follow the guidelines set for the visitor zone, and preexisting walking tracks are used. Use of patterned ground cracks as the preferred route for walking tracks was effective as the active movement of materials in the patterned ground cracks assists surface recovery. Previous work in the McMurdo Dry Valleys, by Campbell et al. (1998), has 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, versus 200 passes, versus 2000 passes, are minimal. The use of a single confined track will preserve the existing undisturbed desert pavement adjacent to current tracks, preserving the natural integrity of the landscape. The cumulative impacts of repetitive visitation are thus minimized by keeping people to one clearly defined walking track. We found VISTA an effective tool to assess cumulative impacts and recovery between seasons at the Taylor Valley

Visitor Zone. VISTA photo-replication showed that the physical impacts of the tracks within the visitor zone persist between seasons. However, distinct foot-prints were not evident.

The Loop Moraine campsite is an excellent example of the rate of recovery in areas of the McMurdo Dry Valleys. Previous studies have shown that most of the ice-free areas in the Ross Sea region of Antarctica are readily disturbed by human activities, and slow to recover in the prevailing cold and arid conditions (Campbell and Claridge 1987; Campbell et al. 1993, 1994, 1998; Claridge et al. 1995; Sheppard et al. 1994). In some cases visual impacts can persist in the landscape for a very long time (Campbell and Claridge 1987; Campbell et al. 1993, 1998). The Loop Moraine campsite challenges this longstanding observation as we observed the widespread trampling around the campsite was undetectable within five years. The scale of the physical impact will naturally have some bearing on recovery time, such as disturbance from bulldozer blades compared with pedestrian foot traffic; the former persisting in the Antarctic landscape for decades (Campbell and Claridge 1987; Campbell et al. 1993, 1998). The Loop Moraine site also illustrated the differences in recovery rates of confined tracks and randomly trampled sites. Evidence of the campsite itself was undetectable, however well used tracks to and from the campsite were visible five years on, and in hindsight the group may have chosen to either rake out formed tracks, or walk to their experimental sites and the toilet facilities in a random and widespread fashion, avoiding the formation of confined walking tracks.

Finally, the CEE for the Cape Roberts Drilling Project was accurate and as predicted, surface compaction and formation of vehicle and walking tracks did result from site activities. The CEE also stated that site restoration would take place, and 10 years on, the impacts of the former occupation were not visible.

Cleanup practices

Observations at the site of the Cape Roberts storage area show that the remediation efforts, and in particular, the use of surface raking, was effective. A rake was used to redistribute surface stones which had concentrated in areas of vehicle activity and foot traffic, as well as to loosen compacted areas. The technique led to recovery of the desert pavement within nine years. The redistribution of slabs of granodiorite and lamprophyre dykes rocks at the Vanda Station site, and volcanic boulders at the former Greenpeace base site, were effective forms of remediation, although repositioning did look unnatural in some cases. Redistribution of disturbed rocks needs to be undertaken with an understanding of their natural position in the environment, and rocks embedded back into the pavement surface for a natural appearance. It is also important to note that there was no relationship between the amount of time the site was occupied and the effectiveness of site rehabilitation, as evidenced when we compare the 5-year occupation of the Greenpeace base site, with the 25-year occupation of the Vanda Station site, and one month at the Loop Moraine site. Former occupation was almost undetectable at all sites and in all cases recovery was a function of the effort of the personnel doing the cleanup and the active wind and water-driven surface processes.

Environmental Impact Assessment effectiveness

Investigation into five sites in the Ross Sea region has demonstrated that overall appropriate site restoration and post-event monitoring is being conducted with an excellent standard of outcomes. On the exterior the EIA process may seem superficial with a lot of generic form-filling. The schemes greatest asset is that it raises awareness by increasing accountability and through motivating members of events to take responsibility for their activities. EIA follow-up investigations such as this are often a neglected element of the EIA process. Effort should be made to systematically carry out evaluations on a regular basis to ensure the process remains working effectively.

Comparison of Antarctic and Arctic Environmental Impact Assessment systems

The Antarctic and Arctic show similarities in some respects; both regions are under growing environmental stress, and have fragile elements susceptible to damage from outside sources; but in terms of environmental protection, sustainability, and international environmental law, the poles differ substantially. The Antarctic, whose environmental legal regime is governed by the Antarctic Treaty System (1959), has been called the model in international law for a purely environmentally focused management regime (Nowlan 2001). A "freeze" on sovereignty claims, has resulted in a single comprehensive environmental protection regime, whose international environmental regulations have then been incorporated into the national legal systems of the Antarctic Treaty Consultative Parties. Furthermore, the development of the legal system occurred under the absence of an indigenous human population, permanent population, or industrial, and resource conflicts; thereby making execution of its principles easier in some respects. The Arctic, on the other hand, is a region dominated by the existing national legal systems of the eight Arctic states. Complicating environmental management are the approximate 10 million people that live in what is defined the Arctic region, of whom 1.5 million are of indigenous origin, most of whom require economic activity for survival. Exploitation of natural resources, particularly mining, is prohibited by the Antarctic Treaty, whereas, mineral exploration and development are well advanced in Canada, the United States, Norway, and Russia, and mining activities are subject to the domestic legal regulatory regime of each Arctic state. The inhabitants of the Arctic therefore need to live under a legal regime that permits them to thrive, while at the same time protecting the fragile environment. In the Arctic, domestic law governs environmental assessment, though the Arctic states are encouraged to follow the voluntary EIA Guidelines (Nowlan 2001). EIAs are undertaken for most large-scale activities, and applied to activities associated with the exploitation of natural resources, public use, military activities, and the development of infrastructure that may cause significant environmental impacts (Nowlan 2001). The EIA assessment, scope, considering alternatives, collection of baseline data, predicting cumulative impacts, and monitoring during and after the activity is essentially the same, however, in the Arctic public participation and consultation between indigenous peoples, groups, organizations, and communities, which have an interest in, or could be affected by, the proposed action is a requirement. Inclusion of public consultation into the EIA process in the Arctic means all those affected by the project are able to provide input into the planning, ensures openness, establishes trust amongst all parties, and ultimately if undertaken effectively, allows communities to accept and contribute positively to the proposed activity. Public consultation can lead to a negative decision on the project, when it is found that the activity will adversely affect local populations beyond acceptable means. Another factor unique to the Arctic EIA process is the possible 'transboundary' impacts which can occur with activities. EIAs can be difficult as project developers and authorities need to make allowances for different legal systems, and matters are further complicated as the citizens within the area of likely impacts of the affected country need to be given the opportunity to also participate in the EIA. In the Arctic past activities which have led to 'transboundary' impacts have included development of oil and gas resources, large-scale hydro-electric projects, and road building. Clearly, bi- or multilateral agreements are required.

Many would ask whether the current Arctic legal regime is protecting the environment, and some would say that the answer depends on what nation is studied, and what environmental issue is considered. The consolidation of the Arctic legal regime into a region wide treaty, like the Antarctic Treaty, has been considered, and there are of course pros and cons. The main advantage in terms of EIA would be increasing states' obligations to protect the environment; however time and expense of developing an international treaty which encompasses all the specific needs of the Arctic, such as the socio-economic and cultural needs of the indigenous peoples, balanced against the unique environmental attributes of the Arctic, is likely to be a difficult task.

Conclusion

Five case studies were investigated to assess the effectiveness of the Environmental Impact Assessment system with respect to predicting and managing the effects of visitor activity in the Ross Sea region of Antarctica. Investigated EIAs included: the decommissioning of the Greenpeace World Park Base, Cape Evans; Taylor Valley Visitor Zone, Taylor Valley; the decommissioning of the Vanda Station; occupation of the Loop Moraine campsite, both in the Wright Valley, McMurdo Dry Valleys; and the occupation and restoration of the ice-free storage area for the Cape Roberts Drilling Project, Cape Roberts. The assessed sites were situated on a variety of landforms, soil parent materials, and local climates. At each site the history of the site was known, the time since last disturbance was well constrained. Assessment of the present state of the sites and accuracy of the EIA predictions compared with the actual impacts were carried out in the austral summers of 2008/2009 and 2009/2010 using visual soil assessment methods.

Each of the five case studies demonstrate a high level of consistency between EIA-predicted impacts and actual impacts, appropriate remediation of sites post-event, and follow-up monitoring where promised. Cleanup practices were of a high standard in each of the case studies investigated. The Loop Moraine field camp site illustrated the differences in recovery rates of confined tracks and randomly trampled sites. Where the EIA impacts were predicted to be 'less than minor and transitory' it was found that evidence of the campsite itself was undetectable, but the well-used tracks to and from the campsite were visible five years on. The raking out of tracks, redistribution of disturbed stones, and careful backfilling of excavations, all assisted in the rehabilitation of the formerly disturbed sites so that former occupation was almost undetectable at all camp sites investigated. In all cases recovery was a function of the effort of the personnel doing the cleanup and active wind, water, and freeze-thaw, driven surface processes.

On the exterior the EIA process may seem superficial with a lot of generic form-filling. However the great benefit of the EIA system is its ability to raise environmental awareness as visitors carry out their activities. The EIA system motivates visitors to take responsibility for their "footprint" on the environment. Thus visitors are more likely to avoid creating impacts and are motivated to restore disturbed surfaces as much as possible prior to their departure. The result is an exceptionally high, world leading, standard of environmental management that reflects the relatively pristine environment in the Ross Sea region of Antarctica.

Uncertainties remain with regard to cumulative impacts. The VISTA (Visitor site assessment scheme) is attempting to provide ongoing monitoring in the Taylor Valley Visitor Zone and building baseline information on recovery between seasons. EIA follow-up investigations such as this study are often a neglected element of the EIA process. Effort should be made to systematically carry out evaluations on a regular basis to ensure the EIA process is effective.

In contrast to the pristine Antarctic, the higher level of human occupation and activity in the Arctic means that EIA practices there are applied only to major development activities that are on a scale not yet contemplated in the Antarctic.

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References

Abaza H, Bisset R, Sadler B (2004) Environmental Impact Assessment and Strategic Environmental Assessment: Towards an Integrated Approach. UNEP

Antarctica (Environmental Protection) Act 1994. Public Act 1994 No. 119. Act is administered by the Ministry of Foreign Affairs and Trade, New Zealand

Antarctica New Zealand (2009) VISTA Update and Review: Visitor Site Monitoring in the Ross Sea region. *Antarctica New Zealand*

Antarctica New Zealand (2011) Statement of Intent 2011-2014. The New Zealand Government

Antarctica New Zealand (2011) Historic hut and Cape Roberts visitor statistics. *Antarctica New Zealand*

Campbell IB, Claridge GCC (1987) *Antarctica, soils, weathering processes and environment*. Amsterdam: Elsevier

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 Record 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. *Antarctic Science 6*(3): 307-314

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

Campbell IB, Keys JR (1993) *Cape Roberts Comprehensive Environmental Evaluation – a survey of the soils and vegetation.* Unpublished report, 9p

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

Codling R (1995) The Precursors of Tourism in the Antarctic, pp. 167-177 in Hall CM, & Johnston M (eds) *Polar Tourism-Tourism in the Arctic and Antarctic Regions.* Wiley, Brisbane

Committee for Environmental Protection (2005) Guidelines for Environmental Impact Assessment in Antarctica, Resolution 4. *CEP Handbook*, 2007

Greenpeace (1986) Greenpeace Antarctic Programme: Environmental Assessment for 1986-97 season. Greenpeace International, Amsterdam

Greenpeace (1991a) *Initial environmental evaluation, removal of World Park Base, Cape Evans.* Greenpeace International, Amsterdam

Greenpeace (1991b) *Greenpeace 1990-1991 Antarctic expedition report.* Greenpeace International, Amsterdam

Greenpeace (1992) *Greenpeace 1991-1992 Antarctic expedition report.* Greenpeace International, Amsterdam

Greenpeace (1993) *The Greenpeace report of the Antarctic environmental impact monitoring programme at World Park Base 1991-1992.* Greenpeace International, Amsterdam

Greenpeace (1994a) *Greenpeace 1992-1993 Antarctic expedition report.* Greenpeace International, Amsterdam

Greenpeace (1994b) *World Park Base Antarctica 1987-1992: treading lightly: a minimal impact Antarctic station.* Greenpeace International, Amsterdam

Greenpeace (1997) *Greenpeace 1996-1997 Antarctic expedition report.* Greenpeace International, Amsterdam

Hayward J, Macfarlane MJ, Keys JR, Campbell IB (1994) Decommissioning Vanda Station, Wright Valley, Antarctica: Initial Environmental Evaluation, March 1994

Keys JR, Barrett P, Cooper A, Davey F, McFarlane M, Preston D, Pyne A, Webster B (1994) *Final Comprehensive Environmental Evaluation: Antarctic Stratigraphic Drilling East of Cape Roberts in Southwest Ross Sea, Antarctica*, prepared and written for the International Steering Committee for Environmental Protection. Department of Conservation, New Zealand

Mear R, Swan R (1987) *In the footsteps of Scott.* 306p. Jonathan Cape, London

Nowlan, L (2001). *Arctic Legal Regime for Environmental Protection.* IUCN, Gland, Switzerland and Cambridge, UK and ICEL, Bonn, Germany. xii + 70 pp.

Preliminary Environmental Evaluation K123 (2004) *Preliminary Environmental Evaluation for K123: Environmental Protection of Soils of the Ross Sea Region*, prepared for Antarctica New Zealand, June 2004

Reich RJ (1980) The development of Antarctic tourism. *Polar Record 20*: 203-214

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

Sheppard DS, Campbell IB, Claridge GGC (1993) Contamination in the Soils at Vanda Station. Institute of Geological and Nuclear Sciences Report to Antarctica New Zealand (unpublished)

Sutherland D (2002) *Lake Vanda Monitoring Report No. 7.* National Institute of Water and Atmospheric Research Ltd, prepared for Antarctica New Zealand

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. *Antarctic Science 21:* 3-33

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

Antarctic Treaty Consultative Meeting documents referenced:

IP = Information Paper
WP = Working Paper

IAATO (2010) IP 113 ATCM XXXIII: *IAATO Overview of Antarctic Tourism: 2009-10 Season and Preliminary Estimates for 2010-11 and Beyond.*

New Zealand, United Kingdom, United States (2006) WP 34 ATCM XXIX: *Ross Sea Protected Area Inspections 2006*

Websites:

Logistics data *at* http://www.comnap.aq (accessed Feb 14, 2011)

Environmental Impact Assessment statement *at* http://www.antarcticanewzealand.govt.nz (accessed Feb 14, 2011)

Tourism Statistics *at* http://www.iaato.org (accessed Feb 14, 2011)

4 A METHOD FOR ASSESSING THE PHYSICAL RECOVERY OF ANTARCTIC DESERT PAVEMENTS FOLLOWING HUMAN-INDUCED DISTURBANCES

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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

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ABSTRACT

With increasing visitor numbers an understanding of the impacts of human activities in Antarctic terrestrial environments has become important. The objective of this study was to develop a means for assessing recovery of the ground surface desert pavement following physical disturbance. A set of 11 criteria were identified to assess desert pavement recovery. Assessed criteria were: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development. Recovery criteria were assigned a severity/extent rating on a scale from zero to four, zero being highly disturbed, and four being undisturbed. A relative % recovery for each criteria was calculated for each site by comparison with a nearby undisturbed control area, and an overall *Mean Recovery Index* (MRI) was assigned to each pavement surface.

To test the method, 54 sites in the Ross Sea region of Antarctica were investigated including areas disturbed by: bulldozer scraping for road-fill, contouring for infrastructure, geotechnical investigations, and experimental treading trial sites. Disturbances had occurred at timescales ranging from one week to 50 years prior to assessment. The extent of desert pavement recovery at the sites investigated in this study was higher than anticipated. Fifty of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery, 30 sites were in an advanced stage of recovery, and four sites were indistinguishable from adjacent control sites (MRI = 100%). It was found that active surfaces, such as the gravel beach deposits at the Greenpeace World Park Base site at Cape Evans, the aeolian sand deposits at Bull Pass, and the alluvial fan deposits of the Loop Moraine field campsite, recovered relatively quickly, whereas less active sites, such as the bulldozed tracks at Marble Point, and Williams Field to McMurdo Station pipeline site on Ross Island, showed only intermediate recovery 20–30 years after disturbance. The slabby grano-diorite surface material at the former Vanda Station site, meant that the impacts that had occurred were hard to detect following decommissioning of the station and site remediation. Desert pavements disturbed by randomly dispersed footprints, temporary field campsites at the Loop Moraine and VXE6 Pond in the Wright Valley, recovered to be undetectable (MRI = 100%) within five years, whereas track formation from repeated trampling, particularly the concentration of larger clasts along the margin of a confined track, persisted for over 15 years (MRI = 82%). The recovery assessment method developed in this study has environmental management applications and potential to advance our ability to predict the recovery of desert pavement following human impacts from activities in Antarctica.

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1. Introduction

Soils and land surfaces of most of the ice-free areas in the Ross Sea region of Antarctica have evolved as a result of slow weathering over long time periods, in an environment governed by low precipitation, severe cold (mean annual air temperatures <−10 °C),

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limited biological activity, and extraordinary landscape stability (Campbell and Claridge, 1987). Antarctic soils generally lack structural development and coherence, and as a consequence, most ice-free areas are readily disturbed by human activities, and slow to recover (Balks et al., 1995; Campbell and Claridge, 1987; Campbell et al., 1993; Claridge et al., 1995; Sheppard et al., 1994). There were more than 60 scientific stations and over 36,000 visitors to the Antarctic in the 2009/2010 summer season (IAATO, 2011). Human influence and impacts are greatest in the vicinity of the bases, such as at Hut Point Peninsula on Ross Island, where the United States and New Zealand Antarctic programmes are estimated to have catered for close to 100,000 people since the late 1950s (Tin et al., 2009). The McMurdo Dry Valleys, and Antarctic mainland coastal margins in the Ross Sea region are estimated to have been visited by about 15,000 people since the 1950s (Tin et al., 2009). With increasing visitor numbers, understanding the effects of human impacts on soil resources has become an important issue in Antarctica (Campbell et al., 1994; Chwedorzewska and Korczak, 2010).

Desert pavements play an important role in the Antarctic cold desert environment, acting as protective armour to stabilize both the slope and the soil. Mature, undisturbed Antarctic desert pavements are typically characterised by a closely packed layer of gravel, cobble, and boulder sized rock material, which can be ventifacted, and coated with desert varnish. Clasts are embedded into a finer matrix; and their undersides are often coated in salts. The clasts are not usually strongly cemented to one another or the substrate beneath. Consequently, once the protective armour of the desert pavement is lost, the underlying fine grained fraction becomes vulnerable to wind and water erosion. Freeze–thaw processes, wind action, and to lesser extent, water action, are recognised as drivers of physical weathering and desert pavement recovery, in polar desert environments (Bockheim, 2010; Campbell and Claridge, 1987; Campbell et al., 1998a). Wind is likely to be the primary driver of desert pavement recovery in most environments in the Ross Sea region (Campbell et al., 1998a).

Desert pavement disturbance can arise from a number of sources ranging from vehicles, that cause overturning of large cobbles, indentation and compression of sub-pavement soils; bulldozer blade scrapes; telecommunications antenna and pipeline installation; active layer removal for road or fill material; and scientific investigations; through to lower level disturbance from camping and pedestrian traffic. There have been limited previous studies on the ability of the Antarctic desert pavement to recover from human disturbances. Salt accumulation on recently disturbed surfaces (Balks et al., 1995; Campbell and Claridge, 1987) has been reported and it has been recognised that older weathering stage 4, 5, and 6 desert pavements are more vulnerable to disturbance (Campbell and Claridge, 1987). Campbell et al. (1993) developed a visual site assessment (VSA) for rapid evaluation of present day disturbance impacts. The VSA rates the extent of surface disturbance against impact assessment criteria, such as evidence of boot imprints, and evidence of foreign objects, as a means of comparing disturbance severity across different sites. The effects of earth moving activities on patterned ground were investigated on 1959-era cut and fill surfaces at Marble Point (Campbell et al., 1994), where slumping, surface salt efflorescences, and changes to the distribution of patterned ground was observed. The rate of walking track formation was investigated near Scott Base and in the McMurdo Dry Valleys, and showed that on some unconsolidated parent materials it takes less than 20 passes for a track to form (Campbell et al., 1998a). A study by Roura (2004) reported the relatively quick recovery of the former Greenpeace World Park Base site at Cape Evans, and showed the advantages of utilising young and active surfaces comprising beach gravels. McLeod (2012) identified differences in soil vulnerability across a variety of landforms and parent materials in the Wright Valley of the McMurdo Dry Valleys.

The objective of this study was to formulate a simple field-based method to quantify the relative stage of desert pavement recovery following physical disturbance. Our aim was to then test the Desert Pavement Recovery Assessment method on a range of previously disturbed sites comprising a variety of parent materials, landforms, and initial disturbance intensities.

2. Desert Pavement Recovery Assessment method

Eleven morphological features were identified to assess desert pavement recovery following disturbance (Table 1). A rating system was defined for each of the recovery criteria (Table 2). Recovery criteria I–VI relate to surface clast characteristics; VII and VIII are desert pavement attributes; and IX–XI are indicators of surface stability. Recovery criteria were assigned a severity/extent rating on a scale from zero to four, zero being highly disturbed, and four being undisturbed (Table 2). Examples of the recovery criteria are shown in Figs. 1–3.

The Desert Pavement Recovery Assessment (DPRA) method categorises the stage of recovery for each criteria along a continuous spectrum of desert pavement rehabilitation. The development

Table 1
Morphological features identified for assessment of desert pavement recovery.

Desert Pavement Recovery Assessment criteria (I–XI)	
Surface clast characteristics	
I	*Embeddedness of surface clasts* refers to the proportion of the clast below the ground surface level. Disturbance can leave clasts "perched" on the surface, or up-ended or double-stacked; whereas mature pavement surfaces are characterised by a smooth layer of adjacently packed flat-lying clasts.
II	*Impressions of removed clasts* are the holes left when surface clasts are moved.
III	*Degree of clast surface weathering* assesses attributes such as roundness and faceting, ventifaction, pitting, and evidence of polish.
IV	*% overturned clasts* were estimated by the proportion of clasts that are overturned as a result of disturbance, with fresh overturns being clearly visible due to salt coatings (previously underneath) exposed on the upturned clast.
V	*Salt on underside of clasts* was determined using ten randomly selected cobbles and noting the proportion of clasts with salt visible on the underside.
VI	*Development of salt coatings* on the undersides of clasts was assessed based on the ten cobbles tested in V above, and the absence/presence, patchiness, and thickness, of the salt coating was assessed.
Desert pavement attributes	
VII	*Armouring (*1 m^2 *test plot).* Desert pavement takes on an armoured appearance over time as finer fragments are fretted from the surface, and fine underlying material winnowed away, to form a well-packed surface layer of interlocking material.
VIII	*Colour contrast (munsell unit difference).* Weathering processes are strongest at the surface and consequently the colour of the material below is paler than the surface material. A strong colour difference, defined by Campbell et al. (1993) as a colour contrast greater than three units apart (Munsell Soil Colour Chart), was evident on recently, and highly, disturbed surfaces, where the previously underlying material is obvious at the surface. A weak colour contrast occurred on surfaces where the natural weathering processes of recovery had begun.
Surface stability indicators	
IX	*Evidence of subsidence and melt-out* often results when active layer material has been removed, thereby causing melting of the newly exposed previous top of the permafrost beneath.
X	*Accumulations of salt on cut surfaces* commonly accompany physical disturbance where permafrost melting and evaporation has occurred.
XI	*Patterned ground development.* At recently disturbed sites the natural patterned ground may be lost due to surface re-contouring. Subsequent melting of the ice-wedges and winter freezing processes can help re-establish patterned ground.

Table 2
Desert Pavement Recovery criteria ratings.

Desert Pavement Recovery criteria		0 Highly disturbed	1 Clearly disturbed	2 Moderately disturbed	3 Weakly disturbed	4 Undisturbed
I	Embeddedness of surface clasts	None	Few	Some	Most	All
II	Impressions of removed clasts	Sharp/fresh	Clear	Distinct	Faint	Not visible
III	Degree of clast surface weathering (i.e. ventifaction, pitting, polish)	Unweathered	Weakly weathered	Moderately weathered	Strongly weathered	Very strongly weathered
IV	% overturned clasts	>75%	50–75%	20–50%	1–20%	0%
V	Salt on underside of clasts – "10 cobble" test	0–20%	20–40%	40–60%	60–80%	80–100%
VI	Degree of development of salt coatings	Not visible	Weakly developed	Moderately developed	Strongly developed	Very strongly developed
VII	Armouring (1 m^2 test plot)	0–20%	20–40%	40–60%	60–80%	80–100%
VIII	Colour contrast (munsell unit difference)	Very strong (>3)	Strong (3)	Moderate (2)	Weak (1)	Not visible (0)
IX	Evidence of subsidence and melt-out	Prominent	Distinct	Faint	Indistinct	Not visible
X	Accumulation of salt on cut surfaces	Abundant	Common	Some	Rare	Not visible
XI	Patterned ground development	Not visible	Indistinct	Faint	Distinct	Prominent

of desert pavement features is dependent on a range of factors including climate, parent material, and surface age. Therefore, to assess the recovery of a surface following disturbance it is necessary to make a comparison of the recovery criteria for the disturbed site with the recovery criteria assessed from an undisturbed site on the same soil-landscape unit.

To calculate a disturbed site's stage of desert pavement recovery, the relative % recovery for each criteria was calculated to establish the *Mean Recovery Index* (MRI):

$$\mathrm{MRI\%} = \left\{\left[\left(\mathrm{I}^{d}/\mathrm{I}^{c}\right) + \left(\mathrm{II}^{d}/\mathrm{II}^{c}\right) + \left(\mathrm{III}^{d}/\mathrm{III}^{c}\right) + \left(\mathrm{IV}^{d}/\mathrm{IV}^{c}\right) + \ldots\right] /11\right\}*100$$

where recovery criteria I through to XI and d = disturbed site, c = control site. The divisor, 11, reflects the number of recovery criteria. For example IV^{d} = the rating of criteria IV at the disturbed site.

If a criterion is not present in the control site, or the disturbed site, that criteria should be left out of the equation and the divisor must be adjusted to reflect the number of recovery criteria assessed.

The *Mean Recovery Index* (MRI) can be calculated for each site that is investigated. Overall stages of desert pavement recovery are defined (Table 3).

The DPRA method was tested at 54 disturbed, and adjacent control, sites and soil samples were collected. Site and soil descriptions were carried out in accordance with Schoeneberger et al. (2002).

3. Study sites

The Desert Pavement Recovery method was tested on 54 sites over the austral summers of 2008/09 and 2009/10 (Table 4). Sites included disturbed areas near: Scott Base, McMurdo Station, and Cape Evans, on Ross Island; the Wright and Taylor valleys in the McMurdo Dry Valleys; and Cape Roberts and Marble Point, on the Antarctic mainland coast (Fig. 4). Sites included areas disturbed by activities such as bulldozer scraping for road-fill, contoured for infrastructure, geotechnical investigation, and treading trial experimental sites; disturbed at timescales ranging from one week to 50 years prior to assessment (Fig. 5).

The sites on Ross Island were all formed from relatively unweathered scoriaceous basaltic material whereas sites on the Antarctic mainland were formed predominately from till materials of mixed lithology (Table 5). The Cape Evans and Cape Roberts sites were relatively active beach deposited material. The Ross Island, Marble Point, and Cape Roberts sites all have moderate snowfalls and are described as within the moist coastal mountain climatic zone of Campbell and Claridge (1987). The Wright Valley sites were all near the valley floor, in a central mountain climatic regime (Campbell and Claridge, 1987) where wind activity is the primary driver of surface processes.

Ross Sea region soils comprise a surface desert pavement and seasonally thawed active layer overlying permafrost. Soils of the study sites were formed from a range of parent materials (Table 5) but were uniformly coarsely textured (predominantly stony gravelly sands), and lacked cohesion and soil structural development. The gravimetric water content of the top 5 cm of soil ranged from 1 to 3% and soils were classed as subxerous to xerous (Campbell and Claridge, 1987). Soils were alkaline, with the pH in the range of 8–10 in the top 5 cm of soil, with small increases with depth. Electrical conductivity can show high spatial heterogeneity in Ross Sea region soils, and ranged between 0.04 mS/cm to 34.1 mS/cm in the top 5 cm of soil, decreasing with depth. Soils of the study sites had low nutrient contents, low organic carbon (0.02%–0.1%), very low total nitrogen (0–0.02%), and low C:N ratios (between 3 and 19). Details of soil analyses are included in O'Neill (2012).

4. Results of the application of the Desert Pavement Recovery Assessment method

The desert pavement recovery assessment of the disturbed study sites showed that 50 of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery and had MRIs greater than 50% (Tables 6 and 7). Thirty sites were in an advanced stage of recovery, with MRIs between 75% and 99%, and four sites had an MRI of 100% and were indistinguishable from adjacent control sites. Three sites showed a stage of incipient desert pavement formation, with MRIs between 25% and 49%, whilst one site had an MRI of 23% (recently or highly disturbed).

Sites showing the lowest MRI (Tables 6 and 7) and stage of desert pavement recovery were the Crater Hill site A, which was disturbed by vehicle traffic within the last 9 months at the Crater Hill Wind Farm (MRI = 23%) (Fig. 6); and the steep walking track in the Taylor Valley Visitor Zone (MRI = 39%) (Fig. 7).

At the other extreme, the four sites with MRIs of 100% (i.e. desert pavement recovery indistinguishable from adjacent control sites, Table 3) included the Crater Hill site C, disturbed 40–50 years prior; the Former Greenpeace World Park Base site, disturbed 18 years prior (Fig. 8a, b); the Taylor Valley Visitor Zone sand-rich till near the pro-glacial lake, disturbed less than one year prior; and the K123 Loop moraine field camp, tent site, disturbed 5 years prior to our investigation (Fig. 8c, d and e) (Tables 6 and 7).

Fig. 1. Examples of the Desert Pavement Recovery Assessment (DPRA) criteria I–V (Tables 1 and 2). a) Embeddedness of surface clasts, DPRA rating 1, clearly disturbed; b) embeddedness of surface clasts, DPRA rating 4, undisturbed; c) impressions of removed clasts, DPRA rating 0, highly disturbed (arrows indicate impression); d) degree of clast weathering, DPRA rating 2, moderately weathered (varnish and pitting); e) % overturned clasts (salt side up, circles indicate overturns), DPRA rating 2, moderately disturbed, 20–50% clasts overturned; f) salt on underside of clasts, as part of "10 cobble" test.

Fig. 2. Examples of the Desert Pavement Recovery Assessment criteria VI–X (Tables 1 and 2). a) Degree of development of salt coatings, DPRA rating 3, strongly developed; b) armouring (1 m^2 test plot), DPRA rating 0, highly disturbed; c) armouring (1 m^2 test plot), DPRA rating 3, weakly disturbed; d) colour contrast (munsell unit difference), DPRA rating 0, very strong (>3 units difference), highly disturbed; e) evidence of subsidence and melt-out (arrows indicate hollows), DPRA rating 0, prominent, highly disturbed; f) accumulation of salt on cut surfaces (arrows pointing to salt deposits), DPRA rating 0, abundant, highly disturbed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

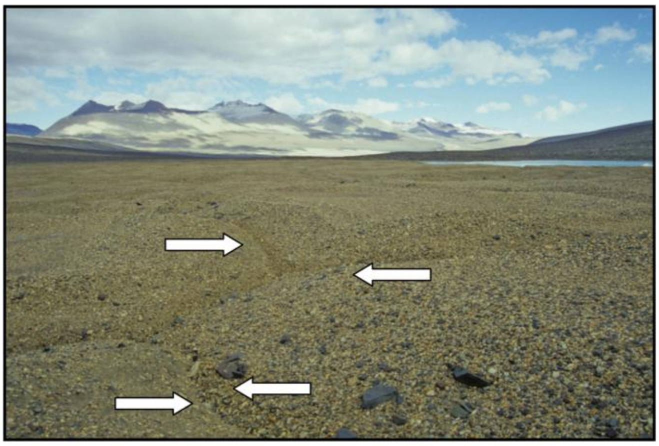

Fig. 3. Example of the Desert Pavement Recovery Assessment (DPRA) criteria XI (Tables 1 and 2). Patterned ground development, DPRA rating 4, prominent or undisturbed (arrows indicate patterned ground cracks).

Table 3
Stages of desert pavement recovery as a function of Mean Recovery Index (MRI).

MRI (%)	Recovery stage
0–24	Recently or highly disturbed
25–49	Incipient pavement
50–74	Intermediate recovery
75–99	Advanced recovery
100	Indistinguishable from control site

5. Discussion

5.1. Desert Pavement Recovery criteria

The 11 desert pavement recovery criteria used to quantify desert pavement recovery at 54 sites in the Ross Sea region of Antarctica provided a useful, semi-quantitative, method to assess desert pavement rehabilitation following physical disturbance. Overall, the extent of desert pavement recovery from the physical impacts of different scales of human activity was higher than anticipated.

The five recovery criteria to show greatest usefulness across the 54 study sites were: embeddedness of surface clasts (recovery criteria I); impressions of removed clasts (II); % overturned clasts (IV); armouring per m^2 (VII); and colour contrast (VIII).

Disturbance to the embeddedness of clasts within the desert pavement was particularly apparent when clasts which have pale-coloured salt coatings on their undersides are up-ended, double-stacked, or overlapping. Depending on the size of the clast, the impressions of removed and upturned clasts can persist for a long time in the Antarctic environment. In most Antarctic settings, wind is the primary driver for reorganisation of material and desert pavement rehabilitation, and processes such as infilling may take a long time (years to decades) to occur. For example, impressions of

Table 4
Location and disturbance history of the sites investigated.

Location	Site description	GPS location	Time since last disturbance	Cause of disturbance	Disturbed area (m^2)
Scott Base	Microbial Experiment site	77° 50′ 53.3″ S, 166° 45′ 37.5″ E	<1 year	Soil sampling	10
	Scott Base to McMurdo Station track	77° 50′ 50.6″ S, 166° 44′ 52.0″ E	Still in use	Walking track	600
	Crater Hill Summit lower track and IR7 site (2)	77° 50′ 38.7″ S, 166° 45′ 14.3″ E	Still in use	Walking track	700
	Active layer disturbance site (cut and fill site)	77° 50′ 53.9″ S, 166° 45′ 42.7″ E	19 years	Bulldozer cut/fill	50
	Williams Field to McMurdo Pipeline	77° 50′ 40.1″ S, 166° 45′ 09.9″ E	19 years	Re-contouring	1000
	Telecom cable site	77° 50′ 48.9″ S, 166° 45′ 11.7″ E	19 years	Bulldozer cut	300
	Up Observation Hill Track	77° 51′ 04.5″ S, 166° 41′ 24.6″ E	Still in use	Walking track	400
	Round Observation Hill Track	77° 51′ 07.7″ S, 166° 42′ 19.0″ E	Still in use	Walking track	500
	Crater Hill site A	77° 50′ 39.7″ S, 166° 43′ 32.7″ E	<1 year	Bulldozer cut	100
	Crater Hill site B	77° 50′ 48.2″ S, 166° 42′ 50.6″ E	16 years	Bulldozer cut	100
	Crater Hill site C	77° 50′ 31.3″ S, 166° 42′ 53.2″ E	40–50 years	Bulldozer cut	100
Cape Evans	Wind Vane Hill Track	77° 38′ 13.1″ S, 166° 25′ 09.3″ E	Still in use	Walking track	200
	Former Greenpeace World Park Base	77° 38′ 05.2″ S, 166° 25′ 20.6″ E	18 years	Station	8000
Marble Point	North of experimental concrete mound	77° 26′ 12.5″ S, 163° 47′ 58.4″ E	40–50 years	Bulldozer cut	10
	57/58 road to tarsealed exp. Mound	77° 25′ 41.4″ S, 163° 44′ 24.9″ E	40–50 years	Vehicle track	1000
	Subsidiary present day vehicle track	77° 26′ 12.7″ S, 163° 47′ 47.9″ E	Still in use	Vehicle track	1000
	Main present day vehicle track	77° 26′ 12.9″ S, 163° 47′ 46.9″ E	Still in use	Vehicle track	1000
	Bulldozed hummocky ground, ice-cored moraine	77° 26′ 12.8″ S, 163° 48′ 03.8″ E	40–50 years	Bulldozer fill	100
	Raised beach sequence – bulldozed sites (3)	77° 25′ 36.0″ S, 163° 44′ 43.0″ E	40–50 years	Bulldozer compacted	200

Table 4 (*continued*)

Location	Site description	GPS location	Time since last disturbance	Cause of disturbance	Disturbed area (m^2)
	K123 Borehole site, Gneiss Point	77° 14′ 39.8″ S, 163° 26′ 14.8″ E	<1 year	Borehole installation/ maintenance	6
	Experimental pit site adj to c.′57/58 track	77° 25′ 50.1″ S, 163° 44′ 25.5″ E	40–50 years	Bulldozed pit	10
	57/58 bulldozer cut track	77° 25′ 50.2″ S, 163° 44′ 27.5″ E	40–50 years	Bulldozer cut	800
	57/58 CampSite, removed late 70s	77° 25′ 13.1″ S, 163° 41′ 04.5″ E	20–30 years	Campsite	100
	K123 soil climate station	77° 25′ 10.4″ S, 163° 40′ 56.6″ E	<1 year	Climate station installation/maintenance	6
	Bulldozer mounds near artificial lake	77° 25′ 09.9″ S, 163° 40′ 39.0″ E	40–50 years	Bulldozer fill	100
	Edge of bulldozed track across wetland	77° 25′ 19.2″ S, 163° 41′ 27.4″ E	40–50 years	Bulldozer cut	100
	Explosion pit, 800 m NE refuelling station, Gneiss Point	77° 24′ 33.2″ S, 163° 41′ 35.4″ E	40–50 years	Bulldozed pit	10
	Debris of Jamesway, 57/58 Camp, bulldozed late 70s	77° 25′ 13.3″ S, 163° 41′ 05.0″ E	20–30 years	Campsite	100
	57/58 CampSite, removed Jamesway site (#2)	77° 25′ 12.8″ S, 163° 41′ 02.4″ E	20–30 years	Campsite	100
	Fire site from late 70s clean-up	77° 25′ 07.8″ S, 163° 40′ 53.9″ E	20–30 years	Campsite	4
Taylor Valley	Taylor Valley Visitor Zone (TVVZ), walking tracks	77° 37′ 35.3″ S, 163° 03′ 18.6″ E	<1 year	Walking track	600
	TVVZ, moist soft sand-rich till near pro-glacier lake	77° 07′ 04.4″ S, 163° 02′ 48.3″ E	<1 year	Pristine site	600
Wright Valley	K123 Loop moraine campsite & tracks (3)	77° 29′ 10.8″ S, 162° 21′ 50.6″ E	5 years	Campsite, walking track	300
	K123 VXE6 Pond campsite	77° 33′ 47.6″ S, 161° 16′ 31.6″ E	3 years	Campsite	100
	Vanda Treading Trial site – Rocky site, Fan site (2)	77° 31′ 33.3″ S, 161° 41′ 28.3″ E	17 years	Treading trial/ walking track	100
	Former Vanda Station, central court area	77° 31′ 41.5″ S, 161° 40′ 18.6″ E	17 years	Station	8000
	Former Vanda Station "Grey Water" Gully	77° 31′ 42.0″ S, 161° 40′ 22.1″ E	17 years	Rubbish disposal	40
	Former Vanda Station, vehicle track to fuel store	77° 31′ 43.6″ S, 161° 40′ 10.0″ E	17 years	Vehicle track	1000
	Former Vanda Station, primary helo pad	77° 31′ 45.3″ S, 161° 40′ 03.4″ E	17 years	Former helo pad	100
	Former Vanda Station, vehicle track to 2nd helo pad	77° 31′ 46.3″ S, 161° 40′ 07.5″ E	17 years	Vehicle track	1000
	Bull Pass refuge hut to seismic hut track	77° 31′ 04.2″ S, 161° 51′ 09.1″ E	<1 year	Walking track	150
	Bull Pass bedrock borehole site	77° 31′ 05.6″ S, 161° 51′ 04.1″ E	<1 year	Borehole installation/ maintenance	6
	Bull Pass soil climate station	77° 31′ 05.6″ S, 161° 51′ 04.1″ E	<1 year	Climate station installation/maintenance	6
Cape Roberts	Cape Roberts 1993 baseline VSA – southern & northern plots (2)	77° 02′ 07.3″ S, 163° 10′ 43.0″ E	10 years	Soil sampling, vehicle/ walking tracks	1500

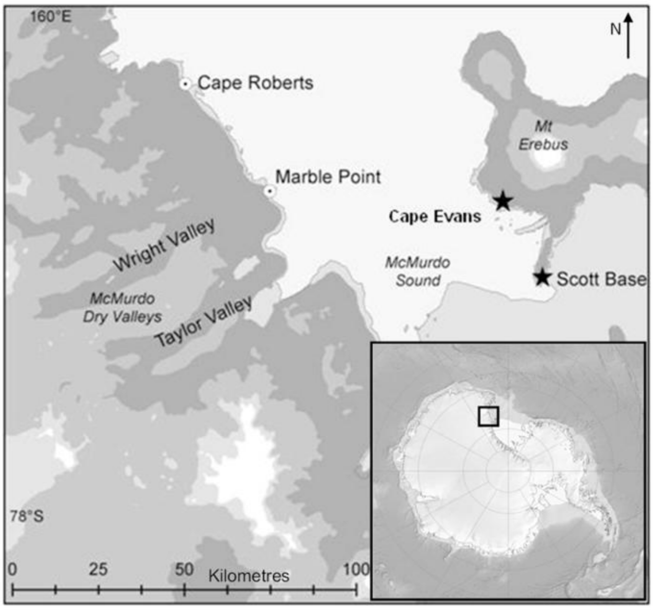

Fig. 4. Location of Ross Sea region study sites.

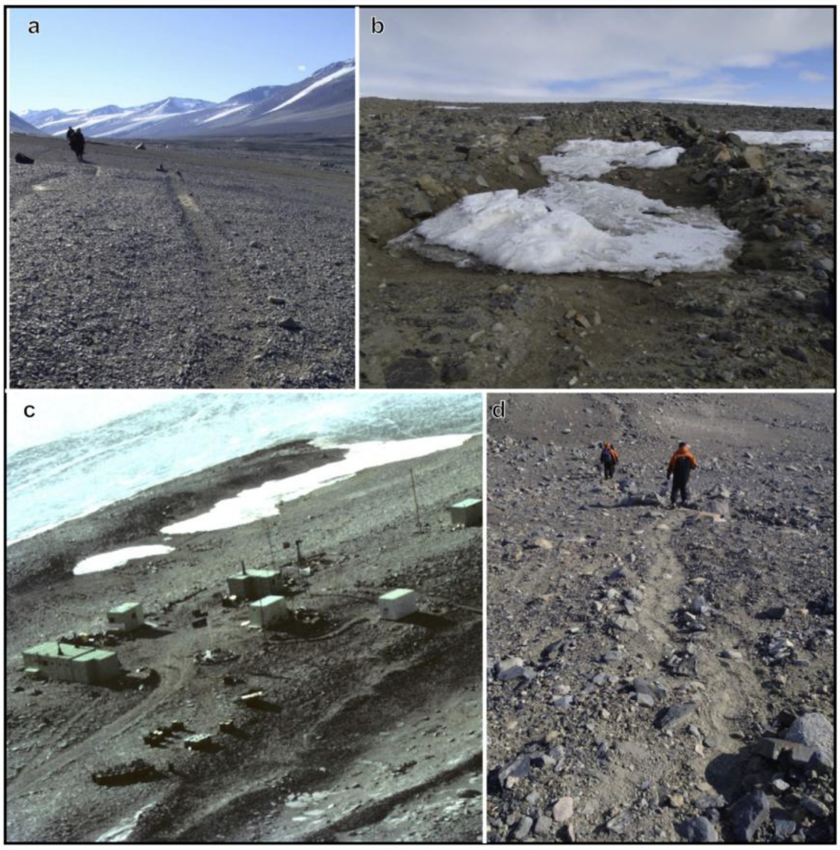

Fig. 5. Examples of disturbed sites investigated. a) Vanda experimental treading trial site, Wright Valley; b) bulldozed pit, Marble Point; c) Former Vanda Station site, Wright Valley c. 1972. Photo: Mike Wing; d) A walking track in the Taylor Valley Visitor Zone, McMurdo Dry Valleys.

removed clasts, 5–10 cm in diameter, were still evident at the Telecom Cable site and the Williams Field to McMurdo Station pipeline site, 19 years after the disturbance took place. Salt veneers on the underside of surface clasts are common in some Ross Sea region settings, making fresh overturns clearly visible compared to the surrounding undisturbed pavement surfaces. Without remediation, and replacing overturned clasts to their original salt-side-down positions and orientations, overturned clasts remain an obvious feature on a disturbed surface. A succession of increasingly armoured desert pavements was apparent in the chronosequence of disturbance skirting Crater Hill near Scott Base (Table 6). Each Crater Hill site, Crater Hill site A, B, and C, comprised scoriaceous basalt parent material, and each was disturbed by bulldozers (active layer removal for roading/fill material). Thus, amongst the Crater Hill succession of sites, time since disturbance was the main variable. The effect of time since disturbance is reflected in the MRIs for the Crater Hill succession: Crater Hill site C, >40 years since last disturbance, MRI = 100%, Crater Hill site B, intermediate aged disturbance and intermediate stage of recovery, MRI = 66%, and Crater Hill site A, <one year since last disturbance, highly disturbed, and MRI = 23% (Table 6).

In many Ross Sea region landscapes there is a marked colour contrast between the highly weathered surface soil material and the less weathered subsurface (Campbell et al., 1998b). Upon disturbance, paler, unweathered, and/or fine textured soil material is exposed at the surface. Surface colour contrast consistently showed the greatest difference amongst the sites disturbed >30–40 years prior to investigation, with geotechnical explosion pit sites at Marble Point, for example, still showing a strong colour contrast more than 40 years after the original disturbance.

The desert pavement recovery criteria that were least commonly identified in the 54 sites in this study were: the degree of surface clast weathering (recovery criteria III); salt accumulation on the underside a clasts (V); evidence of subsidence and melt-out (IX); and patterned ground development (XI).

The degree of surface clast weathering is an important consideration on desert pavement surfaces that have weathering stages 3 through to 6, where a visible difference between a newly disturbed

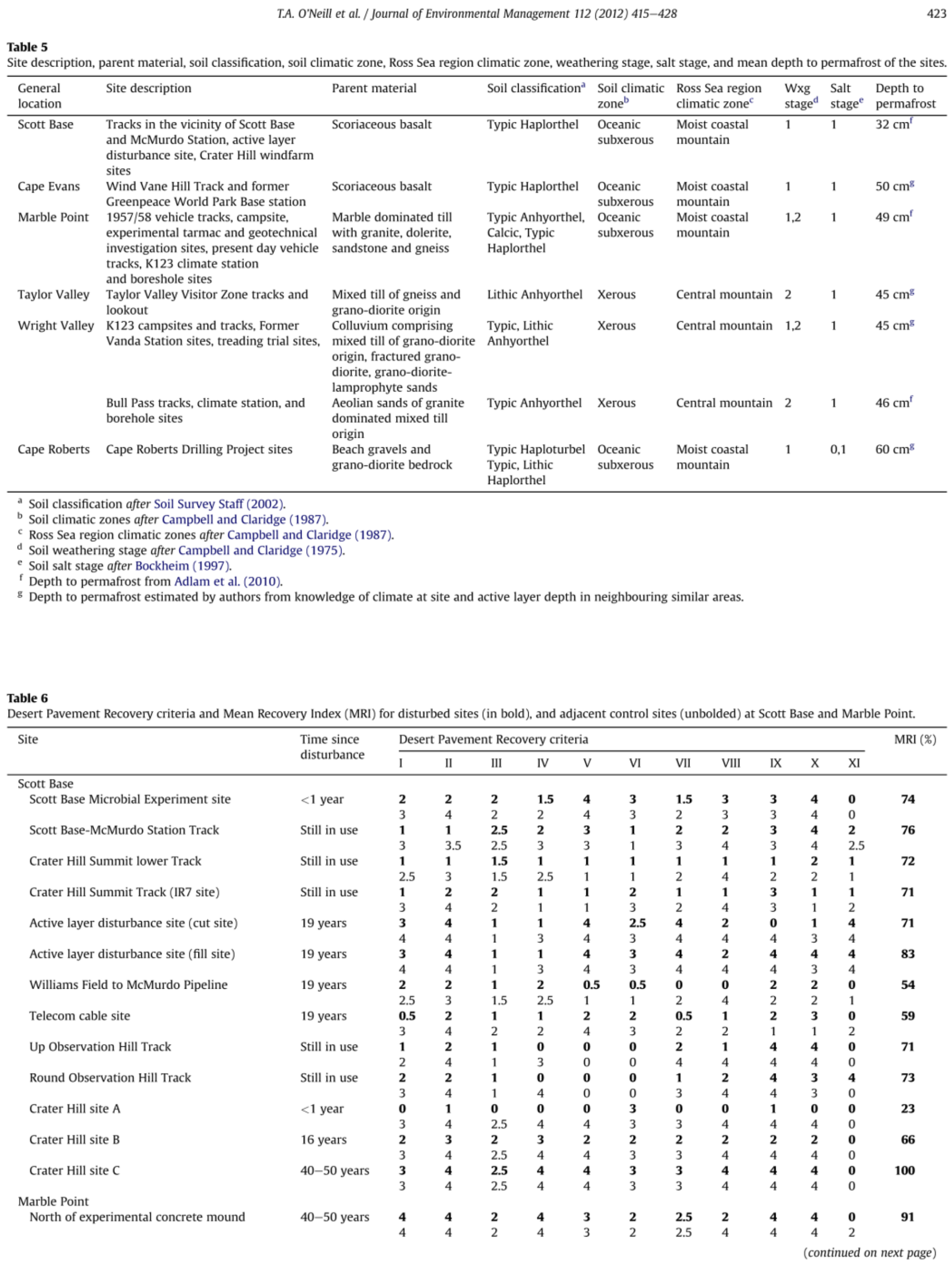

Table 5
Site description, parent material, soil classification, soil climatic zone, Ross Sea region climatic zone, weathering stage, salt stage, and mean depth to permafrost of the sites.

General location	Site description	Parent material	Soil classification[a]	Soil climatic zone[b]	Ross Sea region climatic zone[c]	Wxg stage[d]	Salt stage[e]	Depth to permafrost
Scott Base	Tracks in the vicinity of Scott Base and McMurdo Station, active layer disturbance site, Crater Hill windfarm sites	Scoriaceous basalt	Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	1	32 cm[f]
Cape Evans	Wind Vane Hill Track and former Greenpeace World Park Base station	Scoriaceous basalt	Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	1	50 cm[g]
Marble Point	1957/58 vehicle tracks, campsite, experimental tarmac and geotechnical investigation sites, present day vehicle tracks, K123 climate station and boreshole sites	Marble dominated till with granite, dolerite, sandstone and gneiss	Typic Anhyorthel, Calcic, Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1,2	1	49 cm[f]
Taylor Valley	Taylor Valley Visitor Zone tracks and lookout	Mixed till of gneiss and grano-diorite origin	Lithic Anhyorthel	Xerous	Central mountain	2	1	45 cm[g]
Wright Valley	K123 campsites and tracks, Former Vanda Station sites, treading trial sites,	Colluvium comprising mixed till of grano-diorite origin, fractured grano-diorite, grano-diorite-lamprophyte sands	Typic, Lithic Anhyorthel	Xerous	Central mountain	1,2	1	45 cm[g]
	Bull Pass tracks, climate station, and borehole sites	Aeolian sands of granite dominated mixed till origin	Typic Anhyorthel	Xerous	Central mountain	2	1	46 cm[f]
Cape Roberts	Cape Roberts Drilling Project sites	Beach gravels and grano-diorite bedrock	Typic Haploturbel Typic, Lithic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	0,1	60 cm[g]

[a] Soil classification *after* Soil Survey Staff (2002).
[b] Soil climatic zones *after* Campbell and Claridge (1987).
[c] Ross Sea region climatic zones *after* Campbell and Claridge (1987).
[d] Soil weathering stage *after* Campbell and Claridge (1975).
[e] Soil salt stage *after* Bockheim (1997).
[f] Depth to permafrost from Adlam et al. (2010).
[g] Depth to permafrost estimated by authors from knowledge of climate at site and active layer depth in neighbouring similar areas.

Table 6
Desert Pavement Recovery criteria and Mean Recovery Index (MRI) for disturbed sites (in bold), and adjacent control sites (unbolded) at Scott Base and Marble Point.

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
Scott Base													
Scott Base Microbial Experiment site	<1 year	**2**	**2**	**2**	**1.5**	**4**	**3**	**1.5**	**3**	**3**	**4**	**0**	**74**
		3	4	2	2	4	3	2	3	3	4	0	
Scott Base-McMurdo Station Track	Still in use	**1**	**1**	**2.5**	**2**	**3**	**1**	**2**	**2**	**3**	**4**	**2**	**76**
		3	3.5	2.5	3	3	1	3	4	3	4	2.5	
Crater Hill Summit lower Track	Still in use	**1**	**1**	**1.5**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**72**
		2.5	3	1.5	2.5	1	1	2	4	2	2	1	
Crater Hill Summit Track (IR7 site)	Still in use	**1**	**2**	**2**	**1**	**1**	**2**	**1**	**1**	**3**	**1**	**1**	**71**
		3	4	2	1	1	3	2	4	3	1	2	
Active layer disturbance site (cut site)	19 years	**3**	**4**	**1**	**1**	**4**	**2.5**	**4**	**2**	**0**	**1**	**4**	**71**
		4	4	1	3	4	3	4	4	4	3	4	
Active layer disturbance site (fill site)	19 years	**3**	**4**	**1**	**1**	**4**	**3**	**4**	**2**	**4**	**4**	**4**	**83**
		4	4	1	3	4	3	4	4	4	3	4	
Williams Field to McMurdo Pipeline	19 years	**2**	**2**	**1**	**2**	**0.5**	**0.5**	**0**	**0**	**2**	**2**	**0**	**54**
		2.5	3	1.5	2.5	1	1	2	4	2	2	1	
Telecom cable site	19 years	**0.5**	**2**	**1**	**1**	**2**	**2**	**0.5**	**1**	**2**	**3**	**0**	**59**
		3	4	2	2	4	3	2	2	1	1	2	
Up Observation Hill Track	Still in use	**1**	**2**	**1**	**0**	**0**	**0**	**2**	**1**	**4**	**4**	**0**	**71**
		2	4	1	3	0	0	4	4	4	4	0	
Round Observation Hill Track	Still in use	**2**	**2**	**1**	**0**	**0**	**0**	**1**	**2**	**4**	**3**	**4**	**73**
		3	4	1	4	0	0	3	4	4	3	0	
Crater Hill site A	<1 year	**0**	**1**	**0**	**0**	**0**	**3**	**0**	**0**	**1**	**0**	**0**	**23**
		3	4	2.5	4	4	3	3	4	4	4	0	
Crater Hill site B	16 years	**2**	**3**	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**0**	**66**
		3	4	2.5	4	4	3	3	4	4	4	0	
Crater Hill site C	40–50 years	**3**	**4**	**2.5**	**4**	**4**	**3**	**3**	**4**	**4**	**4**	**0**	**100**
		3	4	2.5	4	4	3	3	4	4	4	0	
Marble Point													
North of experimental concrete mound	40–50 years	**4**	**4**	**2**	**4**	**3**	**2**	**2.5**	**2**	**4**	**4**	**0**	**91**
		4	4	2	4	3	2	2.5	4	4	4	2	

(*continued on next page*)

Table 6 (*continued*)

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
57/58 road to tarsealed exp. mound	40–50 years	**3**	**4**	**2**	**3**	**2**	**1**	**3**	**2**	**4**	**4**	**0**	**96**
		3	4	2	3	2	1	3	4	4	4	0	
Subsidiary present day vehicle track	Still in use	**2**	**4**	**2.5**	**3**	**3**	**1**	**2**	**2**	**4**	**4**	**0**	**89**
		3	4	2.5	4	3	1	3	4	4	4	0	
Main present day vehicle track	<1 year	**2**	**4**	**1**	**3**	**0**	**0**	**2.5**	**2**	**4**	**3**	**0**	**80**
		2	4	1	4	0	0	2.5	4	4	3	2	
Bulldozed, ice-cored moraine	40–50 years	**4**	**4**	**1**	**3**	**0**	**0**	**2.5**	**4**	**0**	**2**	**0**	**75**
		4	4	1	4	0	0	2.5	4	4	4	2	
Raised beach sequence (compacted site)	40–50 years	**2**	**4**	**1**	**3.5**	**2**	**1**	**1.5**	**2**	**4**	**4**	**0**	**78**
		4	4	1	4	2	1	2	4	4	4	2	
Raised beach sequence (cut site)	40–50 years	4	**4**	**1**	**4**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**70**
		4	4	1	4	2	1	2	4	0	0	2	
Raised beach sequence (winrow)	40–50 years	**3**	**4**	**1**	**3.5**	**1**	**0.5**	**2**	**2**	**4**	**0**	**2**	**83**
		4	4	1	4	2	1	2	4	4	0	2	
Borehole site, Gneiss Point	<1 year	**4**	**3**	**3**	**4**	**0**	**0**	**0**	**0**	**4**	**4**	**0**	**94**
		4	4	3	4	0	0	0	0	4	4	0	
Experimental pit site adj to '57/58 track	40–50 years	**2**	**4**	**2**	**0**	**0**	**1**	**2**	**2**	**1**	**2**	**0**	**48**
		4	4	2	4	3	2	2	4	4	4	2	
57/58 bulldozer cut track	40–50 years	**3**	**4**	**2**	**4**	**1**	**1**	**1**	**1**	**4**	**4**	**1**	**65**
		4	4	2	4	3	2	2	4	4	4	2	
57/58 CampSite, removed late 70s	20–30 years	**2**	**4**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**2**	**0**	**51**
		4	4	1	4	4	2	3	4	4	4	0	
K123 soil climate station	<1 year	**2**	**4**	**1**	**3**	**2**	**2**	**3**	**4**	**4**	**4**	**0**	**89**
		4	4	1	4	4	2	3	4	0	0	0	
Bulldozer mounds near artificial lake	40–50 years	**2**	**4**	**1**	**1**	**4**	**1**	**3**	**4**	**4**	**2**	**4**	**83**
		4	4	1	3	4	1	4	4	4	4	4	
Edge of bulldozed track across wetland	40–50 years	**4**	**4**	**1**	**4**	**0**	**0**	**3**	**4**	**4**	**0**	**0**	**98**
		4	4	1	4	0	0	4	4	4	0	0	
Explosion pit, 800 m NE refuelling station	40–50 years	**2**	**4**	**2.5**	**0**	**1**	**1**	**3**	**1**	**0**	**0**	**1**	**45**
		3.5	4	2.5	4	3.5	2	3	4	4	4	4	
Debris of bulldozed Jamesway, '57/58 Camp	20–30 years	**1.5**	**4**	**1**	**0**	**1**	**1**	**2**	**1**	**0**	**2**	**0**	**50**
		4	4	1	4	4	2	3	4	4	4	0	
57/58 CampSite, removed Jamesway (#2)	20–30 years	**1**	**4**	**1**	**1**	**1**	**1**	**3**	**2**	**1**	**1**	**0**	**57**
		4	4	1	4	4	2	3	4	4	4	0	
Fire site from late 70s clean-up	20–30 years	**2.5**	**4**	**1**	**3**	**4**	**2**	**2**	**1**	**3**	**0**	**0**	**80**
		4	4	1	4	4	2	3	4	4	4	0	

Desert Pavement Recovery criteria: I = embeddedness of surface clasts; II = impressions of removed clasts; III = degree of clast surface weathering; IV = % overturned clasts; V = salt on underside of clasts; VI = development of salt coatings; VII = armouring per 1 m^2; VIII = colour contrast; IX = evidence of subsidence/melt out; X = accumulation of salt on cut surfaces; XI = patterned ground development.

surface and a highly ventifacted and pitted desert pavement would be obvious. We were unable to include examples of older, higher elevation, weathering stage 3–6 sites in this study. Salt accumulation on the underside of clasts is also expected to be more useful when older surfaces are investigated, because as soil development increases, salt encrustations become thicker, and can therefore be a good indication of desert pavement maturity, and disturbance. Subsidence, melt-out, and patterned ground development are potentially useful indicators of desert pavement disturbance and recovery only where large-scale bulldozer removal of active layer material has occurred. Only 10 sites out of the 54 sites in this study included large-scale bulldozer activity.

5.2. Factors influencing desert pavement recovery

The cold desert conditions, coupled with factors such as the absence of vegetative cover, scarcity of water, and minimal rate of natural movement of soil materials, inevitably slow soil recovery

Table 7
Desert Pavement Recovery criteria and Mean Recovery Index (MRI) for disturbed sites (in bold) and adjacent control sites (unbolded) at Taylor Valley, Wright Valley, Cape Evans, and Cape Roberts.

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
Taylor Valley													
Taylor Valley Visitor Zone (TVVZ), lower track	<1 year	**1**	**4**	**2.5**	**1**	**3**	**1.5**	**3**	**1**	**4**	**0**	**3**	**76**
		3	4	2.5	4	4	1.5	4	4	4	4	3	
TVVZ, hilltop lookout	<1 year	**2**	**2**	**2.5**	**2.5**	**4**	**2**	**3**	**1**	**4**	**4**	**0**	**71**
		3	4	2.5	4	4	2	4	4	4	4	4	
TVVZ, steep track to head of Canada Glacier	<1 year	**0**	**1**	**2.5**	**0**	**0**	**0**	**0**	**0**	**4**	**4**	**0**	**39**
		3	4	2.5	4	4	2	3.5	4	4	4	3	
TVVZ, moist soft sand-rich till near pro-glacier lake	<1 year	**4**	**4**	**2**	**4**	**0**	**0**	**3**	**4**	**4**	**4**	**0**	**100**
		4	4	2	4	0	0	3	4	4	4	0	
Wright Valley													
K123 Loop moraine campsite, track to sampling site	5 years	**3**	**4**	**2**	**4**	**0**	**0**	**3**	**3**	**4**	**4**	**0**	**93**
		4	4	2	4	0	0	4	4	4	4	0	
K123 Loop moraine campsite, tent site	5 years	**4**	**4**	**2**	**4**	**0**	**0**	**4**	**4**	**4**	**4**	**0**	**100**
		4	4	2	4	0	0	4	4	4	4	0	

Table 7 (*continued*)

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
K123 Loop moraine campsite, toilet track	5 years	**2**	**4**	**2**	**2**	**0**	**0**	**2**	**1**	**4**	**4**	**0**	**82**
		4	4	2	4	0	0	4	4	4	4	0	
K123 VXE6 Pond, campsite	3 years	**3**	**3**	**2.5**	**4**	**3**	**1**	**3**	**4**	**4**	**4**	**0**	**98**
		3	4	2.5	4	3	1	3	4	4	4	0	
Vanda Rocky Treading Trial site	17 years	**3**	**4**	**1.5**	**3**	**2**	**1**	**2**	**3**	**4**	**0**	**0**	**96**
		4	4	1.5	3	2	1	2	4	4	0	0	
Vanda Fan Treading Trial site	17 years	**2**	**4**	**2.5**	**1**	**0**	**1**	**2**	**1**	**4**	**0**	**0**	**62**
		3	4	2.5	4	1	1	3	4	4	0	3	
Former Vanda Station, central court area	17 years	**3**	**4**	**1**	**4**	**0**	**0**	**4**	**2**	**4**	**0**	**0**	**90**
		3.5	4	2	4	0	0	4	4	4	0	0	
Former Vanda Station "Grey Water" Gully	17 years	**3**	**4**	**1.5**	**4**	**0**	**0**	**1**	**4**	**4**	**4**	**0**	**95**
		3	4	1.5	4	0	0	2	4	4	4	0	
Former Vanda Station, track to fuel store	17 years	**1.5**	**4**	**2**	**1**	**0**	**0**	**2.5**	**3**	**4**	**4**	**0**	**87**
		2	4	2	3	0	0	3	4	4	4	0	
Former Vanda Station, primary helo pad	17 years	**2**	**4**	**1**	**4**	**0**	**0**	**2.5**	**3.5**	**4**	**4**	**0**	**97**
		2	4	1	4	0	0	3	4	4	4	0	
Former Vanda Station, vehicle track to 2nd helo pad	17 years	**3**	**4**	**0.5**	**4**	**0**	**0**	**3**	**3.5**	**4**	**4**	**0**	**99**
		3	4	0.5	4	0	0	3	4	4	4	0	
Bull Pass refuge hut to seismic hut track	<1 year	**1**	**1**	**1.5**	**0**	**0**	**0**	**3**	**3**	**4**	**4**	**0**	**85**
		3	4	1.5	0	0	0	3	4	4	4	0	
Bull Pass bedrock borehole site	<1 year	**3**	**4**	**2**	**4**	**0**	**0**	**2**	**4**	**4**	**4**	**0**	**98**
		4	4	2	4	0	0	2	4	4	4	0	
Bull Pass soil climate station	<1 year	**4**	**4**	**2**	**4**	**0**	**0**	**2**	**4**	**4**	**4**	**0**	**99**
		4	4	2	4	0	0	2	3.5	4	4	0	
Cape Evans													
Wind Vane Hill Track	Still in use	**2**	**3.5**	**1**	**3**	**4**	**1**	**3**	**1**	**4**	**2**	**0**	80
		3	4	1	4	4	1	4	1	4	4	0	
Former Greenpeace World Park Base	18 years	**1**	**4**	**1**	**4**	**0**	**0**	**3**	**4**	**4**	**4**	**0**	100
		1	4	1	4	0	0	3	4	4	4	0	
Cape Roberts													
Cape Roberts 1993 baseline VSA, southern plot	10 years	**2**	**4**	**1**	**3**	**0**	**0**	**1**	**2**	**4**	**3**	**0**	91
		2	4	1	3	0	0	2	4	4	3	0	
Cape Roberts 1993 baseline VSA, northern plot	10 years	**3**	**3**	**1**	**3**	**0**	**0**	**2**	**3**	**4**	**4**	**0**	88
		4	4	1	4	0	0	3	4	4	4	0	

Desert Pavement Recovery criteria: I = embeddedness of surface clasts; II = impressions of removed clasts; III = degree of clast surface weathering; IV = % overturned clasts; V = salt on underside of clasts; VI = development of salt coatings; VII = armouring per 1 m^2; VIII = colour contrast; IX = evidence of subsidence/melt out; X = accumulation of salt on cut surfaces; XI = patterned ground development.

rates in the Ross Sea region of Antarctica (Campbell et al., 1993, 1998a). The rate and extent of desert pavement recovery at the sites investigated could be attributed to a combination of the intensity of the initial disturbance; the environmental conditions for the site, including, parent material and surface characteristics (age and weathering stage), availability of water and wind regime; and also the restoration and remediation measures undertaken at the site.

Fig. 6. Crater Hill site A. Mean Recovery Index = 23%. Note lack of clast embeddedness, desert pavement armouring, high% overturned clasts, and accumulation of salt on the newly disturbed surface.

Fig. 7. Steep walking track at the Taylor Valley Visitor Zone. Mean Recovery Index = 39%. Note lack of clast embeddedness, moderate% overturned clasts, impressions of removed clasts, and colour contrast between walking track and adjacent undisturbed material. Arrows indicate fresh footprints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This study assessed a range of sites disturbed at different times and by different intensities of human activity. The visible evidence of historic disturbances around Vanda Station and Marble Point (areas frequently visited over the last two decades by one of the authors) are limited to high intensity disturbances, such as bulldozed areas. Sites associated with high intensity disturbances, where the active layer has been disturbed and/or removed, subsurface soil material displaced, side-mounds formed by bulldozers, or where there are a high proportion of overturned clasts, had the lowest MRIs and disturbance had a lasting visible impact. The once widespread minor disturbances, such as footprints, which would have been widespread around the former Vanda Station and the old Marble Point camp, have recovered to be indistinguishable from the surrounding undisturbed material.

Wind is likely to be the primary driver of desert pavement recovery in most environments in the Ross Sea region (Bockheim, 2010; Campbell et al., 1998a). We assume wind action in valley floors and low ridge sites, such as the Loop Moraine, former Vanda Station, Vanda experimental treading trial sites, and the Taylor Valley Visitor Zone sites in the McMurdo Dry Valleys, assisted in the rehabilitation of the desert pavement. At most sites wind is likely to be the instigator in the first stages of formation of an incipient desert pavement following disturbance. In instances where we had records of low level disturbance, such as impacts from the tent sites at the Loop Moraine field site in the Wright Valley, wind action is likely to have resulted in natural infilling of footprints, sorting of surface materials to re-create 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 several disturbed sites, such as the Loop Moraine walking-tracks, Marble Point bulldozer tracks, or diffuse the “indentation” visible across the walking tracks at the Loop Moraine and the Vanda Fan treading trial site.

The intermittent supply of moisture may have assisted in desert pavement recovery at some of the study sites. Disturbances occurring in the moist coastal climatic zones of Marble Point, the vicinity of Scott Base, Cape Evans, and Cape Roberts, are moistened by occasional summer snowfalls and spring snow thaw. Subsequent repetitive freeze–thaw action may have also aided recovery, and over time, jostled surface clasts into a more embedded position in the desert pavement surface and along with windblown material infilled the impressions of removed clasts. In the drier, central mountain climatic zones, such as the McMurdo Dry Valleys, further from the coast, moisture available for soil surface processes is less, and recovery was generally not as advanced as equivalent intensity disturbances in moister areas.

Campbell et al. (1998a,b) and O'Neill (2012) showed that initial physical disturbance in the landscape is greatest where there was a fine-textured gravel, sand, and pebble pavement and the soils had a low proportion of coarse materials. However, this study has shown in spite of seemingly rapid initial disturbance and obvious visible damage, finer textured desert pavements can undergo rapid rehabilitation under favourable conditions (high moisture and/or wind regime). In many cases the least disturbance and greatest recovery was observed where the desert pavement was predominately boulders and cobbles, as the hardy nature of the surface material, such as the weakly weathered, slabby grano-diorite comprising the former Vanda Station site, showed little evidence of the once widespread trampling and vehicle tracks which would have criss-crossed this area. It is evident that many vehicle and walking tracks developed around the stations and campsites are not preserved as they were on resilient or rocky, parent materials. The ability to recognise young active surfaces, such as active beach deposits, and sand dunes, where material is readily reorganised by wind or water, is important, as in these settings the initial damage may seem high, but the ability of surfaces to recover is greater than some older less resilient landforms and parent materials.

5.3. Site remediation

Site remediation (raking and smoothing of disturbed surfaces to free-up compacted soil, and redistribute out of place stones) was effective, where surface materials were not strongly weathered (weathering stage 1 or 2), and led to accelerated visual recovery of the desert pavement at 11 of the sites studied. Ten years after remediation both of the Cape Roberts study sites were nearly indistinguishable from equivalent control sites (Northern Plot MRI = 88%, Southern Plot MRI = 91%), with no obvious evidence of vehicle traffic or human traffic disturbances. Furthermore, the redistribution of disturbed rocks from vehicle and walking track margins at the former Vanda Station site (MRI = 90%), was effective at reducing visible disturbance and aiding surface pavement recovery. Surface restoration is only a cosmetic effect as the subsurface material, such as an infilled soil pit, remains permanently disturbed.

5.4. Recommendations for future research

The Desert Pavement Recovery Assessment method was formulated as a simple, reproducible method that gives semi-quantitative results for assessing the physical recovery of a site following disturbance. The method was designed to be

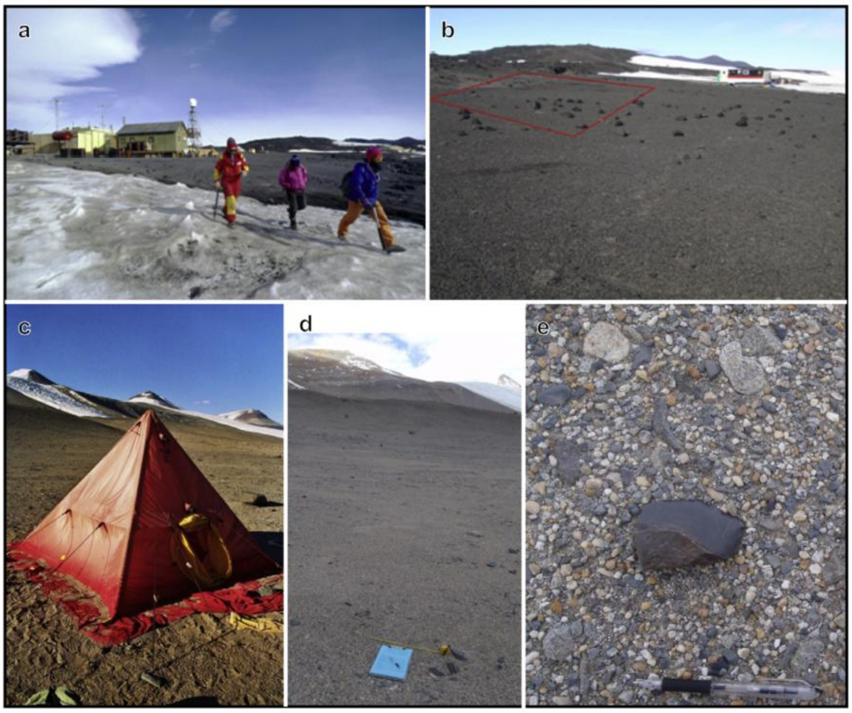

Fig. 8. Examples of sites showing the greatest desert pavement recovery. Greenpeace World Park Base at Cape Evans. a) Greenpeace huts and fuel storage racks in Jan. 1992; b) red rectangle marking the location of the former Greenpeace base, Jan. 2009, Mean Recovery Index = 100%. Site of the Loop Moraine campsite, tent site. c) Loop Moraine tent site, Dec. 2004. Photo: Fiona Shanhun; d) Loop Moraine tent site, 5-years later, Dec. 2009; e) Desert pavement at the Loop Moraine tent site, Dec. 2009, Mean Recovery Index = 100%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

independent of the factors that influence landscape recovery so it could be used simply to determine whether a site had recovered or not, irrespective of time, parent material, and disturbance intensity. Investigation of a greater number of sites with a wider range of disturbance types, older sites of known low and moderate intensity disturbances, and older, highly weathered surfaces (weathering stages 3–6) are needed to develop the method for use as a predictive tool.

The Desert Pavement Recovery Assessment method described in this paper provides an addition to the range of tools available for environmental assessment and management in Antarctica. There is potential to extend the method to assess desert pavement recovery in other parts of the Antarctic continent and high Arctic environments. Future applications could be developed to combine field-based observations applying our Desert Pavement Recovery Assessment method with remotely sensed data, such as reflectance and soil texture density spatial data.

6. Conclusions

The Desert Pavement Recovery Assessment method presented here is a simple field-based method which was formulated and tested on a range of disturbed sites in the Ross Sea region of Antarctica in the austral summer of 2008/09 and 2009/10. The Desert Pavement Recovery Assessment method uses a set of recovery criteria developed to assess ground surface recovery from human disturbance. Assessed criteria were: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development. A method by which an overall *Mean Recovery Index* (MRI) can be calculated has been developed.

The method was tested on 54 sites including areas disturbed by: bulldozer scraping for road-fill, contouring for infrastructure, geotechnical investigations, and experimental treading trial sites. Disturbances had occurred at timescales ranging from one week to 50 years prior to assessment.

The extent of desert pavement recovery at the sites investigated in this study was higher than anticipated. Fifty of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery, 30 sites were in an advanced stage of recovery, and four sites were indistinguishable from adjacent control sites (MRI = 100%).

Five of the 11 recovery criteria proved the most useful in determining the *Mean Recovery Index* of the sites (embeddedness of surface clasts, impressions of removed clasts, % overturned clasts, armouring per m^2, and colour contrast between the disturbed and control desert pavement sites). The remainder, including salt accumulation on the underside of clasts, and the degree of surface clast weathering, are expected to be more useful when older surfaces are investigated.

Of the sites investigated, active surfaces, such as the gravel beach deposits, aeolian sand, and alluvial fan deposits, recovered relatively quickly, whereas less active sites of higher intensity disturbances, such as the bulldozed tracks at Marble Point, showed only intermediate recovery 20–30 years after disturbance. Desert pavements disturbed by randomly dispersed footprints, such as the temporary field campsites at the Loop Moraine, recovered to be undetectable (MRI = 100%) within five years, whereas track formation from repeated trampling, and consequently concentrating larger clasts along the margin of a confined track, persisted for over 15 years (MRI = 82%).

This study introduces a tool which can be used to advance environmental management in the Ross Sea region of Antarctica. Further investigation into older, highly weathered landscapes, and a greater number of sites impacted by low-to-moderate intensity disturbances is needed to further develop the method and allow it to be used as a predictive tool.

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References

Adlam, L.S., Balks, M.R., Seybold, C.A., Campbell, D.I., 2010. Temporal and spatial variation in active layer depth in the McMurdo Sound region, Antarctica. Antarct. Sci. 22 (1), 45–52.

Balks, M.R., Campell, D.I., Campbell, I.B., Claridge, G.G.C., 1995. Interim Results of 1993/94 Soil Climate, Active Layer, and Permafrost Investigations at Scott Base, Vanda and Beacon Heights, Antarctica. University of Waikato, Antarctic Research Unit Special Report, No. 1, 64 pp.

Bockheim, J.G., 1997. Properties and classification of cold desert soils from Antarctica. Soil Sci. Soc. Am. J. 61, 224–231.

Bockheim, J.G., 2010. Evolution of desert pavements and the vesicular layer in soils of the Transantarctic mountains. Geomorphology 118 (3–4), 433–443.

Campbell, I.B., Claridge, G.G.C., 1975. Morphology and age relationships of Antarctic soils. In: Suggate, R.P., Cresswell, M.M. (Eds.), Quaternary Studies. Royal Society of New Zealand Bulletin, vol. 13, pp. 87–88.

Campbell, I.B., Claridge, G.G.C., 1987. Antarctica: Soils, Weathering Processes and Environment. Elsevier, New York.

Campbell, I.B., Balks, M.R., Claridge, G.G.C., 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, I.B., Claridge, G.G.C., Balks, M.R., 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, I.B., Claridge, G.G.C., Balks, M.R., 1998a. Short- and long-term impacts of human disturbances on snow-free surfaces in Antarctica. Polar Rec. 34 (188), 15–24.

Campbell, I.B., Claridge, G.G.C., Campbell, D.I., Balks, M.R., 1998b. The soil environment of the McMurdo dry valleys, Antarctica. In: Ecology of the Antarctic Dry Valleys. Antarctic Research, 72, pp. 297–322.

Chwedorzewska, K.J., Korczak, M., 2010. Human impact upon the environment in the vicinity of Arctowski Station, King George Island, Antarctica. Polish Polar Res. 31 (1), 45–60.

Claridge, G.G.C., Campbell, I.B., Powell, H.K.J., Amin, Z.H., Balks, M.R., 1995. Heavy metal contamination in some soils of the McMurdo Sound region, Antarctica. Antarct. Sci. 7 (01), 9–14.

IAATO, 2011. Tourism Statistics. http://iaato.org/tourism-statistics (accessed 04.09.11.).

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.

O'Neill, T.A., 2012. Soil Physical Impacts and Recovery Rates Following Human-induced Disturbances in the Ross Sea region of Antarctica. PhD Thesis. University of Waikato, New Zealand.

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.

Schoeneberger, P.J., Wyosocki, D.A., Benham, E.C., Broderson, W.D., 2002. Field Book for Describing and Sampling Soils, Version 2.0. National Resources Conversation Service, National Soil Survey Center, Lincoln, Nebraska.

Sheppard, D.S., Campbell, I.B., Claridge, G.G.C., 1994. Contamination of Soils About Vanda Station, Antarctica, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. Report 40/20.

Soil Survey Staff, 2002. Keys to Soil Taxonomy, nineth ed. U.S. Dept. Agric., Natural Resource Conservation Service, Washington, D.C.

Tin, T., Fleming, Z.L., Hughes, K.A., Ainley, D.G., Convey, P., Moreno, C.A., Pfeiffer, S., Scott, J., Snape, I., 2009. Impacts of local human activities on the Antarctic environment. A review. Antarct. Sci. 21 (1), 3–33.

5 VISUAL RECOVERY OF DESERT PAVEMENT SURFACES FOLLOWING IMPACTS FROM VEHICLE AND FOOT TRAFFIC IN THE ROSS SEA REGION OF ANTARCTICA

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Visual recovery of desert pavement surfaces following impacts from vehicle and foot traffic in the Ross Sea region of Antarctica

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Abstract: Sites of past human activity were investigated to assess the visual recovery of the desert pavement following impacts from human trampling and vehicle traffic. Visually disturbed and nearby control sites were assessed using comparative photographic records, a field-based Visual Site Assessment, and Desert Pavement Recovery Assessment. Sites included: vehicle and walking tracks at Marble Point and Taylor Valley; a campsite, experimental treading trial site, and vehicle tracks in Wright Valley; and vehicle and walking tracks at Cape Roberts. The time since last disturbance ranged from three months to over 50 years. This investigation also attempted to determine what has the greatest lasting visual impact on soil surfaces in the Ross Sea region: dispersed trafficking or track formation? Walking tracks remained visible in the landscape (due to larger clasts concentrating along track margins) long after the desert pavement surface had recovered. However, randomly dispersed footprints were undetectable within five years. For many sites, allowing widespread trampling will give lower medium-term visible impact than concentrating traffic flow by track formation. For steep slopes and sites where repeated visits occur, use of a single track is recommended. Some 1950s vehicle tracks remain visible in the Antarctic landscape, but where visually obvious impacts were remediated, evidence of former occupation was almost undetectable.

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Key words: foot-tracking, human impacts, surface morphology, surface recovery, tracks

Introduction

Soils of the ice-free areas of the Ross Sea region of Antarctica have evolved over millions of years in an environment characterized by low precipitation, hyper-aridity, severe cold, limited biological activity, and extraordinary landscape stability (Campbell & Claridge 1975, 1987, Doran *et al*. 2002, Pointing *et al*. 2009). Ross Sea region soils generally lack structural development and coherence, and the loose material is covered by a thin protective layer of gravel, or coarse sand, known as a desert pavement (Cooke 1970, McFadden *et al*. 1987, Bockheim 2010). Mature, undisturbed Ross Sea region desert pavements are typically characterized by a closely packed layer of gravel, cobble, and boulder-sized rock material, which depending on its age, can be ventifacted, and coated with desert varnish (Campbell & Claridge 1987, Bockheim 2010). Desert pavement clasts are embedded into a finer matrix, and their undersides are often coated in salts.

Desert pavement disturbance can arise from a number of sources, and at different intensities, ranging from human trampling, to vehicles that cause overturning of large stones. In the Ross Sea region overturned stones are visible as undersides are often less weathered, lighter coloured, and coated in salts. Other disturbances range from indentation and compression of sub-surface soils, bulldozer blade scrapes, and removal of tens of centimetres of material for road fill, to station construction and complete re-contouring of the immediate landscape. Most desert pavement surfaces are easily disturbed by foot traffic (Campbell & Claridge 1987, Campbell *et al*. 1993, Balks *et al*. 1995), with walking tracks forming within the first 20 passes on unconsolidated surface materials (Campbell *et al*. 1998). A walking 'track', as defined in this study, is an area where a visible pathway has been formed by repeated foot traffic. Once the desert pavement is disturbed, underlying finer, loose material is susceptible to wind erosion. The prevailing cold desert conditions result in slow rehabilitation rates, with some visual impacts suggested as persisting from decades to potentially hundreds of years (Campbell & Claridge 1987, Campbell *et al*. 1993, 1998, Harris 1998). Freeze-thaw processes, wind action, and to a lesser extent, water action, are recognized as drivers of physical weathering and desert pavement recovery in polar desert environments (Campbell & Claridge 1987, Campbell *et al*. 1998, Bockheim 2010). Wind action is probably the primary driver of surface recovery in the Ross Sea region of Antarctica, and over time wind action moves clasts back into their flat-lying preferred state of minimum energy (McFadden *et al*. 1987), whilst finer material is winnowed away, restoring a protective desert pavement.

There have been limited previous studies on the ability of Ross Sea region desert pavements to recover from human disturbance. Campbell *et al*. (1993) developed a

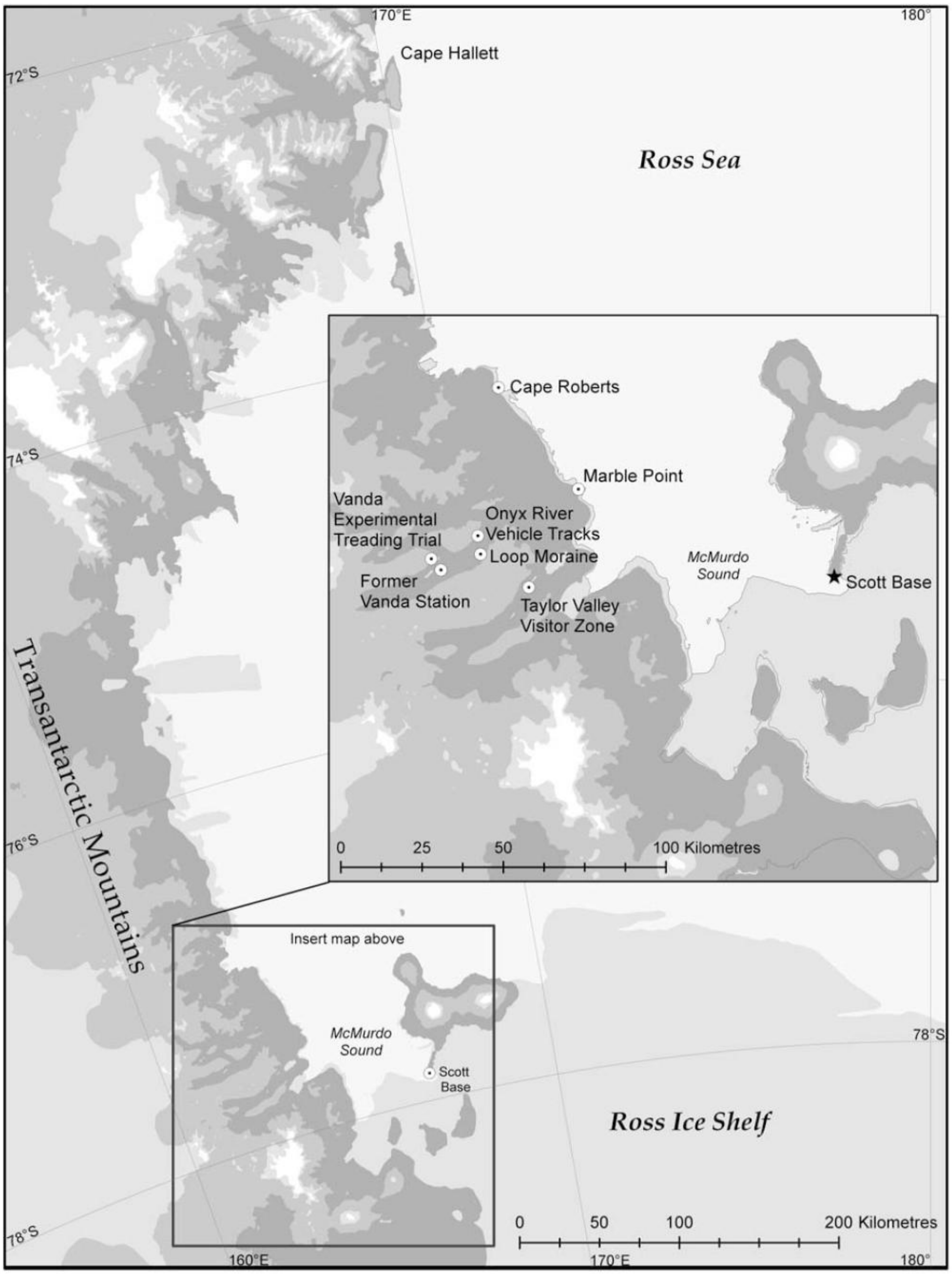

Fig. 1. General location of the 12 Ross Sea region study sites. Note: there are two study sites at the Loop moraine, two sites at the Vanda experimental treading trial, three sites at Marble Point, and two sites at Cape Roberts.

Table I. Site characteristics of the 12 Ross Sea region study sites.

General location	Site description	Time since disturbance	Landform	Parent material	Ross Sea region climatic zone^{a}	Soil classification^{b}	Soil climatic zone^{c}
Marble Point	Vehicle tracks around former base and present-day refuelling station. Site of a former US base and experimental airfield constructed in 1957/58, and present-day outpost for helicopter refuelling station.						
	Main present-day vehicle track (77°26'12.9"S, 163°47'46.9"E). Visibly disturbed area: 1500 m^2	still in use	outwash till	marble dominated till with granite, dolerite, sandstone and gneiss	moist coastal mountain	Calcic Haplorthel	subxerous
	1957/58 bulldozer track (77°25'50.2"S, 163°44'27.5"E). Visibly disturbed area: 1500 m^2	50 years	outwash till	same as above	moist coastal mountain	Typic Haplorthel	subxerous
	Edge of bulldozed track across saturated ground (77°25'19.2"S, 163°41'27.4"E). Visibly disturbed area: 400 m^2	50 years	outwash till	same as above	moist coastal mountain	Typic Haplorthel	subxerous
Taylor Valley	Taylor Valley Visitor Zone (77°37'35.3"S, 163°03'18.6"E). Walking track from hilltop lookout to terminus of the Canada Glacier. Visibly disturbed area: 300 m^2	10 months	moraine	mixed till of gneiss and granodiorite origin	central mountain	Typic Haplorthel Typic Haploturbel	xerous
Wright Valley	Loop moraine field site (77°29'10.8"S, 162°21'50.6"E). Former New Zealand Programme campsite occupied 2004/05 summer.						
	Tent site. Visibly disturbed area: 0 m^2	5 years	moraine-alluvial fan	granodiorite-dominated till/alluvial fan deposits	central mountain	Typic Anhyorthel	xerous
	Walking tracks. Visibly disturbed area: 450 m^2	5 years	same as above	same as above	central mountain	Typic Anhyorthel	xerous
	Vanda experimental treading trial sites (77°31'10.0"S, 161°40'43.4"E). Treading trial undertaken at two sites during 1993/94.						
	"Vanda Fan". Visibly disturbed area: 20 m^2	17 years	alluvial fan	colluvium comprising mixed till of granodiorite, fractured	central mountain	Typic Anhyorthel	xerous
	"Vanda Rocky". Visibly disturbed area: 6 m^2	17 years	low ridge on valley floor	granodiorite bedrock, granodiorite-lamprophyte sands	central mountain	Lithic Anhyorthel	xerous
	Former Vanda station site (77°31'41.5"S, 161°40'18.6"E). Remediated site of the former New Zealand Vanda station. Visibly disturbed area: 1000 m^2	17 years	low ridge on valley floor	surface lag layer of mixed till over granodiorite blocks, bedrock, erosion-resistant lamprophyre dykes	central mountain	Lithic Anhyorthel	xerous

Table I. Continued

General location	Site description	Time since disturbance	Landform	Parent material	Ross Sea region climatic zone[a]	Soil classification[b]	Soil climatic zone[c]
	Late 1960s vehicle tracks (77°29'02.2"S, 162°21'27.5"E). Tractor, tractor-trailer, sled, and gnat tracks, adjacent to the Onyx River. Visibly disturbed area: 500 m^2 section assessed of a *c.* 10 000 m^2	40 years	valley floor	colluvium comprising mixed till of granodiorite origin	central mountain	Typic Anhyorthel	xerous
Cape Roberts	Former Cape Roberts Project storage area (77°02'07.3"S, 163°10'43.0"E). Remediated ice-free storage site for the Cape Roberts Drilling Project.						
	"Northern Plot". Visibly disturbed area: 100 m^2	10 years	raised beach	beach gravels and granodiorite bedrock	moist coastal mountain	Typic Haplorthel	subxerous
	"Southern Plot". Visibly disturbed area: 100 m^2	10 years	raised beach	same as above	moist coastal mountain	Typic Haploturbel Lithic Haplorthel	subxerous

Notes: [a]Ross Sea region climatic zones after Campbell & Claridge (1987). [b]Soil classification after Soil Survey Staff (2002). [c]Soil moisture zones after Campbell & Claridge (1987).

Visual Site Assessment (VSA) for rapid evaluation of present-day low-intensity disturbance impacts. The VSA rates the extent of surface disturbance against impact assessment criteria, such as evidence of boot imprints, as a means of comparing disturbance severity across different sites. The rate of walking track formation was investigated near Scott Base and in the McMurdo Dry Valleys, and showed that on some unconsolidated parent materials it takes less than 20 passes for a track to form (Campbell *et al.* 1998). Campbell *et al.* (1998) also showed that once a track has formed the cumulative impacts of larger numbers of people following the same track: 20 passes, versus 200 passes, versus 2000 passes, are minimal. Salt accumulation on recently disturbed surfaces (Campbell & Claridge 1987, Balks *et al.* 1995) has been reported and it has been recognized that older, strongly weathered, desert pavements are more vulnerable to disturbance (Campbell & Claridge 1987). A study by McLeod (2012) identified differences in soil vulnerability in the McMurdo Dry Valleys, and Roura (2004) reported the relatively quick recovery of the former Greenpeace World Park Base (unofficial name) site at Cape Evans. Investigation into the direct effects of foot traffic on soil nematode populations in the Taylor Valley by Ayres *et al.* (2008) showed that trampling had a negative effect on the soil ecosystem, even at low intensities, and to protect microbial populations they recommended limiting foot traffic to established paths.

Under Annex I and II of the Protocol on Environmental Protection to the Antarctic Treaty all activities undertaken in Antarctica must be planned and conducted to limit adverse impacts on the Antarctic environment, and associated ecosystems (Annex II, Article 1(d) and 1(h)). Multiple walking tracks and widespread visible disturbance can detract from the visual quality of the Antarctic environment, which the public perceive to be pristine and deserving of a high level of protection (Kiernan & McConnell 2001). With the expansion of scientific expeditions and their supporting logistics, as well as the increase in tourism and non-governmental activities, understanding how best to minimize the human-induced impacts from low-intensity field camps, tourist visits, or national programme science events, has become an important issue (Campbell *et al.* 1998, Tin *et al.* 2009). Between-site differences in rehabilitative capability have implications for the environmental management of activities. In this paper we investigate the visible recovery of desert pavement surfaces from low-intensity disturbance (foot and vehicle traffic). In focussing on the visible component of surface recovery we only consider the wilderness and aesthetic values (which have been given legal protection under the Protocol since 1998). Assessment of the recovery of soil physical properties and the biota residing within the soil, although important, was beyond the scope of this paper.

The objective of this study was to assess the impacts of, and recovery from, foot and vehicle traffic on varying land surfaces in the Ross Sea region of Antarctica. We also attempted to answer the long-standing question: what has the greatest lasting visual impact on soil surfaces in the Ross Sea region: dispersed trafficking or confined human movements which form a "track"?

Study sites

Study site overview

Twelve sites of past pedestrian and vehicle disturbance, and adjacent control sites, were assessed over the 2008/09 and 2009/10 field seasons (Fig. 1). The assessed sites were situated on a variety of landforms, soil parent materials, and local climates (Table I). At each site the history of the site and time since last disturbance was known, and ranged from three months to over 50 years prior to assessment.

The studied sites in the McMurdo Dry Valleys (Wright Valley and Taylor Valley) and at Marble Point on the Antarctic mainland were formed predominantly from till materials of mixed granite-gneiss-marble-diorite lithology. The Cape Roberts site comprised beach-deposited gravelly sand material over granodiorite bedrock. The Cape Roberts and Marble Point sites have moderate snowfalls and are described as within the moist coastal mountain climatic zone of Campbell & Claridge (1987). The Wright Valley and Taylor Valley sites were all near the valley floor, in a central mountain climatic regime, where wind activity is considered to be the predominant driver of surface processes (Campbell & Claridge 1987) (Table I). All sites were salt stage 1 (Bockheim 1997) and all sites were weathering stage 2 (Campbell & Claridge 1975) except the Cape Roberts sites which were weathering stage 1.

Marble Point vehicle track sites

Marble Point (Fig. 1), on the western side of McMurdo Sound, consists of *c.* 20 km^2 of ice-free undulating land up to 122 m above sea level (Campbell *et al*. 1994). The US military built a camp known as North Base (unofficial name) at Marble Point in 1956 including a 500 m aeroplane runway. The United States Naval Construction Battalion Reconnaissance Unit and a civilian contractor undertook extensive engineering surveys over the summers of 1957/58 and 1958/59 to test the feasibility of building a 3 km long, hard-surface air strip (Broadbent 1994, 2009). Base construction, occupation, and geotechnical investigation resulted in many vehicle tracks scattered across the area. Most of the "North Base" camp was cleared before military departure in January 1959 (Broadbent 1994). Marble Point is the site of a present-day helicopter refuelling station and since about the year 2000 vehicle use has been confined to one main track.

Taylor Valley Visitor Zone

The Taylor Valley Visitor Zone (TVVZ) (Fig. 1) is located adjacent to the Canada Glacier, within Antarctic Specially Managed Area 2 (ATCM 2011) of the McMurdo Dry Valleys. Designated as a Visitor Zone in 1995, the TVVZ provides visitors with a spectacular Dry Valleys vista. The TVVZ is *c.* 350 x 300 m, dominated by a low hill (*c.* 30 m high), and is covered in gravely rocky till, relatively undisturbed desert pavement and patterned ground. There are established walking tracks and small guided groups walk around the site, passing by a pro-glacial lake and the terminus of the Canada Glacier, up a steep track to a lookout point. Access is by helicopter only. A total of 434 people have landed between the summers of 2006/07 and 2008/09. Research programme activity also occurs in the vicinity of the site, with substantial US Antarctic Program camps at nearby Lake Fryxell and Lake Hoare, so total visitor numbers are difficult to quantify.

Loop moraine campsite

A temporary summer field research campsite was located adjacent to the Loop moraine (unofficial name) in the lower Wright Valley (Fig. 1), during the summer of 2004/05. The camp consisted of three tents, which were occupied for one month by four people. At the end of January 2005 all tents and equipment were removed and any obviously disturbed stones were returned to their original position and orientation. At the time of departure from the site footprints were widely evident around the area where the tents had been and distinct walking tracks had formed between the campsite and the toilet facilities (about 100 m away), and campsite and a stream-side experiment (about 300 m away). New Zealand and US national programme records indicate that the site has been undisturbed since the summer of 2004/05.

Vanda experimental treading trial sites

At the eastern end of Lake Vanda, in the Wright Valley, are the Vanda experimental treading trial sites (Fig. 1). The trial was undertaken at two sites of contrasting parent material, the Vanda Fan and Vanda Rocky sites (unofficial names), during the 1993/94 summer season (Campbell *et al*. 1998). Campbell *et al*. (1998) recorded changing ground surface characteristics as the walking track formed after 20, 50, 100, and 200 passes. The two sites have been undisturbed since the trial was established and no remediation of the sites was attempted.

Former Vanda station

Vanda station (unofficial name) (Fig. 1) was established adjacent to Lake Vanda, in the 1968/69 summer to support research in the Wright Valley. Human occupation left the

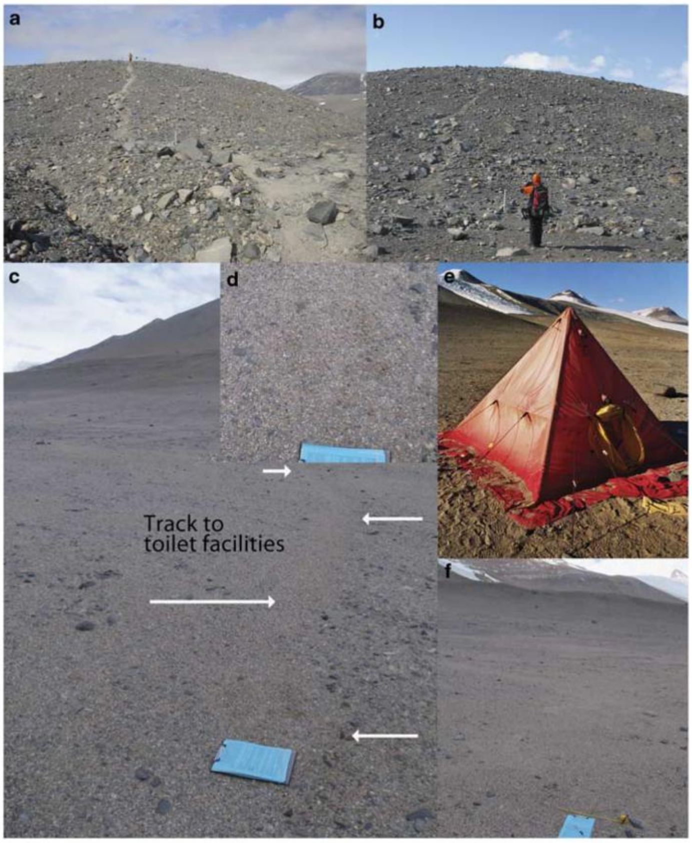

Fig. 2. Taylor Valley Visitor Zone and Loop moraine sites. **a.** Taylor Valley Visitor Zone, walking track from the helicopter landing site to the hilltop lookout, 2006/07 season, after 96 tourist visitors. Picture: Jana Newman. **b.** Walking track from the helicopter landing site to the hilltop lookout, December 2009, before first tourist group of the season. **c.** Loop moraine 2004/05 walking track to toilet, track margin visible (white arrows), after five years recovery, December 2009. **d.** Recovery of the desert pavement on the track surface, after five years. **e.** Loop moraine tent site, December 2004. Picture: Fiona Shanhun. **f.** Loop moraine tent site, five years later, December 2009.

former station site disturbed by trampling, vehicle movement, excavations, and accidental spills (Webster *et al*. 2003), and extensive vehicle tracks criss-crossed the site. Concerns over rising lake levels and the potential for leaching from contaminated ground into the lake system forced a step-wise decommissioning of the station over the summers of 1992/93 to 1994/95 (Hayward *et al*. 1994).

Vehicle tracks in the Wright Valley

Overland vehicles, including tractors, gnats (small three-wheeled off-road vehicles), trailers, and sleds, were used to transport equipment and supplies along the Wright Valley (Harris 1998). Vehicles criss-crossed the floodplain of the Onyx River as they travelled along the valley floor towards Lake Vanda and Vanda station (Fig. 1). The use of vehicles in the Dry Valleys was discontinued in the late 1970s (Harris 1998), with a move to helicopter transport. There are a few areas along the valley floor where traces of vehicle tracks are still visible.

Cape Roberts drilling project ice-free storage area

Cape Roberts (Fig. 1) is a small ice-free coastal peninsula situated on the southern side of Granite Harbour on the Antarctic mainland. In the early 1980s two New Zealand Antarctic Programme huts were erected and since then a variety of tracked-vehicles have entered the area. During the summers of 1995/96 through to 1999/2000 the (previously disturbed) site was used for winter storage of vehicles, drilling, and camp equipment, for the Cape Roberts Drilling Project (CRP) (Waterhouse 2001). A baseline survey of the ice-free storage area was carried out by Campbell & Keys (1993) in the summer of 1992/93. The baseline VSA was

Fig. 3. Vanda experimental treading trial and former Vanda station sites. **a.** "Vanda Rocky" site, 192 passes, December 1993. **b.** "Vanda Rocky" site, after 17 years of recovery, December 2009. Note the "out of place" stones that were used to secure the measuring tape in December 1993. **c.** "Vanda Fan" site, immediately after 200 passes, December 1993. **d.** "Vanda Fan" site, after 17 years of recovery, December 2009. **e.** Vanda station, January 1992, immediately prior to removal. **f.** Site of the former Vanda station mess hut, December 2009. The three people are marking the corners of the former buildings.

carried out on two 10 x 10 m plots ("Northern" and "Southern" plots) and provided environmental data which would enable the impact of the project to be assessed at its conclusion (Campbell & Keys 1993). During the CRP there were about 100 visitors per annum (Waterhouse 2001), and impacts included disturbance attributed to transport of large containers, vehicles, and helicopters. Annual environmental monitoring surveys were undertaken during the project.

Table II. Impact assessment criteria scoring system used for Visual Site Assessment (modified from Campbell *et al.* (1993), and Kiernan & McConnell (2001)).

Impact assessment criteria		Severity and extent of impacts (class)			
		1	2	3	4
A	Disturbed surface stones	none visible (0)	few (< 10)	many (10–25)	abundant (> 25)
B	Impressions of removed rocks	none visible	just visible	distinct	fresh
C	Boot imprints	none visible	just visible	distinct	fresh
D	Visibly disturbed area	< 5 m^2	5–10 m^2	20–100 m^2	> 100 m^2
E	Surface colour difference (Munsell units difference)	none visible (0)	weak contrast (-1)	moderate contrast (-2)	strong contrast (> 3)
F	Other surface impressions (e.g. hollows from backfilled excavations)	none visible	weakly visible	distinct	very fresh
G	Walking tracks	not visible	weakly defined	moderately defined	strongly defined
H	Foreign objects	none visible (0)	few (< 10)	some (10–25)	many (> 25)
I	Visible fuel spills	none visible	faintly distinguished	visible	very obvious
J	Salt deposition	none visible	faintly distinguished	visible	abundant
K	Visual biological disturbance	none visible	< 1 m^2	1–5 m^2	> 5 m^2
L	Cumulative impact	disturbance not visible	weakly evident	clearly visible	disturbed and very obvious
M	Stratigraphic disturbance	negligible	within one unit	within two units	multiple units
N	Morphological or textural change	negligible	just evident	moderate change	very obvious
O	Rock cairns	none	rare or small	moderately common	very common
P	Other disturbances (e.g. paint marks)	none	rare or small	moderately obvious	very obvious

Following conclusion of the CRP, all storage materials were removed and site restoration was undertaken over the summers of 1999/2000 and 2000/01. Rakes were used to redistribute soil material disturbed by vehicle and walking tracks, and all indentations left by bulldozers and sledge skis were raked over. Remediation occurred at a site of localized hydraulic fluid contamination, where the drill rig had been located (75 m south-west of the permanent huts, within the "Southern plot" of Campbell & Keys (1993)), and 0.6 m^3 of contaminated material was removed, and the area was filled in and left to recover (Cowie 2001). The original huts were left in place to support ongoing tide gauge measurements.

Methods

Photograph comparisons

Study sites were analysed using comparative photographic records, the established and widely used VSA of Campbell *et al.* (1993), and the use of a new Desert Pavement Recovery Assessment (DPRA) method (O'Neill *et al.* 2012). A collection of existing photographs were used to accurately identify and relocate previously disturbed sites. Using the historic photographs the authors lined up features in the landscape to exactly identify a site and photographed the same view as the original photograph (e.g. Figs 2 & 3).

Table III. Desert Pavement Recovery Assessment criteria ratings (O'Neill *et al.* 2012).

Desert Pavement Recovery Assessment criteria		Highly disturbed 0	Clearly disturbed 1	Moderately disturbed 2	Weakly disturbed 3	Undisturbed 4
I	Embeddedness of surface clasts	none	few	some	most	all
II	Impressions of removed clasts	sharp/fresh	clear	distinct	faint	not visible
III	Degree of clast surface weathering (i.e ventifaction, pitting, polish)	unweathered	weakly weathered	moderately weathered	strongly weathered	very strongly weathered
IV	% overturned clasts	> 75%	50–75%	20–50%	1–20%	0%
V	Salt on underside of clasts "10 cobble" test	0–20%	20–40%	40–60%	60–80%	80–100%
VI	Degree of development of salt coatings	not visible	weakly developed	moderately developed	strongly developed	very strongly developed
VII	Surface armouring (1 m^2 test plot)	0–20%	20–40%	40–60%	60–80%	80–100%
VIII	Colour contrast (Munsell unit difference)	very strong (> 3)	strong (3)	moderate (2)	weak (1)	not visible (0)
IX	Evidence of subsidence and melt-out	prominent	distinct	faint	indistinct	not visible
X	Accumulation of salt on cut surfaces	abundant	common	some	rare	not visible
XI	Patterned ground development	not visible	indistinct	faint	distinct	prominent

Table IV. Visual Site Assessment results for the 12 study sites, Ross Sea region, Antarctica.

Site	Impact assessment criteria* - severity/extent of impacts (1 = none visible, 4 = most severe)															
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Marble Point																
Main present-day vehicle track	4	1	1	4	1	3	1	1	1	3	1	4	3	1	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1957/58 bulldozer cut track	2	1	1	4	1	1	1	1	1	1	1	4	4	4	1	1
- control	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1
1957/58 bulldozed track across saturated ground	4	1	1	4	1	3	1	1	1	1	1	4	2	4	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Taylor Valley Visitor Zone																
Walking-track from lookout to glacier terminus	4	2	4	4	4	1	4	1	1	1	1	4	4	4	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Wright Valley																
Loop moraine campsite																
Walking track from tent site to toilet facilities	4	1	1	4	3	1	3	1	1	1	1	3	2	4	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tent site	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Vanda Experimental Treading Trial sites																
"Vanda Fan" treading trial walking track	4	1	1	3	3	1	4	1	1	1	1	4	4	4	2	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
"Vanda Rocky" treading trial walking track	2	1	1	2	1	1	1	1	1	1	1	2	2	2	2	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Former Vanda station site																
Central court and mess hut area	4	1	1	4	3	1	1	4	1	1	1	2	2	2	1	2
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Late 1960s vehicle tracks adj. to Onyx River	4	1	1	4	2	3	1	1	1	1	1	3	3	4	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Former Cape Roberts Project storage area																
"Northern Plot"	4	1	1	4	1	3	1	1	1	1	1	3	2	2	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
"Southern Plot"	4	1	1	4	3	3	1	1	1	3	1	3	2	3	1	1
- control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

*Impact assessment criteria: A = disturbed surface stones, B = impressions of removed rocks, C = boot imprints, D = visibly disturbed area, E = surface colour difference (Munsell units difference), F = other surface impressions (e.g. shallow concavities from backfilled excavations), G = walking tracks, H = foreign objects, I = visible fuel spills, J = salt deposition, K = biological disturbance, L = cumulative impact (scale 1–10), M = stratigraphic disturbance, N = morphological or textural disturbance, O = rock cairns, P = other, paint marks etc. (modified from Campbell *et al*. (1993) and Kiernan & McConnell (2001)).

Visual Site Assessment

The VSA method of Campbell *et al*. (1993) was used to assess the present-day visual impacts at a representative area at each site. The VSA method of Campbell *et al*. (1993) is a rapid visual evaluation of terrestrial impacts and 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 (see Campbell *et al*. 1993 for full methods and illustrations). We used Kiernan & McConnell's (2001) modified version of the original VSA which included an additional five criteria: evidence of salt deposition, stratigraphic disturbance, textural disturbance, presence of rock cairns, and "other", such as paint marks, to give a total of 16 impact assessment criteria (Table II). Criteria are rated between one and four, one being no visible impact, and four being the most severe. A VSA was undertaken on the entire disturbed area, or typical representative area for large-scale disturbances. An adjacent equivalent control was also selected, and a VSA was undertaken. Control sites showed no visual evidence of disturbance and were situated adjacent to visually disturbed sites, comprising the same parent material, slope, aspect, and landform. The baseline VSA of the "Northern" and "Southern" plots carried out at Cape Roberts by Campbell & Keys (1993) was repeated in this investigation.

Desert Pavement Recovery Assessment

The DPRA of O'Neill *et al*. (2012) was used to quantify the relative stage of desert pavement recovery following physical disturbance. The DPRA is an assessment method based on a set of 11 morphological features (termed recovery assessment criteria) that change over time as a desert pavement re-establishes and stabilizes (Table III). The DPRA gives an indication of where a disturbed site is placed, with respect to visual recovery, along the continuous spectrum of desert pavement rehabilitation. Recovery assessment criteria I–VI (Table III) relate to surface clast characteristics, such as embeddedness of surface clasts, impressions of removed clasts, and degree of clast surface weathering. Recovery assessment criteria VII and VIII are desert pavement attributes, such as pavement armouring per 1 m^2 (interlocking nature of the desert pavement, % of large to small clasts) and pavement colour contrast. Recovery assessment criteria IX–XI are indicators of surface stability, such as evidence of subsidence or melt out, or evidence of patterned ground development. Criteria are assigned an extent of development rating from zero to four, zero being undeveloped (or highly disturbed), and four being highly developed (or undisturbed). A detailed description of the DPRA is included in O'Neill *et al.* (2012). The development of desert pavement features is dependent on a range of factors including climate, parent material, and surface age. Therefore, to assess the visual recovery of a surface following disturbance it is necessary to make a comparison of the recovery criteria for the disturbed site with the recovery criteria assessed from an adjacent undisturbed equivalent surface. Finally an overall mean recovery index (MRI) can be assigned to each pavement surface, based on the mean percentage recovery for all criteria, with values decreasing as visible disturbance increases. A site with an MRI between 0 and 24% is rated as highly disturbed; 24–49%, forming an incipient

Table V. Desert Pavement Recovery Assessment results for the 12 study sites, Ross Sea region, Antarctica. Note: mean recovery index (MRI) is based on the percentage recovery of each criterion, relative to the equivalent control surface.

Site	Desert Pavement Recovery Assessment criteria*											
	Extent of development (0 = undeveloped/highly disturbed, 4 = highly developed/undisturbed)											MRI
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	%
Marble Point												
Main present-day vehicle track	2	4	1	3	0	0	2.5	2	4	3	0	80
- control	2	4	1	4	0	0	2.5	4	4	3	2	
1957/58 bulldozer cut track	2	1	1	4	1	1	1	1	4	4	4	51
- control	4	4	2	4	3	2	2	4	4	0	4	
1957/58 bulldozed track across saturated ground	4	4	1	4	0	0	3	4	4	0	0	98
- control	4	4	1	4	0	0	4	4	4	0	0	
Taylor Valley Visitor Zone												
Walking track from lookout to glacier terminus	0	1	2.5	0	0	0	0	0	4	4	0	39
- control	3	4	2.5	4	4	2	3.5	4	4	4	3	
Wright Valley												
Loop moraine campsite												
Walking track from tent site to toilet facilities	2	4	2	2	0	0	2	1	4	4	0	82
- control	4	4	2	4	0	0	4	4	4	4	0	
Tent site	4	4	2	4	0	0	4	4	4	4	0	100
- control	4	4	2	4	0	0	4	4	4	4	0	
Vanda Experimental Treading Trial sites												
"Vanda Fan" treading trial walking track	2	4	2.5	1	0	1	2	1	4	0	0	62
- control	3	4	2.5	4	1	1	3	4	4	0	3	
"Vanda Rocky" treading trial walking track	3	4	1.5	3	2	1	2	3	4	0	0	96
- control	4	4	1.5	3	2	1	2	4	4	0	0	
Former Vanda station site												
Central court and mess hut area	3	4	1	4	0	0	4	2	4	0	0	90
- control	3.5	4	2	4	0	0	4	4	4	0	0	
Late 1960s vehicle tracks adj. to Onyx River	4	1	1	4	2	3	1	1	4	0	2	79
- control	4	4	1	4	0	0	2.5	2	4	0	2	
Former Cape Roberts Project storage area												
"Northern Plot"	3	3	1	3	0	0	2	3	4	4	0	88
- control	4	4	1	4	0	0	3	4	4	4	0	
"Southern Plot"	2	4	1	3	0	0	1	2	4	3	0	91
- control	2	4	1	3	0	0	2	4	4	3	0	

*Desert Pavement Recovery Assessment criteria: I = embeddedness of surface clasts, II = impressions of removed clasts, III = degree of clast surface weathering, IV = % overturned clasts, V = salt on underside of clasts, VI = development of salt coatings, VII = armouring per 1 m^2, VIII = colour contrast, IX = evidence of subsidence/melt out, X = accumulation of salt on cut surfaces, XI = patterned ground development. MRI = mean recovery index.

pavement; 50–74%, the site is in an intermediate stage of rehabilitation; and 75–99%, advanced recovery. Sites with an MRI of 100% are indistinguishable from an undisturbed control site.

Results

Visual Site Assessments

Eleven of the twelve study sites (all except the tent site at the Loop moraine), showed some differences between the disturbed and equivalent control sites, with respect to the 16 visual impact assessment criteria measured (Table IV). The five most common visual impacts amongst the 12 study sites were disturbed surface stones (A on Table II), visibly disturbed area (D), cumulative impact (L), evidence of stratigraphic disturbance (M), and textural changes to the surface (N). At no sites were there visible fuel spills (I), or visual biological disturbance (K). Impressions of removed rocks (B), boot imprints (C), and salt deposition (J), were observed at three sites.

Desert Pavement Recovery Assessments

Eleven of the 12 study sites (all except the TVVZ walking track) had MRIs greater than 50% (Table V). Sites showing the greatest visual differences in desert pavement compared to an undisturbed control were the steep walking track in the TVVZ (MRI of 39%) and the 1957/58 bulldozer cut surface at Marble Point (MRI of 51%). The "Vanda Fan" experimental treading site showed intermediate desert pavement recovery with an MRI of 62%, whereas the "Vanda Rocky" site had an MRI of 96%, almost fully recovered (Table V).

Of the 11 desert pavement recovery criteria assessed, the five criteria that showed the greatest differences between disturbed and control sites were the embeddedness of surface clasts (I on Table III), impressions of removed clasts (II), the percentage of overturned clasts (IV), armouring per 1 m^2 (VII), and the colour contrast between the disturbed and control desert pavements (VIII) (Table V). At a limited number of sites accumulations of salt on the underside of clasts (V) were associated with desert pavement recovery, whereas at other sites there were isolated instances where evidence of subsidence (IX), and patterned ground development (XI), were seen to be a function of the stage of the desert pavement recovery. The TVVZ steep walking track was assigned a rating of zero (i.e. highly disturbed) for four of the five most common recovery assessment criteria (embeddedness of surface clasts, percentage of overturned clasts, armouring, and colour contrast) (Table V).

Marble Point vehicle tracks

The present-day Marble Point roadway between the landing beach and refuelling station was clearly evident. Two-to-three month old vehicle tracks had salt efflorescences on them, which were considered to be a result of salts precipitating on the surface following disturbance. Although salt was absent on both 1957/58 era examples described here, surficial salt deposits were evident on some older bulldozer cut surfaces at Marble Point, unmodified since the 1957/58 camp construction. Evidence of permafrost degradation and slumping was visible at a number of bulldozer cut tracks that linked the former camp with the beach staging area where supplies and equipment would have been offloaded. Large boulders lined the margins of the 1957/58 era bulldozed track, and cleat marks were visible in the inner part of the track. Algal growth was equally abundant across the late 1950s vehicle track crossing the periodically saturated ground and undisturbed saturated area, in spite of traces of the track remaining a distinct feature of the contemporary landscape. The present-day vehicle track and the late 1950s vehicle track across the saturated ground were in an advanced stage of desert pavement rehabilitation, with MRIs of 80% for the present-day vehicle track, and 98% for the vehicle track crossing the saturated ground (Table V). The 1957/58 era bulldozed track had an MRI of 51%, or intermediate recovery, reflected in the abundance of non-embedded rocks, impressions of removed rocks, lack of salt on the underside of rocks, and less surface "armouring" at the disturbed site. A strong colour contrast between the vehicle track and the adjacent control was also observed (Table V).

Taylor Valley Visitor Zone

The Taylor Valley Visitor Zone was visited in late December 2009, prior to the arrival of the first tourists for the 2009/10 summer. The walking track between the hilltop lookout and the terminus of the Canada Glacier sloped between 8° and 15° and was clearly visible (Fig. 2b). There was an abundance of disturbed surface stones, a clear surface colour difference, stratigraphic disturbance, and textural change (Table IV). On the steepest part of the slope our footprints broke through the desert pavement and well into the underlying fine-grained material, leaving distinct footprints. The walking track showed no visible footprints on our arrival, suggesting that individual footprints are obliterated over the course of the winter season. However, photograph-replication revealed that the colour contrast between the walking track and the adjacent control persisted between seasons (cumulative), but was less pronounced after the site had a winter to recover, implying that some desert pavement recovery occurs between tourist seasons (Fig. 2a & b). The TVVZ steep walking track had the lowest MRI of all the study sites (39% or incipient desert pavement formation) due to an abundance of impressions of removed clasts, non-embedded clasts, > 75% overturned clasts, and strong colour contrast, compared to the adjacent control site (Table V). The visibly disturbed area was about 300 m^2 (300 m long x 1 m wide), and the cumulative impact of visitors using the walking track on a regular basis was obvious.

Loop moraine campsite

At the Loop moraine campsite, the 2004/05 walking track between the tents and toilet facilities had abundant disturbed surface stones, and distinct surface texture change (Table IV). The ground surface had an indentation effect, the result of sorting of rock material and compaction of the inner part of the track (Fig. 2c & d). The walking track had a moderate colour contrast between the track and the adjacent undisturbed material, which is probably the result of the larger, and darker, dolerite rocks having moved to the outer margins of the track due to foot traffic (Fig. 2c). The visibly disturbed area was about 450 m^2 (300 m long x 1.5 m wide), and the foot track was clearly evident five years after the disturbance.

In contrast, at the Loop moraine campsite, the impacts around the tent site, caused by widespread random trampling (Fig. 2e), were undetectable (Fig. 2f). There were no visibly disturbed stones, no impressions of rocks removed, no boot imprints and no visible surface colour difference. In less than five years the desert pavement at the tent site showed visual recovery to pre-disturbance condition (Fig. 2e & f) and was visually indistinguishable from the surrounding undisturbed material (Table IV). The tent site was the only site with an MRI of 100%, whilst the walking track from the campsite to the toilet facilities was in an advanced stage of desert pavement recovery with an MRI of 82% (Table V).

Vanda experimental treading trial sites

Most impacts at the "Vanda Rocky" experimental treading site were minimal or non-existent (Fig. 3a & b). Only the "softer" mixed till sections, between the slabs of coarser granodiorite bedrock, showed traces of the track (Fig. 3b). There were some unnaturally positioned bedrock slabs lining the middle of the track which had been placed there to hold the measuring tape during the experiment. There were no impressions of removed rocks, no boot imprints, or salt deposits on the surface of the "Vanda Fan" and "Vanda Rocky" treading trial sites (Table IV). In contrast, the experimental walking track on the "Vanda Fan" site, formed on an alluvial fan comprising soft mixed till materials, remained an obvious feature in the landscape 17 years after the treading trial experiment (Fig. 3c & d). The "Vanda Fan" site had an abundance of disturbed surface stones, obvious stratigraphic disturbance, and a moderate surface colour contrast (Table IV). Whilst the desert pavement of the inner part of the track had partially recovered, the larger clasts which were once scattered

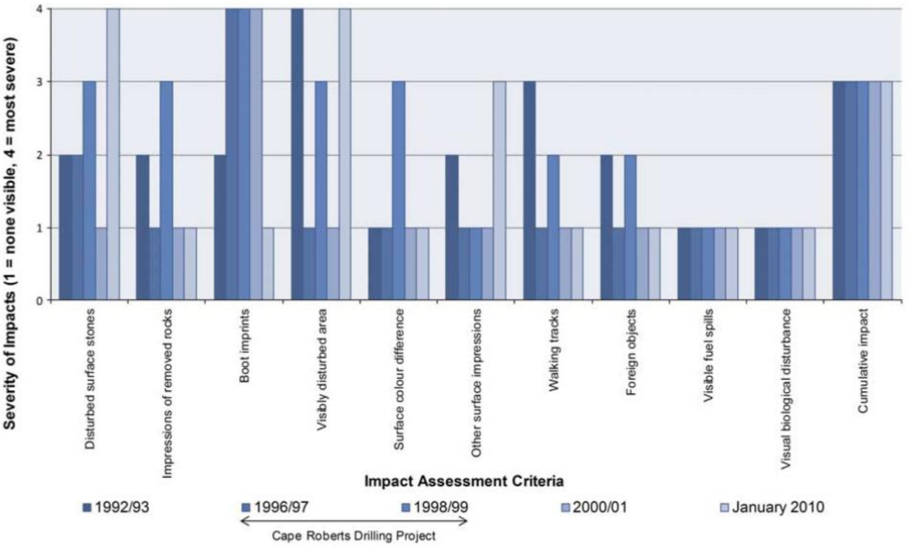

Fig. 4. Visual Site Assessment of Cape Roberts Project (CRP) "Northern Plot" monitoring site, pre-CRP (1992/93, after Campbell & Keys 1993), during CRP (1996/97 and 1998/99, after Waterhouse 2001), after remediation (2000/01, after Cowie 2001), and ten years after remediation (January 2010). Note: January 2010 control scores are not shown, however, each impact assessment criteria scored a one.

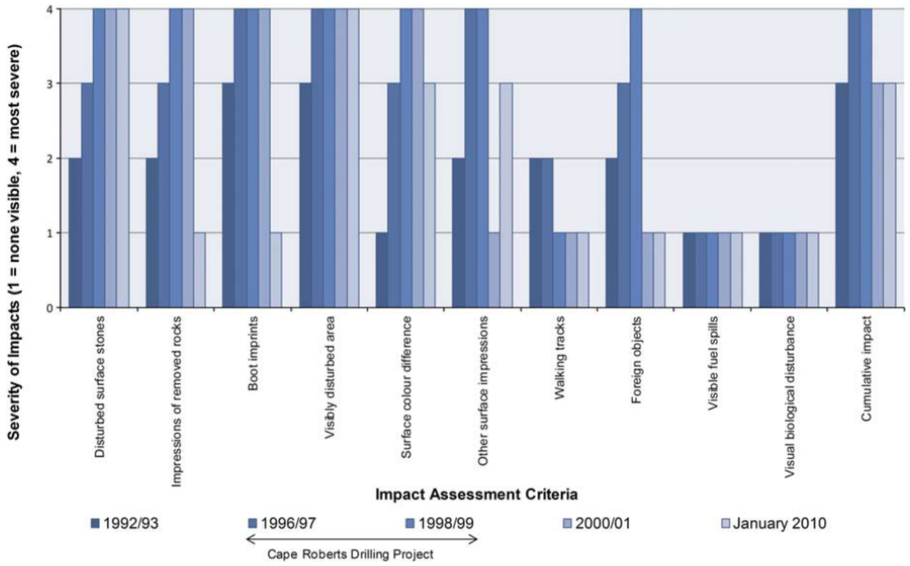

Fig. 5. Visual Site Assessment of Cape Roberts Project (CRP) "Southern Plot" monitoring site, pre-CRP (1992/93, after Campbell & Keys 1993), during CRP (1996/97 and 1998/99, after Waterhouse 2001), after remediation (2000/01, after Cowie 2001), and ten years after remediation (January 2010). Note: January 2010 control scores are not shown, however, each impact assessment criteria scored a one.

across the entire ground surface were concentrated along the margins of the walking track and the associated indentations persisted in the landscape (Fig. 3d). The "Vanda Fan" site was in an intermediate stage of visual desert pavement recovery (MRI of 62%), whilst the "Vanda Rocky" site, which had higher cobble to sand fraction and greater resistance to the original trampling impacts, was in an advanced stage of desert pavement recovery (MRI of 96%) (Table V). The visibly disturbed area of the "Vanda Fan" site was 20 m^2, with 6 m^2 at the "Vanda Rocky" site.

Former Vanda station site

Thorough cleanup of the former Vanda station site made it difficult to locate the site of the former central court and mess hut (Fig. 3e & f), even though a member of our party had stayed at the site on a number of occasions. There were no visible footprints or evidence of vehicle or walking tracks within the central court area. All building materials had been removed and displaced rocks had been redistributed. There were no impressions of removed rocks, no boot imprints, no visible salt deposition, or visual evidence of biological disturbance, although there were some nails and other foreign objects visible in the central area (Table IV). It is probable that the foreign objects observed at the surface at the time of investigation were exposed by the same winnowing processes that rehabilitate the desert pavement. Clasts were less embedded and there was a greater proportion of smaller rock fragments at the former station site compared with the control site. The site of the former Vanda station had a MRI of 90% (Table V), indicating the desert pavement is in an advanced stage of rehabilitation.

Late 1960s Wright Valley vehicle tracks

Tracks from 1960s and 1970s tracked and two-wheeled vehicles were clearly visible in some areas on the valley floor of the Onyx River floodplain, with abundant disturbed surface stones, and a distinct textural change between the impacted area and its paired control (Table IV). Coarser material had been effectively "sorted" to the margins of the track by wheeled vehicles, with finer grained material concentrated in the inner part of the track. The 1960s and 1970s Wright Valley vehicle tracks had an MRI of 79% (advanced stage of rehabilitation) (Table V).

Cape Roberts drilling project ice-free storage area

Visual Site Assessment results for the Campbell & Keys (1993) "Northern Plot" and "Southern Plot" were combined with mid-project VSA monitoring undertaken in the summers of 1996/97, 1998/99, and post-remediation observations, 2000/01, to show recovery over time (Figs 4 & 5).

At the "Northern Plot" VSAs showed the site was overall in better condition in 2010 than in the pre-CRP baseline assessment in 1992/93 (Fig. 4). This probably reflects effective site cleanup and restoration in 1999/2000 and 2000/01. The Cape Roberts sites had been disturbed on numerous occasions prior to the commencement of the Cape Roberts Drilling Project. In 2010 there was an improvement in four impact assessment criteria, including, a decrease in impressions of removed rocks, boot imprints, presence of foreign objects, and evidence of formed walking tracks. Four criteria remained the same, and the evidence of cumulative impact remained consistent at $> 100\,\mathrm{m}^2$. Mid-project 1996/97 and 1998/99 VSAs showed an increase in impressions of removed rocks, evidence of walking tracks, and foreign objects over the duration of the drilling project. The abundance of disturbed surface stones, and other surface impressions, shows only partial recovery to baseline 1992/93 condition (Fig. 4), with rehabilitation probably an ongoing process. The "Northern Plot" had an MRI of 88% (Table V).

Visual impacts were consistently greater at the "Southern Plot" as it was the site where most vehicle and walking tracks were concentrated, and the location of the fuel rack and huts. The "Southern Plot" showed deterioration in some of the criteria re-assessed in 2010. There was a decline in four impact assessment criteria, including an increase in abundance of disturbed surface stones, and visibly disturbed areas, and evidence of other surface impressions, such as Hagglund vehicles tracks and helicopter skid marks (Fig. 5). Three impact assessment criteria remained the same, such as the extent of cumulative impact which remained consistent at $> 100\,\mathrm{m}^2$, and four showed an improvement beyond the 1992/93 baseline assessment (impressions of removed rocks, boot imprints, evidence of walking tracks, and foreign objects). The surface colour contrast between the impacted site and the surrounding undisturbed material showed the greatest increase in the first few years of the project. Both the visibly disturbed area and cumulative impacts increased rapidly at the beginning of the CRP (see 1996/97 and 1998/99 VSAs, Fig. 5), and remained "severe" over the duration of the project. The 2010 assessment showed no obvious evidence of post-CRP environmental monitoring soil sampling pits, nor visible evidence of the removal of contaminated sand and gravel that was taken during remediation (Waterhouse 2001).

Discussion

Random versus confined trafficking

In general, walking single file (compared with widespread trampling) reduces spatial and visual impact, but increases local impact (Campbell *et al*. 1998, Ayres *et al*. 2008). On young active surfaces, such as the Cape Roberts ice-free storage site, which rejuvenate quickly, the pattern of disturbance in less important. However, on repetitive use, once a confined track is formed and larger clasts concentrated to the margins of the track, giving an "indentation" appearance, visual impacts are more permanent (as we described at both the "Vanda Fan" treading trial site, and the Loop moraine walking track).

The Loop moraine campsite challenges the longstanding assumption that all disturbed desert pavements in Antarctica take many years to rehabilitate (Campbell *et al*. 1993, 1998). The Loop moraine campsite also illustrated the differences in recovery rates between confined walking tracks and randomly trampled sites. Evidence of the heavily trampled tent site was undetectable (MRI of 100%), however, walking tracks formed to-and-from the campsite were visible five years later (MRI of 82%). In hindsight, personnel occupying this camp may have chosen to either rake out the margins of formed tracks, or walk to their experimental sites and toilet in a random and widespread fashion, avoiding the formation of walking tracks. In the case of non-repeat events such as the Loop moraine campsite, we consider the formation of walking tracks should be avoided as random, widespread trampling had less lasting visual impact on the environment.

Tourist operators visiting the Taylor Valley Visitor Zone walk on established walking tracks. The walking tracks follow the margins of patterned ground polygons (known as patterned ground cracks), which are the most favourable place to concentrate visitor flow as material in patterned ground cracks is more likely to be naturally moved through freeze-thaw processes than material in polygon centres. Campbell *et al*. (1998) showed tracks form within the first 20 or so passes in unconsolidated materials common in the Ross Sea region, and that cumulative impacts of increasing traffic are minimal. Thus, where repeated use is planned, we consider it preferable to keep visitors to a single, confined track especially where the site has steeply sloped surfaces, with material at the angle of repose, and slopes are susceptible to down-slope movement of surficial materials when disturbed by walking.

Remediation

Site remediation (raking and smoothing of disturbed surfaces to free-up compacted soil, and redistribute out of place stones) was effective and led to accelerated visual recovery of the desert pavement on the sites studied. Ten years after remediation both the Cape Roberts study sites were nearly visually indistinguishable from equivalent control sites ("Northern Plot" MRI of 88%, "Southern Plot" MRI of 91%). We suggest the redistribution of larger stones and raking the margins of walking tracks that result from field camps (such as the Loop moraine walking track from the tent site to the toilet) would enhance the visual aesthetics by eliminating unnatural surface irregularities, and facilitate the visible recovery of previously disturbed desert pavement. Larger stones, such as those used to pin down tents at the Loop moraine campsite, must however, 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. The redistribution of disturbed rocks from vehicle and walking track margins was an effective means of remediation at the former Vanda station site (MRI of 90%), but needs to be undertaken with an understanding of the rock material's natural position in the environment.

Our observations are consistent with Campbell *et al*. (1998) and Kiernan & McConnell (2001), who concluded that the natural processes of visible recovery can be given a head start by sensible rehabilitation. While the natural stratigraphy of a site cannot be restored, it is possible to mimic the natural geomorphology, dramatically reduce visual impacts, and reduce longer term changes to geomorphic processes that may cause ongoing environmental harm (Kiernan & McConnell 2001). Although raking will enhance the visual aesthetics of a site there is a question of whether by raking we are further damaging the remaining microbial communities living in the surface material. The impacts of remediative 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 Protocol on Environmental Protection to the Antarctic Treaty to protect soil biota. Value judgments must be considered, particularly whether potential adverse impacts to biota outweigh the longer-term positive effects of site restoration. Where moderate to high-intensity disturbances have dramatically 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 (also) adversely affected.

Factors influencing desert pavement recovery

The rate and extent of desert pavement recovery at the sites investigated could be attributed to a combination of the intensity of the initial disturbance; the environmental conditions for the site, including, parent material and surface characteristics (age and weathering stage), availability of water and wind regime; and also the restoration and remediation measures undertaken at the site.

Intensity of initial disturbance

Low intensity trampling impacts the top 0–5 cm of a desert pavement and underlying soil, whereas bulldozer tracks where the active layer was removed and cleat marks cut into the new surface affects the rehabilitative capability of the landscape. Where the intensity of disturbance was low, such as widespread trampling around the tent site at the Loop moraine, factors such as wind and site remediation can have the ability to restore the surface to near original visual condition. The 1957/58 bulldozed vehicle track at Marble Point, had formed side mounds with material pushed to the side of the track. With day-to-day use the track would have undergone surface compaction, thus increasing soil bulk density (Campbell *et al*. 1998). Repetitive disturbance, such as the disturbance associated with repetitive foot traffic at the Taylor Valley Visitor Zone, although of low intensity, has a cumulative effect. Cumulative disturbances at the visitor zone did not allow full recovery of the desert pavement between summer seasons (MRI of 39%), although some recovery in terms of track colour contrast occurred over one winter season. Even once people have stopped using the track, such as the 1960s vehicle tracks in the Wright Valley (MRI of 79%), or Marble Point 1957/58 vehicle tracks (MRI of 51%), the visual impacts are likely to be long-lasting without the redistribution of displaced materials. At both Marble Point and in Wright Valley, there would have been a range of lower intensity impacts in the 1950s through to the 1970s that are no longer visible and hence not recorded here. In many cases only the highest level of intensity, bulldozed tracks and similar impacts, now remain evident for study.

Parent material and surface characteristics

Why are disturbances of equal intensity preserved at some sites and not at others? The effects of the Vanda treading trial and persistence of the resultant walking track were obvious at the "Vanda Fan" site (MRI of 62%), 17 years after the event. The colour difference associated with disturbance had largely disappeared (probably a result of wind removing the lighter coloured material exposed at the surface), however displacement of coarser particles to the margins of the track and compaction of the soft fine-grained parent material remained. Upon revisiting the "Vanda Rocky" site (MRI of 96%), traces of the track were only visible in the fine-grained sections of the track. It was obvious comparing the two parent materials that the lasting visible impact can be lessened by, wherever possible, following routes across bouldery surfaces or bedrock. Late 1960s vehicle tracks (MRI of 79%) were not continuously preserved along the Wright Valley floor, but only in softer material that had not been reworked by Onyx River flood events. In finer grained materials the initial disturbance can seem rapid and damage high, such as the Loop moraine tent site (MRI of 100%), however these materials can undergo rapid rehabilitation under favourable conditions (high moisture and/or wind regime). At the former Vanda station site (MRI of 90%), the hardy nature of the slabby granodiorite surface material meant when combined with the site remediation there was little evidence of the once widespread trampling and vehicle tracks.

Wind and moisture regime

Wind is probably the primary driver of surface recovery in most environments in the Ross Sea region (Campbell *et al*. 1998) and we assume wind action in valley floors and low ridge sites winnows away the finer-grained material from the disturbed site until sufficient coarser-grained material is exposed and a new protective desert pavement is formed. At the Loop moraine tent site (MRI of 100%) wind action probably resulted in natural infilling of footprints and return to original surface colour. Wind action, however, was not sufficient to redistribute larger clasts that lined the margins of the Loop moraine walking-tracks or diffuse the "indentation" visible at the Loop moraine tracks (MRI of 82%) and the "Vanda Fan" treading trial site (MRI of 62%). The wind regime in the valley floors is likely to have contributed to the partial obliteration of late 1960s and 1970s vehicle tracks (MRI of 79%) along the Onyx River floodplain (along with intermittent floods from the Onyx River). In comparison, some higher and older floodplain terraces vehicle tracks remain in the landscape after over 40 years. In other areas, such as the relatively young active beach gravel sites at Cape Roberts, the soil materials are unweathered gravels which are consistent down the soil profile. As a consequence the desert pavement lacks the distinct armoured appearance and wind and water (snow melt) action quickly dissipates surface/subsurface colour contrasts.

The intermittent supply of moisture at the Cape Roberts sites (MRIs between 88% and 91%) and Marble Point (moistened by spring snow thaw and occasional summer snowfalls) may have assisted wind action in desert pavement recovery. In the drier, central mountain climatic zone, such as the "Vanda Fan" treading trial site, Loop moraine walking track, 1960s and 1970s vehicle tracks adjacent to the Onyx River, and walking tracks at the TVVZ, moisture available for soil surface processes is much less (*c.* 0.2% moisture in topsoil compared with 1–2% in coastal areas), and recovery was not as advanced as equivalent intensity disturbances in the moist coastal climatic zones of Cape Roberts and Marble Point.

Applications of this research

Our paper suggests that long-term environmental impacts in Antarctica can be reduced through careful site remediation and site selection, but perhaps more importantly by taking appropriate action in the project design, planning, and operational stages of the activity to minimize impacts so that remediative measures are minimal, if required at all.

Many of the soil impacts caused by low intensity soil disturbance activities like camping can be avoided, remedied, or at least mitigated if field parties are aware of the longevity of impacts and recovery capabilities of the areas they are working in. Avoiding forming walking tracks will lessen the lasting visible impact to the environment. The ability to recognize young active surfaces, such as active beach deposits, and sand dunes, where material is readily reorganized by wind or water, is important, as in these settings the initial damage of foot traffic may seem high, but the ability of surfaces to recover is greater than some older less resilient landforms and parent materials.

Further work is needed to investigate the rehabilitative capability of older sites with strongly developed desert pavements. Investigation into sites which have completely recovered, such as the sections of Wright Valley floor where the 1960s and 70 s vehicle tracks have not been preserved, and have fully recovered, could also be undertaken. By revisiting recovering sites and verifying the predicted environmental impacts, we are able to contribute to understanding the best approaches to minimize visual impacts on the Antarctic landscape.

Conclusions

Twelve sites of past human occupation and activity were investigated to assess the visual impacts of, and recovery from, foot and vehicle traffic. Study sites comprised a variety of landforms, parent materials, and climates, with the time since last disturbance ranging from three months to about 50 years prior to assessment. The extent of soil surface recovery from the physical impacts of foot and vehicle traffic in the Ross Sea region was higher than anticipated.

Eleven of the 12 study sites (all except the TVVZ walking track) had a MRI greater than 50%. Sites showing the greatest visual differences in desert pavement compared to an undisturbed control were the steep walking track in the TVVZ (MRI of 39%) and the 1957/58 bulldozer cut surface at Marble Point (MRI of 51%). Sites with the highest MRIs were the former tent site at the Loop moraine (MRI of 100%, indistinguishable from the control site) and the vehicle track crossing periodically saturated ground at Marble Point (MRI of 98%), which was in an advanced stage of desert pavement recovery.

Formed walking tracks remained visible in the landscape due to the persistence of larger rocks and loose material concentrated at the outer margins of the walking track. However, randomly dispersed footprints on surfaces were often recovered and undetectable within five years. Widespread, dispersed trampling around one-off campsites is recommended to minimize overall visible impact in the medium term. Walking in patterned ground cracks minimized impacts on stable desert pavement surfaces and should be undertaken where practicable. At steep sloped sites, and sites where repeated visits occur, such as the TVVZ, the use of a single confined walking track is recommended.

Concentrating activity on more resilient parent materials, such as bouldery or bedrock surfaces, as seen at the former Vanda station site (MRI of 90%), and the "Vanda Rocky" treading trial (MRI of 96%), lessens lasting visible impacts to the environment. Where softer sediment cannot be avoided, site remediation was effective at reducing visible disturbance and aiding surface pavement recovery.

Site remediation activities, including replacing larger moved stones back in their original positions, ensuring that surface stones are placed with the weathered side up, and raking of gravel sand-sized displaced materials, can all be effective at enhancing the rate and degree of surface recovery. Remedial activities such as raking should only be carried out on areas that have been disturbed already, where there are gravelly sand materials which lack a strongly developed desert pavement. Consideration must be given to ensuring that the overall environmental effects of the remediative activities do not cause more impact than they cure, particularly with respect to impacts on microbial communities. Further investigation into older, highly weathered landscapes (where there is a greater weathering contrast between surface and subsurface materials), a greater number of previously disturbed sites (on varying landforms, parent materials, climatic regimes, and impact intensities), and recovered sites are needed to further advance our understanding of differences in surface rehabilitative capabilities.

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References

ATCM (Antarctic Treaty Consultative Meeting). 2011. Management Plan for Antarctic Specially Managed Area No. 2, McMurdo Dry Valleys, Southern Victoria Land. Measure 10, *Final Report of the Thirty-fourth Antarctic Treaty Consultative Meeting*. Buenos Aires, Argentina, 348 pp.

Ayres, E., Nkem, J.N., Wall, D.H., Adams, B.J., Barnett, J.E., Broos, E.J., Parsons, A.N., Powers, L.E., Simmons, B.L. & Virginia, R.A. 2008. Effects on human trampling on populations of soil fauna in the McMurdo Dry Valleys, Antarctica. *Conservation Biology*, **22**, 1544–1551.

Balks, M.R., Campbell, D.I., Campbell, I.B. & Claridge, G.G.C. 1995. Interim results of 1993/94 soil climate, active layer, and permafrost investigations at Scott Base, Vanda and Beacon Heights, Antarctica. *University of Waikato, Antarctic Research Unit Special Report*, No. 1, 64 pp.

Bockheim, J.G. 1997. Properties and classification of cold desert soils from Antarctica. *Soil Science Society of America Journal*, **61**, 224–231.

Bockheim, J.G. 2010. Evolution of desert pavements and the vesicular layer in soils of the Transantarctic Mountains. *Geomorphology*, **118**, 433–443.

Broadbent, N.D. 1994. An archaeological survey of Marble Point, Antarctica. *Antarctic Journal*, **19**, 3–6.

Broadbent, N.D. 2009. From ballooning in the Arctic to 10,000-foot runways in Antarctica: lessons from historic archaeology. *In* Krupnik, I., Lang, M.A. & Miller, S.E., *eds. Smithsonian at the poles: contributions to International Polar Year Science*. Washington, DC: Smithsonian Institution, 49–60.

Campbell, I.B. & Claridge, G.G.C. 1975. Morphology and age relationships of Antarctic soils. *Royal Society of New Zealand Bulletin*, **13**, 83–88.

Campbell, I.B. & Claridge, G.G.C. 1987. *Antarctica: soils, weathering processes and environment*. Amsterdam: Elsevier, 368 pp.

Campbell, I.B. & Keys, J.R. 1993. *Cape Roberts comprehensive environmental evaluation - a survey of the soils and vegetation*. Christchurch: Antarctica New Zealand, 9 pp.

Campbell, I.B., Balks, M.R. & Claridge, G.G.C. 1993. A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record*, **29**, 321–328.

Campbell, I.B., Claridge, G.G.C. & Balks, M.R. 1994. The effects of human activities on moisture content of soils and underlying permafrost from the McMurdo Sound region, Antarctica. *Antarctic Science*, **6**, 307–314.

Campbell, I.B., Claridge, G.G.C. & Balks, M.R. 1998. Short- and long-term impacts of human disturbances on snow-free surfaces in Antarctica. *Polar Record*, **3**, 15–24.

Cooke, R.U. 1970. Stone pavements in deserts. *Annals of the Association of American Geographers*, **60**, 560–577.

Cowie, J. 2001. *Cape Roberts project K001: clean up phase*. Christchurch: Antarctica New Zealand, 8 pp.

Doran, P.T., Priscu, J.C., Lyons, W.B., Walsh, J.E., Fountain, A.G., McKnight, D.M., Moorhead, D.L., Virginia, R.A., Wall, D.H., Clow, G.D., Fritsen, C.H., McKay, C.P. & Parsons, A.N. 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature*, **415**, 517–520.

Harris, C.M. 1998. Science and environmental management in the McMurdo Dry Valleys, Antarctica. *Antarctic Research Series*, **72**, 337–350.

Hayward, J., MacFarlane, M.J., Keys, J.R. & Campbell, I.B. 1994. *Decommissioning Vanda station, Wright Valley, Antarctica: initial environmental evaluation*. Christchurch: Antarctica New Zealand, 20 pp.

Kiernan, K. & McConnell, A. 2001. Land surface rehabilitation research in Antarctica. *Proceedings of the Linnean Society of New South Wales*, **123**, 101–118.

McFadden, L.D., Wells, S.G. & Jercinovich, M.J. 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, 219 pp. [Unpublished.]

O'Neill, T.A., Balks, M.R. & López-Martínez, J. 2012. A method for assessing the physical recovery of Antarctic desert pavements following human-induced disturbances. *Journal of Environmental Management*, **112**, 415–428.

Pointing, S.B., Chan, Y., Lacap, D.C., Lau, M.C.Y., Jurgens, J.A. & Farrell, R.L. 2009. Highly specialized microbial diversity in hyper-arid polar desert. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 19 964–19 969.

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 Record*, **40**, 51–67.

Soil Survey Staff. 2002. *Keys to soil taxonomy*, 9th ed. Washington, DC: US Department of Agriculture, Natural Resource Conservation Service, 332 pp.

Tin, T., Fleming, Z.L., Hughes, K.A., Ainley, D.G., Convey, P., Moreno, C.A., Pfeiffer, S., Scott, J. & Snape, I. 2009. Impacts of local human activities on the Antarctic environment. *Antarctic Science*, **21**, 3–33.

Waterhouse, E. 2001. *Cape Roberts Project final environmental report 1995–2001*. Christchurch: Antarctica New Zealand, 66 pp.

Webster, J., Webster, K., Nelson, P. & Waterhouse, E. 2003. The behaviour of residual contaminants at a former station site, Antarctica. *Environmental Pollution*, **123**, 163–179.

6 SHORT-TERM EFFECTS OF HUMAN DISTURBANCE ON SOIL BACTERIAL COMMUNITY STRUCTURE AT AN EXPERIMENTAL SITE, SCOTT BASE, ROSS SEA REGION OF ANTARCTICA

In press as:

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The short-term effects of surface soil disturbance on soil bacterial community structure at an experimental site near Scott Base, Antarctica

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Abstract

Humans are visiting Antarctica in increasing numbers and the ecological effect of rapid soil habitat alteration due to human-induced physical disturbance is not well understood. An experimental soil disturbance trial was set up near Scott Base on Ross Island, to investigate the immediate and short-term changes to bacterial community structure following surface soil disturbance. Three blocks, each comprising an undisturbed control, and an area disturbed by removing the top 2 cm of soil, were sampled over a time series (0, 7, 14, 21, and 35 days), to investigate changes to bacterial community structure using DNA profiling by terminal restriction fragment length polymorphism (TRFLP). The simulated disturbance did not cause any major shifts in the structure of the bacterial communities over the 35 day sampling period. Ordination showed that the bacterial community composition correlated strongly with soil EC ($R^2 = 0.55$) and soil pH ($R^2 = 0.67$), rather than the removal of the top 2 cm of surface material. Although the replicate blocks were visually indistinguishable from one another, high local spatial variability of soil chemical properties was found at the study site and different populations of bacterial communities occurred within 2 m of one another, within the same landscape unit. Given the current knowledge of the drivers of bacterial community structure, i.e. soil EC, soil pH, and soil moisture content, a follow-up investigation incorporating DNA and RNA-based analyses over a time frame of 2-3 years would lead to a greater understanding of the effects of soil disturbance on bacterial communities.

Introduction

Approximately 25,000 km^2, or half of Antarctica's ice-free, and soil forming, areas are found in the Ross Sea region of Antarctica (Fox and Cooper 1994; British Antarctic Survey 2005). Ross Sea region ice-free areas are found discontinuously distributed around the coastal margins and in the

McMurdo Dry Valleys, the largest continuous expanse of ice-free ground. Soil ecosystems in the Ross Sea region terrestrial environment are characterised by low and fluctuating temperatures, high aridity, low precipitation, low moisture availability, desiccating winds, high exposure to UV radiation, and low levels of organic matter (Campbell and Claridge 1987; Wynn-Williams 1990). Despite the hostile environment, Antarctic mineral soils can harbour bacterial numbers of up to 10^9 cells g^{-1} dry soil (Bölter 1995; Aislabie et al. 2006, 2008; Xiao et al. 2007; Cannone et al. 2008; Ganzert et al. 2011).

Ross Sea region soils comprise a surface desert pavement and seasonally thawed active layer overlying permafrost. Mature, undisturbed Ross Sea region desert pavements are typically characterised by a closely packed layer of gravel, cobble, and boulder-sized rock material, which depending on its age, can be ventifacted, and coated with desert varnish (Campbell and Claridge 1987; Bockheim 2010). Desert pavement clasts are embedded into a finer matrix, and their undersides are often coated in salts. The soils beneath are alkaline, generally lack structural development and coherence, and are coarsely textured with very low organic matter contents (Campbell and Claridge 1987; Balks et al. 2002; Aislabie et al. 2004). Soils of the coastal regions, such as Scott Base, contain ice-cemented permafrost (Balks et al. 2002; Bockheim and McLeod 2006), and predominantly NaCl and $NaSO_4$ salts consistent with direct marine input (Campbell and Claridge 1987; Campbell et al. 1998). Mean annual soil temperatures in the Ross Sea region range from –15 ˚C 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 means 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).

In polar climates a 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), 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. 2006b; Sparrow et al. 2011). Soil pH is thought to influence nutrient availability, soil carbon, and soil cation solubility (Lauber et al. 2009), as well as influence bacteria competitiveness, and their ability to grow and survive outside optimum soil pH (Lauber et al. 2009). Microbes are sensitive to the concentration of soluble salts in soils and past studies have shown that high 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, 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 as salt efflorescences (Campbell et al. 1993, 1998; Balks et al. 1995). Microbes have semi-permeable membranes capable of rapidly equilibrating with surrounding water. Increased available moisture over short periods may have had a positive impact on microbial communities as previous studies have shown increases in soil CO2 efflux (Treonis et al. 1999; Moorhead et al. 2003; Ayres et al. 2010). Conversely, frequent wetting and drying events and fluctuations in soil temperature can also be stressful to microbes, as they must expend energy to regulate osmotic pressure to their microenvironment (Nkem et al. 2006; Ball et al. 2012) and bacterial metabolism may be affected. As the soil dries out again the matric potential of the soil decreases, salts concentrate, and water films around aggregates become thinner and disconnected. Water is held more tightly to the aggregate surfaces and restricts nutrient diffusion (Chowdhury et al. 2011), bacterial activity, and growth. To achieve osmotic regulation bacteria synthesize amino acids and other organic compounds, as solutes (Csonka 1989). Accumulating and disposing of solutes can be energetically expensive for organisms, and it is those organisms that have adapted to survive episodic stresses that are likely to dominate soil environments (Schimel et al. 2007).

Under Annex I and II of the Protocol on Environmental Protection to the Antarctic Treaty all activities undertaken in Antarctica must be planned and coordinated to limit adverse impacts on the environment, and associated ecosystems (Annex II, Article I (d) and I (h)). Over recent decades there has been a rapid increase in the number of people visiting Antarctica, with annual visitor numbers for the 2010/2011 season exceeding 34,000 people (IAATO 2011). The majority of visits concentrate around the limited ice-free areas where the national programme stations, historic huts, and wildlife hotspots are located. With increasing human presence comes increased human-induced disturbance of the ice-free areas and potentially the organisms and communities residing within the soil. Desert pavement disturbance can arise from a number of sources, and at different intensities, ranging from human trampling, to vehicles that cause overturning of large stones. In the Ross Sea region overturned stones are visible as undersides are often less weathered, lighter coloured, and coated in salts. Other disturbances range from indentation and compression of sub-surface soils, bulldozer blade scrapes, and removal of tens of centimetres of material for road fill, to base construction and complete re-contouring of the immediate landscape. The physical effects of human disturbance on soil properties were first studied in the Ross Sea region by Campbell et al. (1993, 1994, 1998), who reported increased soil compaction with increasing trampling intensity, as well as increases in soil albedo (due to the exposure of lighter subsurface material following surface disturbance). An experimental trial undertaken by Balks et al. (1995) replicated moderate-to-high intensity physical disturbance by physically removing the soil active layer at two sites in the Ross Sea region (Scott Base and Marble Point). Balks et al. (1995) observed the precipitation of salt efflorescence's on the surface of the recently disturbed sites as the exposed underlying material equilibrated with the environment. Changes to soil surface albedo, soil moisture, and the soil surface (slumping) were also noted as a consequence of removal of the soil active layer (Balks et al. 1995).

Previous human disturbance research in Antarctica has focussed little attention on the impacts caused to biotic communities and biogeochemical cycling. Biota-focussed studies have been limited to two trampling studies investigating the long-term impacts to soil fauna. The first investigated changes to nematode populations in walking tracks within the U.S. McMurdo Dry Valleys Long Term Ecological Research project site (Ayres et al. 2008); and the second focussed on changes to soil collembola populations at different trampling intensities on Livingston Island in the South Shetland Islands, Antarctic Peninsula (Tejedo et al. 2009). 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 to 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. Tejedo et al. (2009) showed the dominant species of collembola in Livingston Island soils decreased with increasing trampling intensity and increasing soil compaction. Overall, little is known about the response of Antarctic soil microbial communities to human disturbance or what timescale responses can be detected.

The objective of this study was to investigate the immediate and short-term changes to bacterial community structure in response to simulated soil surface disturbance. We hypothesized that soil environmental factors, such as soil salinity, pH, and soil moisture, would be altered by the simulated disturbance, and would result in a shift and detectable difference in the bacterial community structure at disturbed and undisturbed sites. We also attempted to determine which environmental variables had the greatest influence on the bacterial community structure at the site.

Materials and methods

Site description and sample collection

The trial was undertaken near Scott Base, on Ross Island, in the Ross Sea region of Antarctica (Fig. 1, Table 1). The trial site was on a hillside approximately 200 m NW of Scott Base in an area where the desert pavement was largely undisturbed, though some surface trampling from people walking across the area had inevitably occurred since establishment of Scott Base in 1957. Scott Base experiences moderate snowfall (mean snowfall 90 days a year) (Claridge et al. 1999), with each snowfall generally amounting to a few millimetres, but occasional falls of a few centimetres can occur during a 24-hour period (Bromley 1994). When the experiment was established in

December 2009 the study site was free from snow but during subsequent samplings in January 2010 the site was intermittently covered by several centimetres of snow which was cleared before sampling on Days 14 and 21. It can therefore be assumed that the area is occasionally flushed by melting snow or downslope water flow. Soils of the study site were Typic Haplorthels (Soil Survey Staff 2010).

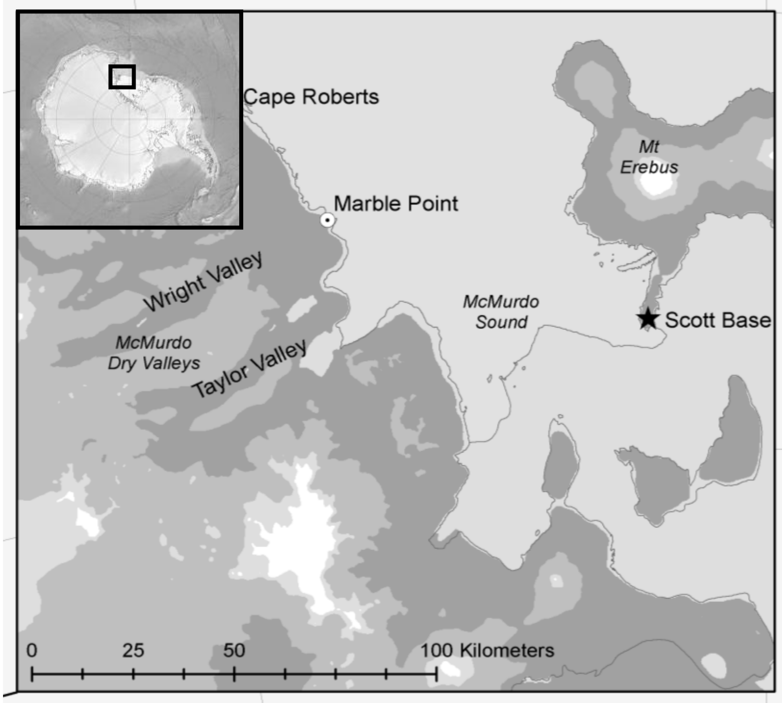

Fig. 1 Map showing the location of the Scott Base study site (denoted by a star) located on Hut Point Peninsula, Ross Island, in the Ross Sea region of Antarctica

Table 1 Description, geographical, geological, and pedological characteristics of the study site

Site description and landform	Flat shoulder area of a hillslope comprising small terracettes. Slope of 0-2°, aspect 135° and elevation of 41 m.a.s.l. The site is approximately 300 m NW of Scott Base, and 50 m NW of the Scott Base climate station[1]
GPS coordinates	77° 50' 53.3" S, 166° 45' 37.5" E
Parent material	Weakly weathered scoriceous basalt boulders through gravel, with some granite and sandstone gravel and sand-sized clasts
Soil classification[2]	Typic Haplorthel
Brief soil description	2 cm of desert pavement scoriceous gravels and cobbles, over loose stony gravelly sands. Ice-cemented permafrost ~32 cm[3]. Depth to ice-cement at time of sampling, 30 cm. Weathering stage 1[4]. Salt stage 1[5]
Soil climatic zone[6]	Oceanic subxerous
Ross Sea Region climatic zone[7]	Moist coastal mountain; mean annual temperature -19°C, annual precipitation 188 mm

[1]Scott Base climate station, installed Jan. 1999, provides continuous climate and soil climate records: http://soils.usda.gov/survey/scan/antarctica/ScottBase/. [2]Soil Classification after Soil Survey Staff (2010); [3]Depth to permafrost from Adlam et al. (2010), calculated over eight successive summers from 1999/2000 to 2006/2007 [4]Soil weathering stage after Campbell and Claridge (1975); [5]Soil salt stage after Bockheim (1997); [6]Soil climatic zones after Campbell and Claridge (1969); [7]Ross Sea Region climatic zones after Campbell and Claridge (1987)

Soil sampling and experimental design

Three replicate blocks (Block 1, 2, and 3) were marked out using metal pegs (Fig. 2). Each block was 150 cm x 75 cm and randomly assigned a control and a disturbed quadrant (75 cm x 75 cm). Using a sterilised trowel the top 2 cm of one half of each block was removed (to form the disturbed quadrant). Replicate blocks were approximately 2 m apart and occurred on the same landscape unit on a flat shoulder area (0-2 degrees slope) within the overall hillslope.

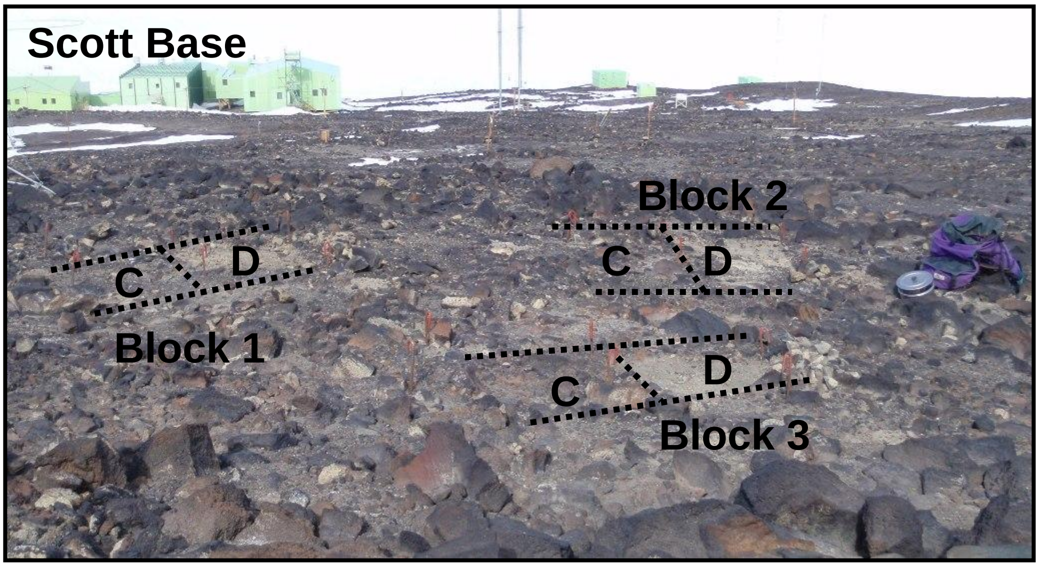

Fig. 2 Scott Base study site, showing blocks 1 to 3. Control quadrants are denoted by the letter "C" and disturbed quadrants by the letter "D" (photo taken on Day 0 after disturbance and sampling)

Soil samples were collected aseptically at four depth intervals. Depth A = desert pavement (DP) to 2 cm, Depth B =immediately below, 2 to 5 cm depth, and Depth C = 2 to 5 cm, new surface, and Depth D = 5 to 8 cm immediately below the new surface (Fig. 3), on Day 0, 7, 14, 21, and 35. The disturbed sites were sampled twice on Day 0, immediately before disturbance (Day 0_{pre}), and again, immediately after disturbance (Day 0_{post}).

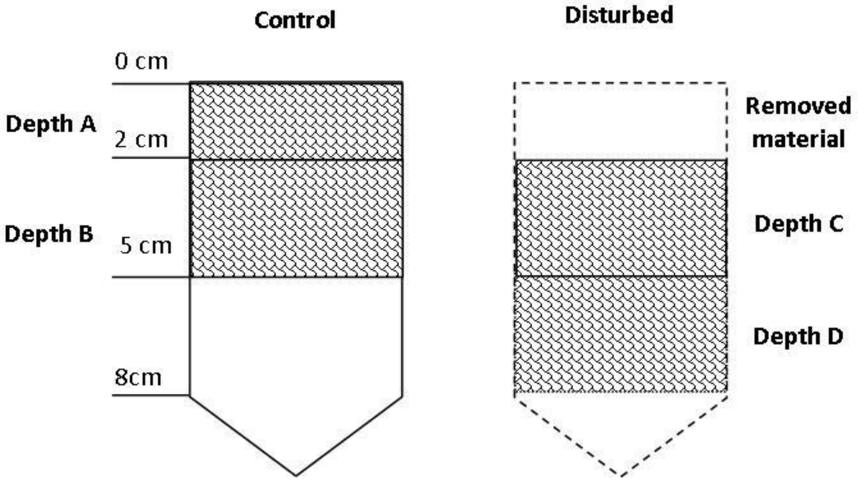

Fig. 3 Schematic diagram of sampling depths in control and disturbed quadrants of each block

In this experiment we considered Depth B of the control was equivalent material (in stratigraphic succession) to Depth C of the disturbed quadrant. Depth C had been exposed at the surface by the removal of the top 2 cm of material.

A composite sample of approximately 200 g was collected with a sterile spatula, from the disturbed and control quadrants of Blocks 1, 2, and 3; at each depth interval. Homogenized samples were sieved to 2 mm and double bagged into a Whirlpak® bag (Fisher Scientific Ltd., Ontario, Canada), frozen at -20 ˚C, and transported back to New Zealand for processing.

Soil bacterial community structure analysis

DNA was extracted in duplicate from 1 g of soil (wet weight) through mechanical cell disruption using zirconium beads, phosphate buffer (100mM NaH_2PO_4, pH 8.0), SDS (sodium dodecyl sulphate) lysis buffer (100mM NaCl, 10% SDS, 500 mM Tris, pH 8.0) and chloroform after Foght et al. (2004).

Polymerase Chain Reaction (PCR) was undertaken following Singh et al. (2006). Samples were amplified by PCR using an Eppendorf Master Cycler Gradient using bacteria primers 63f VIC and 1087r (Applied Biosystems). Samples were run on the MTRFLP PCR step-cycle programme, as follows: initial activation step of 95 ˚C for 15 minutes, followed by 30 cycles of a 30 second denaturation step at 95 ˚C; 45 second annealing at 55 ˚C; and a 90 second elongation step at 72 ˚C; with a final extension step for 30 minutes at 72 ˚C (QIAGEN Multiplex PCR Handbook, 02/2008). PCR amplification products were visualised on a 1.5% w/v agarose/0.5x TBE gel (Bio-Rad MB certified). PCR products were purified using the QIAquick PCR Purification Kit (Qiagen), following the manufacturer’s instructions. The DNA concentrations of the purified PCR products were quantified using a Nanovue spectrometer (GE Life Sciences). The PCR products were digested with *MspI* and *HhaI* in a 30 µL reaction mixture containing 400 ng of PCR products, NEBuffer 4, acetylated BSA, and water. Samples were incubated at 37 ˚C for 3 hours followed by an inactivation step at 95 ˚C for 15 minutes (QIAGEN Multiplex PCR Handbook, 02/2008). The digests were purified using a MinElute reaction cleanup kit (Qiagen) following the manufacturer’s instructions, and 1 µL aliquots of each sample containing the fluorescent labelled terminal restriction fragments were separated using an ABI PRISM 3100 Genetic Analyser (Applied Biosystems).

TRFLP profiles were produced using Gene-Mapper (version 4.0) software (Applied Biosystems) and terminal restriction fragments (TRFs) were quantified using the advanced mode and second-order algorithm. TRF analysis was performed between 50 and 500 basepair (bp) as previously described by MacDonald et al. (2008, 2009), which was within the linear range of the internal size standard. For microbial community analysis, two TRF peaks separated from one another by >1 bp were considered as distinct TRFs. The relative abundance was calculated as a proportion of the total peak height of all the TRFs in the profile. All peaks with heights that were less than 0.5% of the total peak height were removed from the data before statistical analysis. To condense the two subsamples for each replicate to a single value, the maximum peak height between the two samples was used for each TRF (Appendix 6).

Ordination of microbial communities

Data input into the ordination was relative amount of each individual TRF found in the soil samples over time, depth, and disturbance, with the Bray and Curtis (1957) metric as the measure of community distance. PC-Ord software (McCune and Mefford 2011) was used to determine directionality and correlation of gradients in the measured soil parameters. Multi-response permutation analysis (MRPP), a non-parametric multivariate analysis procedure, was used to test the bacterial community response to disturbance (Mielke 1984).

Soil chemical analyses

The sampled soils (air-dried and sieved to <2 mm size) were analysed for gravimetric soil moisture, soil pH, soil electrical conductivity (EC), and total phosphorus using standard methods (Blakemore et al. 1987). Total carbon and nitrogen were measured using a LECO FP 2000 analyser at 1050 ˚C (LECO, St Joseph's, Michigan). All soil chemical properties were rated (as high, medium, low etc.) following Blakemore et al. (1987), and were the mean of two sub-samples per depth (Appendix 4).

Soil pH, soil EC, moisture, total P, N and C were log(n + 1) transformed prior to analysis to meet assumptions of normality and homogeneity of variance. A restricted maximum likelihood (REML) linear mixed model (LMM) was used to assess both time and treatment effects. Time, treatment and time*treatment were the fixed effects and block*time*treatment the random effect. The REML approach was used over a univariate repeated measures ANOVA because preliminary statistics indicated that treatment variance differentially varied over time (as demonstrated by epsilon values < 0.6). Day, depth and day*depth interactions were considered significant at $p < 0.05$. We considered p values < 0.10 marginally significant. Comparison of depths A and C (the surface layers after disturbance) (Fig. 3), and between B and C (the pre-disturbance equivalent layers) were of interest and compared by contrast, all other comparisons were made by least significant difference only if the ANOVA was significant (i.e. Fishers protected LSD) at $\alpha = 0.05$.

Results

Treatment effects on bacterial community structure

Ordination was used to illustrate bacterial community composition as indicated by TRFLP profiles (Fig 4). Only the first two axes of ordination are presented as these accounted for most of the variance in bacterial community composition (Axis 1 = 60%, Axis 2 = 20%). There was no significant grouping of plots in the ordination space by treatment. Permutation analysis (MRPP) also did not indicate significant differences between the post-disturbance surface layers (Depths A versus C) or the equivalent pre-disturbance sub-surface layers (Depth B vs C) (Fig 4), as the standard errors of the centroids overlap, but did indicate significant difference between the A and D (a consequence of differences in depth, p value < 0.03). Overall the removal of the top 2 cm of soil did not appear to cause any major shifts in the structure of the bacterial communities over the 35 day sampling period.

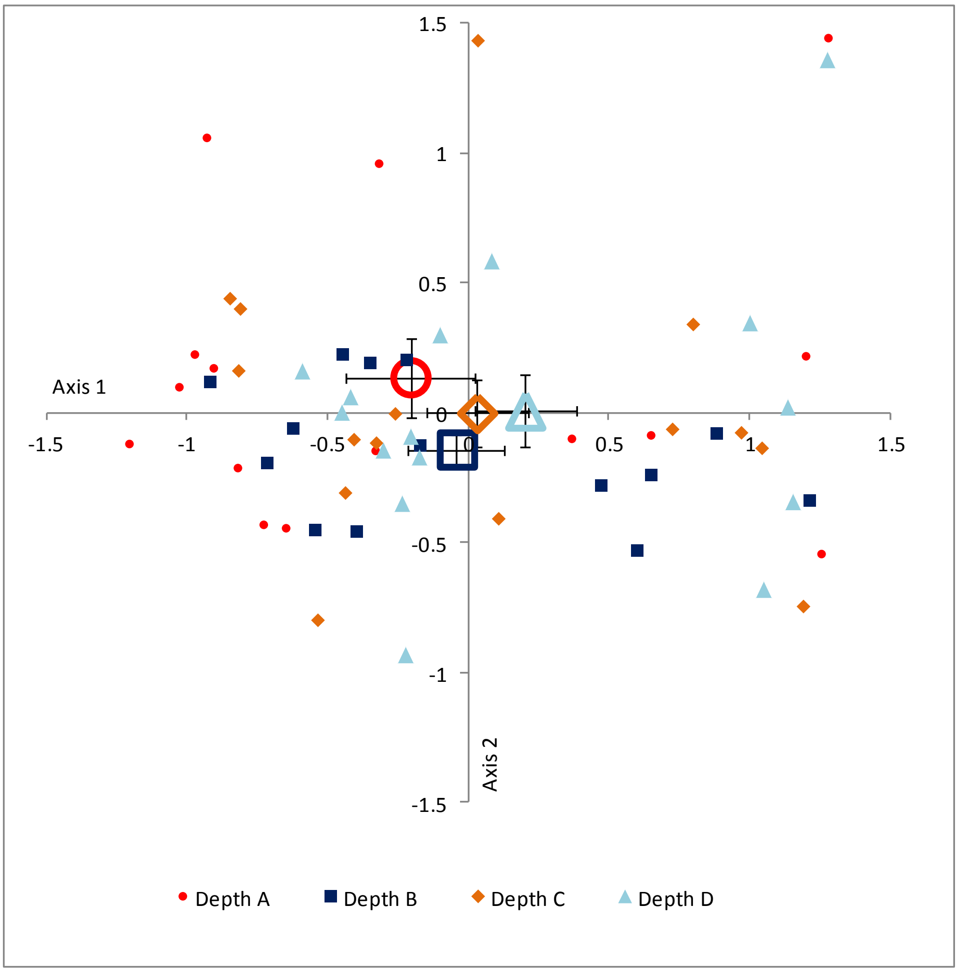

Fig. 4 PC-Ord ordination showing the effects of treatment (disturbance) on the bacterial community composition at the Scott Base disturbance trial. The overall treatment means of each depth over time are shown, and centroids show the average position of the individual treatments in the ordination space. Circles = Depth A, control 0-2 cm; Squares = Depth B, control 2-5 cm; Diamonds = Depth C, disturbed 2-5 cm (post-disturbance exposure surface); Triangles = Depth D, disturbed 5-8 cm. Depth B and C are equivalent depths. Standard errors are shown

There was, however, a significant grouping of TRFs in the ordination space by block (Fig. 5). We will explore the similarities and differences in soil chemical characteristics in each block and the effect on TRF clustering in the next section.

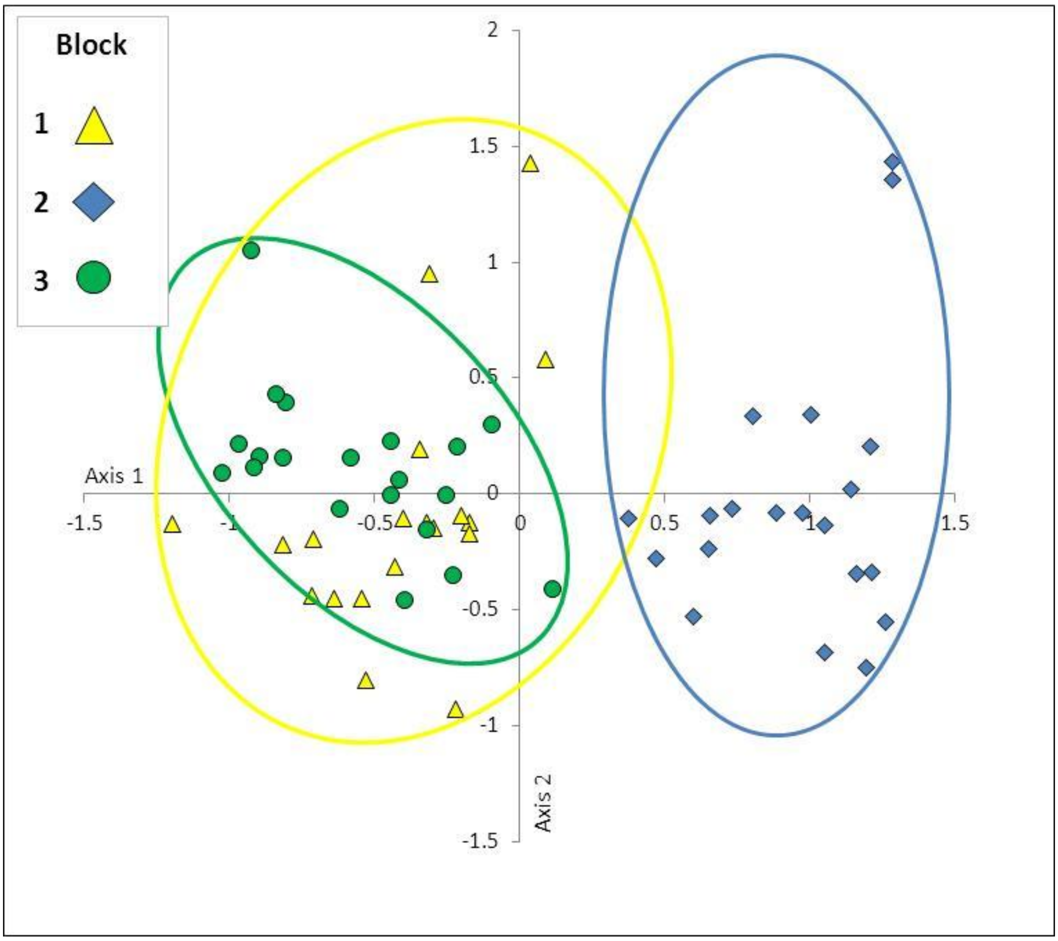

Fig. 5 PC-Ord ordination of the Scott Base disturbance trial soil samples based on TRF profiles of bacterial community composition. A significant 'block effect' of the ordination space are depicted. Triangles = Block 1, Diamonds = Block 2, and Circles = Block 3

Soil chemical characteristics

Soil means of measured soil parameters over all time periods for treatments and depths are presented in Table 2. Soil pH and soil electrical conductivity data is presented for each individual block (Tables 3 and 4).

Water content was low in all blocks and increased with depth, from 1-2% in surface samples to 2-3% in subsurface samples, of the treated (disturbed) and untreated quadrants. There was a moistening effect from snowfall that occurred between Day 14 and Day 21, which penetrated to at least Depth D (8 cm below the surface). During this time soil moisture increased from about 1% to 9% between Day 14 and Day 21 then dried out back to background at the surface within 2 weeks (by Day 35), but remained elevated at subsurface depths during the sampling period. There was a significant time interaction for water (Table 5).

Table 2 Soil means over all time periods for treatment and depths. Depth A = Control desert pavement to 2 cm, Depth B, immediately below, 2 to 5 cm, Depth C = Disturbed 2 to 5 cm (new surface), and Depth D = 5 to 8 cm immediately below the new surface. Data shown are means ± standard error, and n =3. Values with the same superscript letters within a row are not significantly different

Variable	Control		Disturbed	
	Depth A	Depth B	Depth C	Depth D
Water (%)	3.5 (0.70)^{a}	3.9 (0.45)^{b}	3.5 (0.66)^{a}	4.1 (0.46)^{b}
pH	9.5 (0.07)^{a}	9.6 (0.07)^{a}	9.6 (0.12)^{a}	9.5 (0.12)^{a}
EC (mS/cm)	0.49 (0.09)^{a}	0.36 (0.07)^{ab}	0.31 (0.07)^{bc}	0.21 (0.04)^{c}
Organic C (%)	0.14 (0.02)^{a}	0.13 (0.01)^{a}	0.15 (0.01)^{a}	0.12 (0.01)^{a}
Total N	0.02 (0.003)^{a}	0.02 (0.001)^{a}	0.02 (0.002)^{a}	0.02 (0.002)^{a}
C/N	7 (0.34)^{a}	7 (0.31)^{a}	7 (0.24)^{a}	7 (0.21)^{a}
Total P (mg/kg)	1333 (30.30)^{a}	1354 (37.43)^{a}	1308 (38.18)^{a}	1305 (34.81)^{a}

All samples were strongly alkaline (pH 8.8 – 10.1) and soil pH showed some slight increases with depth but was not consistent across all blocks (Tables 2 and 3). Blocks 1 and 3 were slightly more alkaline than Block 2 (Table 3). Depth C (disturbed) had a similar pH to the Depth B as they were effectively an equivalent depth (Fig. 3, Table 3). Blocks showed some small variability in soil pH with time (Table 5), which could be due to sample variability with respect to salt, rather than treatment.

Electrical conductivity (EC) was highly variable between blocks and with depth, and ranged between 0.04 mS/cm to 1.23 mS/cm (Table 4). EC was highest in the Depth A (0-2 cm) samples in each block (ranging from 0.10 mS/cm to 1.23 mS/cm) and decreased with depth in all blocks (ranging from 0.04 mS/cm to 0.91 mS/cm) and with treatment (Tables 2 and 5). This is because removal of the top 2 cm of surface material in the disturbed quadrants of each block effectively removed the thickness of soil which had the highest salt concentration. Prior to initial disturbance on Day 0 the top 2 cm of the ‘to be’ disturbed quadrant of Block 3 had the highest EC of all blocks at 2.42 mS/cm. After disturbance the top of the exposed “new surface” Depth C had an EC of 0.91 mS/cm; disturbance effectively removed 62% of the original salt content (and residing microbes in the upper 2 cm of soil). Block 2 had the lowest EC (and lowest pH) at both surface and subsurface depths compared with Blocks 1 and 3. There was a decrease in EC across all blocks, depths, and treatments, which coincided with snowfall between Day 14 to Day 21 (Tables 4 and 5) and increased soil moisture.

Table 3 pH of soil samples analysed for bacterial community composition studies (mean of two sub-samples at each depth and treatment)

Soil pH		Day 0	Day 7	Day 14	Day 21	Day 35
Block 1	Depth A Control	9.7	9.3	9.8	9.6	9.6
	Depth B Control	9.7	9.5	9.9	9.8	10.1
	Depth C Disturbed	9.7	9.7	9.9	9.8	9.8
	Depth D Disturbed	9.6	9.6	9.9	9.5	9.8
Block 2	Depth A Control	9.3	9.2	9.3	9.3	9.2
	Depth B Control	9.3	9.4	9.2	9.2	9.2
	Depth C Disturbed	9.0	8.8	9.0	9.1	8.9
	Depth D Disturbed	8.8	9.0	9.1	8.9	8.9
Block 3	Depth A Control	9.7	9.6	9.7	10.1	9.8
	Depth B Control	9.6	9.7	9.9	10.0	9.8
	Depth C Disturbed	9.9	9.7	10.1	10.0	10.0
	Depth D Disturbed	10.0	9.8	10.0	9.9	10.1

Table 4 Electrical conductivity (mS/cm) of soil samples analysed for bacterial community composition studies (mean of two sub-samples at each depth and treatment)

Soil EC		Day 0	Day 7	Day 14	Day 21	Day 35
Block 1	Depth A Control	0.35	0.35	0.45	0.18	0.57
	Depth B Control	0.20	0.41	0.40	0.17	0.37
	Depth C Disturbed	0.33	0.25	0.19	0.25	0.19
	Depth D Disturbed	0.12	0.15	0.21	0.19	0.13
Block 2	Depth A Control	0.22	0.26	0.13	0.14	0.10
	Depth B Control	0.11	0.09	0.13	0.11	0.08
	Depth C Disturbed	0.08	0.06	0.07	0.08	0.04
	Depth D Disturbed	0.07	0.05	0.06	0.07	0.04
Block 3	Depth A Control	1.23	1.01	1.07	0.68	0.61
	Depth B Control	0.57	0.62	0.91	0.77	0.28
	Depth C Disturbed	0.91	0.78	0.60	0.35	0.55
	Depth D Disturbed	0.47	0.52	0.34	0.44	0.27

Table 5 F-values from overall analysis of variance of soil parameters over all time periods

Variable	Water	pH	EC	Organic C	Total N	C/N	Total P
Block[1]	0.12	28.36***	140.07***	6.19**	14.22***	10.82***	1.54
Treatment	6.41**	0.22	17.18***	1.27	1.47	0.74	0.79
Time	209.87***	3.08^	2.32	3.64*	0.79	1.79	59.76***
Treatment x Time	9.87***	1.04	1.51	1.63	1.71	1.18	1.20

Significance: ^p <0.1,*p <0.05, **p <0.01, ***p <0.001

[1] Block statistics from repeated measures ANOVA

Preliminary statistical analysis indicated a significant "block effect" p <0.001 for EC, pH, Total C, Total N, and C/N; and not significant for Total P and water p >0.5

The organic C content was low (0.1% to 0.28%) and Total N was very low (0.01% to 0.04%) in all blocks and did not show much variation with depth, treatment, or time. C/N ratios were low and ranged between 6 and 10, and did not change significantly with time or treatment. Total P ranged from 1600 mg/kg to 1000 mg/kg and decreased in all blocks, and depths, over time (Table 5, $p < 0.001$), but did not change significantly with disturbance.

Soil chemical characteristic effects on bacterial community structure

Correlation of the soil characteristics to the ordination axis showed that axis 1 scores were strongly correlated with the gradients of soil pH ($R^2 = 0.67$), and EC ($R^2 = 0.55$), and also correlated with organic C ($R^2 = 0.30$) and Total N ($R^2 = 0.47$), indicating that differences in soil pH, soil EC, and C and N are likely to be the drivers of bacterial community composition (Fig. 6). Axis 2 scores correlated less strongly with water ($R^2 = 0.20$), and also sampling date ($R^2 = 0.24$) which was most likely driven by changes in water content. From the bioplots (Figs. 5 and 6) it is evident that there is an overriding “block effect” (i.e. Block 2 differs from Block 1 and Block 3. Block 2 $R^2 = 0.83$) where heterogeneity in significant soil parameters between blocks is clustering TRFs (Fig. 5). From these results it can be inferred that the bacterial community structure of Blocks 1 and 3 were influenced by higher soil pH and higher soil salinity (EC). The structure of the bacterial community of Block 2 was primarily related to lower salinity, lower pH, and slightly higher organic C (Tables 3 and 4).

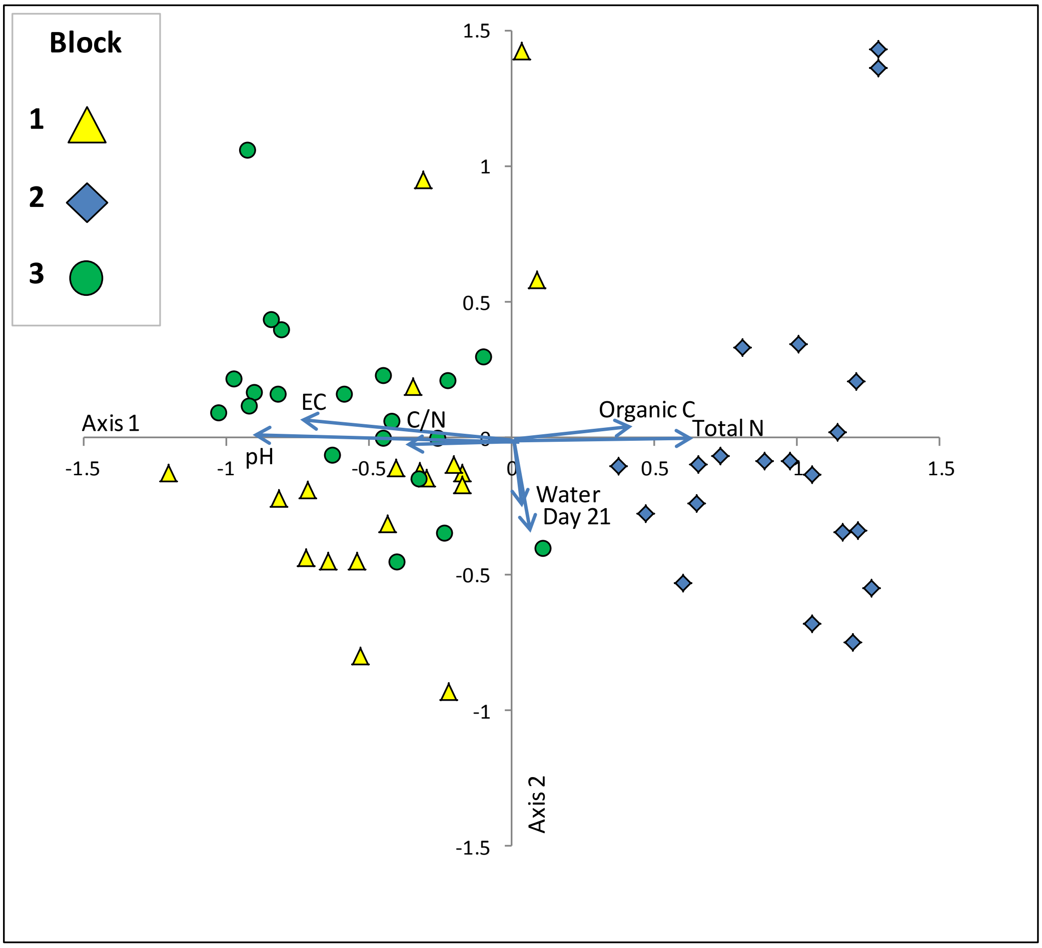

Fig. 6 Bioplot showing the PC-Ord ordination of the Scott Base disturbance trial soil samples based on TRF profiles of bacterial community composition. The gradients of environmental variables with a statically significant fit, R^2 >0.2, to the ordination space are depicted. Note TRFs clustering into blocks. Triangles = Block 1, Diamonds = Block 2, and Circles = Block 3

Discussion

In this study we used TRFLP analysis to investigate the immediate and short-term changes to bacterial community structure in response to soil surface disturbance. We hypothesized that there would be a measurable difference in bacterial community composition between disturbed and undisturbed sites, following removal of the surface material. However, in the time frame of the experiment we did not see clear changes to the structure of the bacterial communities at the study site.

Given that we know the drivers of bacterial community structure are predominantly soil EC, soil pH, and soil moisture (Aislabie et al. 2008, 2011; Barrett et al. 2006; Yergeau et al. 2007; Ganzert et al. 2011; Chong et al. 2012), we would expect that a disturbance of sufficient intensity to affect those properties mentioned (e.g. changes to soil EC and soil moisture resulting from soil active layer disturbance, Balks et al. 1995), and cause a shift in bacterial community structure.

Furthermore, any soil disturbance that would affect ecosystem functioning at a higher level, 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 bacterial community structure (or in this case declines in nematode abundance could be due to shifts in bacterial diversity and abundance). A possible reason why we did not see a shift could relate to the time frame of the experiment (Ayres et al. 2010; Sparrow et al. 2011) and the life-cycle of the bacterial communities (Schimel et al. 2007). Schimel et al. (2007) states that damage from environmental stresses is usually greater when microbes are active and growing, so at certain times in an organism's life-cycle they will be more vulnerable to environmental change. The use of RNA-based analyses could better reflect changes in metabolically active community structure (Griffiths et al. 2003; Yergeau and Kowalchuk 2008). Some CO_2 efflux studies have suggested that metabolic processes, such as respiration, are detectable and responsive to changes in environmental variables (Cary et al. 2010; Sparrow et al. 2011), and may be more sensitive indicators of early alterations in bacterial community structure following soil disturbance. However, Shanhun et al. (2012) have suggested that much of the CO_2 evolution from soil that correlates with changes in temperature and moisture is derived from abiotic changes in CO_2 in soil solution, and thus microbial respiration may have often been overestimated.

Abiotic soil factors contributing to bacterial community structure

Ordination showed that the bacterial community composition at the study site correlated strongly with soil EC and soil pH (Fig. 6). Although the replicate blocks were visually indistinguishable from one another, high local spatial variability of soil chemical properties existed at the study site and distinct bacterial communities were present within 2 m of one another, and within the same landscape unit (i.e. the 'block effect', $R^2 = 0.83$). TRF profiles showed Block 2 supported a bacterial community distinct from that of Blocks 1 and 3 (Fig. 5), and complementary soil chemical analyses revealed the biota of Block 2 were residing in soil which had an order of magnitude lower EC and lower pH than Blocks 1 and 3 (Tables 3 and 4). High local spatial variability in soil distribution is a common feature in Ross Sea region soils (McLeod 2012). As a consequence, high local spatial variability in environmental parameters, such as soil organic matter, salinity, and local moisture, at 10-500 m scales have been shown to influence microbial community abundance and diversity (Barrett et al. 2004; Brinkmann et al. 2007; Chown and Convey 2007; Engelen et al. 2008; Chong et al. 2009; Ball and Virginia 2012). Studies by Aislabie et al. (2008, 2012) supported this observation and found that the composition of bacterial communities in Ross Sea region soils tended to be more similar from the same site and differ by geographic location (Aislabie et al. 2012); as soil clone libraries revealed that community composition could be discriminated on the basis of soil properties (Aislabie et al. 2008).

The local variation in salt content within the study site, and the ability for local bacterial communities to tolerate osmotic stress is likely to account for some of the distinct community structure differences observed across the blocks. Bacteria can be sensitive to the concentration of soluble salts in soils which can also be influenced by repeated and rapid wetting and drying cycles associated with snowfall events (Table 4). Studies by Ayres et al. (2010) have shown that topsoil salinity can fluctuate with snow accumulation and melt, which along with associated changes to soil moisture was reflected in changes in dominant species of soil nematodes. Ball and Virginia (2012) observed a similar trend of highly variable soil characteristics coinciding with proximity to sometimes small scale, discontinuous seep patches (a product of melt water pulses from permafrost, glaciers, and snow patches). Studies by Ball et al. (2011) and Ball and Virginia (2012) suggest that the nearby McMurdo Dry Valleys have recently experienced several discrete warm events. Warmer temperatures result in increased availability of liquid water, which in turn can redistribute salts and affect biological communities and biogeochemical cycling. Ball and Virginia (2012) found EC and pH in particular were significantly influenced by position along the seep patch transects, and EC was significantly higher towards the middle of the patch and at the soil surface. The decline in surface and subsurface soil EC between Day 14 to Day 21, observed across all blocks, was most pronounced in the surface of the more saline Blocks 1 and 3, and was less pronounced in Block 2, likely due to lower background salt concentrations. As soils dry back down after a wetting event, microbes can encounter additional stress as water potentials decline, salts can concentrate, and cells must accumulate solutes to reduce their internal water potential to avoid dehydrating and dying (Harris 1981). The spatial variability in salt concentration evident across the blocks is potentially the result of a number of microtopographic variations including effects of uneven distribution of surface rocks on shading, hence evaporation and salt accumulation, moisture movements, and trapping of windblown snow. Any of these factors could account for the differences seen in soil EC and pH and thereby may influence habitat suitability over short distances.

Heterogeneity

Local scale heterogeneity in measured soil parameters made it difficult to determine the communities' response to the simulated disturbance. Limitations in the design of this experiment included the number of replicate blocks and the length of the sampling period. Both limitations were governed by the opportunistic nature of this experiment and limited time at Scott Base.

There is a question whether or not the one-off, low level, disturbance simulated in this experiment was of sufficient intensity to cause a shift in bacterial community structure at the study site. Inherently, the larger the perturbation outside natural environmental variations, the larger the stress on the biotic system, which may or may not have the ability to quickly adapt to the new conditions and avoid local decimation. Previous studies by Campbell et al. (1994) at Marble Point and in the vicinity of Scott Base (Balks et al. 1995) have shown moderate disturbance from earthworks and construction activities disturbed underlying permafrost, and resulted in lowering of the surrounding ground surface (by up to 10 cm in one year, Balks et al. 1995), slumping, and release of salts that were contained within the permafrost. At Marble Point Campbell et al. (1994) observed salt efflorescences on surfaces disturbed during earthworks carried out in the 1958/59 summer; which were still visible some 40-years after the initial disturbance (and on sampling had a soil EC of 1.6 mS/cm in the top 2 cm of the soil surface, 40-years on). We would propose that any moderate intensity disturbance, capable of modifying soil moisture and releasing soluble salts into biological communities resident in the near-surface environment is likely to have a negative and measurable impact on the local community.

A longer term experiment would eliminate those soil parameters which showed temporal fluctuations over the 35 day sampling period, such as water content, which were influenced by snowfall events. At present any small changes we observed over the short sampling period may simply reflect variation in response to another factor, rather than the response to the simulated surface disturbance. Soil sampling over a longer period of time may eliminate this uncertainty and also ensure the complete life-cycle of the community was represented. An example by Ayres et al. (2010) undertaking long term snow accumulation experiments in the McMurdo Dry Valleys saw a clear shift in the dominant nematode species over and above the local temporal variations in soil moisture associated with snow fall and snow melt. A further investigation by Sparrow et al. (2011) showed that the response of the soil microbial community to addition of C and N substrates, although detectable, was slow and only apparent after two years.

Conclusions

The simulated disturbance (removal of the top 2 cm of soil) at the Scott Base experimental site did not cause any major shifts in the structure of the bacterial communities over the 35 day summer sampling period. TRFLP analysis revealed that the soil replicate blocks investigated supported distinct bacterial communities; and the composition of communities reflected the different spatial variability in soil physiochemical properties of the blocks. Soil EC and pH strongly correlated with TRFLP patterns and can be inferred as the most important factors controlling bacterial composition at the study site. Our data highlights the importance of local scale heterogeneity in structuring soil bacterial communities, and that distinct communities are possible within 2 m of one another, and within the same landscape unit. Given the current knowledge of the drivers of bacterial community structure, i.e. soil EC, soil pH, and soil moisture content, we expect a disturbance of sufficient intensity to affect those properties mentioned, will cause a shift in bacterial community structure, over and above the time frame measured in this experiment. A more rigorous follow-up investigation incorporating DNA-RNA-based analyses and CO_2 efflux studies over a time frame of 2-3 years would lead to a greater understanding of the effects of soil disturbance on bacterial communities.

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References

Adlam LS, Balks MR, Seybold CA, Campbell DI (2010) Temporal and spatial variation in active layer depth in the McMurdo Sound Region, Antarctica. Antarct Sci 22:45-52

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

Aislabie JM, Chhour KL, Saul DJ, Miyauchi S, Ayton J, Paetzold RF, Balks MR (2006) Dominant bacteria in soils of Marble Point and Wright Valley, Victoria Land, Antarctica. Soil Bio Biochem 38:3041-3056

Aislabie JM, 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 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 ML, 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

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 22:1544-1551

Ayres E, Nkem JN, Wall DH, Adams BJ, Barnett JE, Simmons BL, Virginia RA, Fountain AG (2010) Experimentally increased snow accumulation alters soil moisture and animal community structure in a polar desert. Polar Biol 33:897-907

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. University of Waikato,Antarctic Research Unit Special Report 1

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

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

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

Barrett JE, Virginia RA, Wall DH, Parsons AN, Powers LE, Burkins MB (2004) Variation in biogeochemistry and soil biodiversity across spatial scales in a polar desert ecosystem. Ecol 85:3105–3118

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 Bio Biochem 38:3019–3034.

Belbin L (1991) Semi-strong hybrid scaling, a new ordination algorithm. J Veg Sci 2:491–496

Blakemore LC, Searle PL, Daly BK (1987) Methods for Chemical Analysis of Soils. New Zealand Soil Bureau Scientific Report 80, Wellington, New Zealand

Bockheim JG (1997) Properties and classification of Cold Desert soils from Antarctica. Soil Sci Soc Am J 61:224-231

Bockheim JG, McLeod M (2006) Soil formation in Wright Valley, Antarctica since the late Neogene. Geoderma 37:109–116

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

Bölter M (1995) Distribution of bacterial numbers and biomass in sols and on plants from King George Island (Arctowski Station, Maritime Antarctica). Polar Biol 15:115-124

Bray JR, Curtis JT (1957) An Ordination of the Upland Forest Communities of Southern Wisconsin Ecol Monogr 27:325-349

Brinkmann M, Pearce DA, Ott S (2007) The cyanobacterial community of polygon soils at an inland Antarctic nunatak. Polar Bio 30:1505-1511

British Antarctic Survey (2005). *Antarctic Factsheet Geographical Statistics*. British Antarctic Survey, Cambridge, UK. 4p

Bromley M (1994) The climate of Scott Base 1957-1992. National Institute of Water and Atmospheric Research Report 94-002

Campbell IB, Claridge GGC (1975) Morphology and age relationships of Antarctic soils. In: Suggate RP, Cresswell MM (eds) Quaternary Studies, R Soc New Zealand Bull vol 13, pp 87–88

Campbell IB, Claridge GGC (1969) A classification of frigic soils-the zonal soils of the Antarctic continent. Soil Sci107:75–85

Campbell IB, Claridge GGC (1987) Antarctica: soils. Weathering processes and environments. Elsevier, New York

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: 321-328

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

Campbell IB, Claridge GGC, Campbell DI, Balks MR (1998) The soil environment of the McMurdo Dry Valleys, Antarctica. In: Priscu J (ed) Ecosystem dynamics in a polar desert: the McMurdo Dry Valleys. American Geophysical Union Antarctic Research Series, vol 72, pp 297-322

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: 129-138

Chong CW, Dun MJ, Convey P, Tan GYA, Wong RCS, Tan IKP (2009) Environmental influences on bacterial diversity of soils on Signy Island, maritime Antarctic. Polar Biol 32:1571-1582

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 Doi:10.1017/S0954102012000028

Chowdhury N, Marschner P, Burns R (2011) Response of microbial activity and community structure to decreasing soil osmotic and matric potential. Plant Soil 344:241-254

Chown SL, Convey P (2007) Spatial and temporal variability across life's hierarchies in the terrestrial Antarctic. Philos Trans R Soc London Ser B362: 2301-2331

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

Cowan DA, Russell NJ, Mamais A, Sheppard DM (2002) Antarctic Dry Valley mineral soils contain unexpectedly high levels of microbial biomass. Extremophiles 6:431-436

Csonka LN (1989) Physiological and genetic responses of bacteria to osmotic stress. Microbiol Rev 53:121–147

Engelen A, Convey P, Hodgson DA, Worland MR, Ott S (2008) Soil properties of an Antarctic inland site: implications for ecosystem development. Polar Bio 31:1453-1460

Foght J, Aislabie J, Turner S, Brown CE, Ryburn J, Saul DJ, Lawson W (2004) Culturable bacteria in subglacial sediment and ice from two Southern Hemisphere glaciers. Microbial Ecol 47:329–340

Fox AJ, Cooper PR (1994) Measured properties of the Antarctic Ice Sheet, derived from the SCAR digital database. Polar Rec 30:201-204

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. Microbial 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

Griffiths RI, Whiteley AS, O'Donnell AG, Bailey MJ (2003) Influence of depth and sampling time on bacterial community structure in an upland grassland soil. FEMS Microbiol Ecol 43: 35-43

Harris RF (1981) Effect of water potential on microbial growth and activity. In: Parr JF, Gardner WR, Elliott LF (eds) Water potential relations in soil microbiology. American Society of Agronomy, Madison, Wisconsin, USA

Hogg ID, Cary SC, Convey P, Newsham KK, O'Donnell AG, Adams BJ, Aislabie J, Frati F, Stevens MI, Wall DH (2006) Biotic interactions in Antarctic terrestrial ecosystems: Are they a factor? Soil Bio Biochem 38:3035-3040

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

IAATO (2011) Tourism statistics. http://iaato.org/tourism-statistics. Accessed 4 November 2011

Lauber CL, Hamady M, Knight R, Fierer N (2009) Pyrosequencing-based assessment of soil pH as a predictor of soil community structure at the continent scale. Appl Environ Microb 75:5111-5120

McCune, B, Mefford, MJ (2011) PC-ORD. Multivariate Analysis of Ecological Data. Version 6.04 MjM Software, Gleneden Beach, Oregon, USA

Macdonald CA, Campbell CD, Bacon JR, Singh BK (2008) Multiple profiling of soil microbial communities identifies potential genetic markers of metal-enriched sewage sludge. FEMS Microbiol Ecol 65:555–564

Macdonald CA, Thomas N, Robinson L, Tate KR, Ross DJ, Dando J, Singh BK (2009) Physiological, biochemical and molecular responses of the soil microbial community after afforestation of pastures with Pinus radiata. Soil Bio Biochem 41:1642-1651

McLeod M (2012) Soil and Permafrost Distribution, Soil Characterisation and Soil Vulnerability to Human Foot Trampling, Wright Valley, Antarctica. Ph.D. Thesis, University of Waikato, New Zealand.

Mielke PW (1984) Meteorological applications of permutation techniques based on distance functions. In: Krishanaiah, PR, Sen, PK (eds) Handbook of Statistics. North-Holland, Amsterdam, pp 813– 830

Moorhead DL, Barrett JE, Virginia RA, Wall DH, Porazinska D (2003) Organic matter and soil biota of upland wetlands in Taylor Valley, Antarctica. Polar Biol 26:567–576

Nkem JN, Virginia RA, Barrett JE, Wall DH, Li G (2006) Salt tolerance and survival thresholds for two species of Antarctic soil nematodes. Polar Bio 29:643-651

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 Lett 158:121-126

Schimel J, Balser TC, Wallenstein M (2007) Microbial stress-response physiology and its implications for ecosystem function. Ecol 88:1386-1394

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

Singh BK, Nazaries L, Munro S, Anderson IC, Campbell CD (2006) Use of multiplex terminal restriction fragment length polymorphism for rapid and simultaneous analysis of different components of the soil microbial community. Appl Environ Microbiol 72:7278–7285

Soil Survey Staff (2010) Keys to Soil Taxonomy (10th ed) U.S. Dept. Agric., Natural Resource Conservation Service. Washington, D.C.

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 Bio Biochem 75: 2188-2197

Tejedo P, Justel A, Benayas J, Rico E, Convey P, Quesada A (2009) Human impact on soils in an Antarctic Specially Protected Areas: tools to evaluate SCAR recommendations. Antarct Sci 21. doi:10.1017/S0954102009001795

Treonis AM, Wall DH, Virginia RA (1999) Invertebrate biodiversity in Antarctic dry valley soils and sediments. Ecosystems 2:482-492

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

Wall DH, Virginia RA (1999) Controls on soil biodiversity: insights from extreme environments. Applied Soil Ecology 13:137-150

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) Adv Microb Ecol 2:71-146

Xiao X, Li M, You Z, Wang F (2007) Bacterial communities inside and in the vicinity of the Chinese Great Wall Station, King George Island, Antarctica. Antarct Sci 19:11-16

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

Yergeau E, Kowalchuk, G (2008) Responses of Antarctic soil microbial communities and associated functions to temperature and freeze-thaw cycle frequency. Appl Microbiol 10:2223-2235

7 ROSS ISLAND RECREATIONAL WALKING TRACKS: RELATIONSHIPS BETWEEN SOIL PHYSIOCHEMICAL PROPERTIES AND USE

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Ross Island recreational walking tracks: relationships between soil physiochemical properties and use

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Abstract

The objective of this research was to record the number of people using the Ross Island recreational walking tracks, and to examine the relationships between the number of users, track morphological characteristics, and soil physiochemical properties. Infrared track counters provided 2-years of data on five walking tracks on Ross Island in the Ross Sea region of Antarctica. Track width and track incision were measured and soil sampling was undertaken in the vicinity of the track counter and an adjacent control site.

Between January 2009 and January 2011 5084 passes were recorded on the Scott Base to McMurdo Station walking track, 2842 on the Wind Vane Hill walking track, 3561 on the Round Observation Hill walking track, 10936 on the Up Observation Hill track, and 693 on the Crater Hill summit walking track. There were more users on all tracks in the 2010/2011 summer season than the 2009/2010 summer season. The highest frequency of visitors occurred on Sundays during the summer (November to January). There was no relationship between the number of passes on the track and the measured impact indicators indicating that higher usage of a formed track had little cumulative impact. Track width and incision were related to the slope of the terrain, with tracks traversing flatter areas generally wider (R^2 = 0.85) and less incised (R^2 = 0.96), than those traversing steeper hillsides. Soil

bulk density was higher in the walking tracks than adjacent control areas ($p < 0.05$).

Introduction

Walking tracks are a fundamental part of recreation zones in wilderness areas, providing recreation opportunities, access, as well as resource protection by concentrating visitor flow (Hill and Pickering 2009), controlling erosion, and limiting damage to flora, fauna, and places of heritage and cultural importance. A walking 'track', as defined in this study, is an area of continuous bare-ground which forms a pathway and which is formed by foot traffic. The term "track", as used in this study, is analogous to the use of 'trail' in other studies. In environmentally sensitive areas, such as Antarctica, the balance between maintaining an areas inherent ecological qualities and allowing the public to enjoy these qualities through recreational activity is delicate.

Science and tourism in Antarctica has seasonal visitation patterns with a sudden influx of visitors over the austral summer. The most popular sites, such as Deception Island and Half Moon Island in the Antarctic Peninsula, have up to 20,000 visitors over the summer season (IAATO 2011). In the Ross Sea region, although visitor numbers are fewer and the tourist season is shorter (between November and February) each year there are increasing visitor numbers (Antarctica New Zealand 2012). Scott's Terra Nova Hut at Cape Evans, for example, is visited by approximately 1100 people annually (Antarctica New Zealand 2012). About 70% of visitors to Cape Evans are United States Antarctic Programme (USAP) and New Zealand Antarctic Programme (NZAP) personnel, the remainder are ship-based tourists.

The study of impacts from recreational use of environmentally sensitive or protected areas is referred to as recreation ecology (Liddle 1997; Hammitt and Cole 1998; Leung and Marion 2000; Newsome and others 2002). Early recreation ecology research focussed on describing readily observable impacts of hiking and camping, particularly soil and vegetation loss and change. Common impacts from walking track use include (Hill and Pickering 2009):

- Soil: compaction, loss of organic matter, loss of soil, reduction in moisture and microbial activity;
- Vegetation: reduced height, loss of ground cover, loss of fragile species, increase in resistant species and introduction of non-native species, exposed roots;
- Wildlife: habitat alteration, habitat loss, introduction of non-native species, modification of behaviour, reduced reproduction;
- Track erosion (track deepening) resulting in rutted tracks, conduits for water and soil transport, thereby accelerating soil erosion;
- Track widening: common when users spread laterally to avoid wet, muddy, or icy areas; and
- Proliferation of unplanned or subsidiary walking tracks to access lookout points or take shortcuts.

Impacts are affected by season of use, rainfall, and topography, such as slope and aspect (Hill and Pickering 2009).

Few studies into the impacts of recreational walking tracks and camping on the terrestrial environment have been conducted in Antarctic and sub-Antarctic environments. Scott and Kirkpatrick (1994) investigated the effects of human trampling on the sub-Antarctic vegetation on Macquarie Island; and Gremmen and others (2003) also noted trampling impacts on plants on sub-Antarctic Marion Island. Impacts varied according to vegetation and soil types, but impacts in both studies included track widening and soil compaction. Ayres and others (2008) investigated the impacts to soil fauna (nematodes) in the Taylor Valley of the McMurdo Dry Valleys under low, intermediate, and high levels of human foot traffic. Ayres and others (2008) noted decreased abundances of the dominant nematode in heavily used walking tracks, compared with tracks experiencing lower levels of use. Trampling on vegetation-free soils in the South Shetland Islands in the Antarctic Peninsula led to increases in soil compaction and decreases in the abundance of soil arthropods (Tejedo and others 2005, 2009). Campbell and others (1998a) measured the rate at which tracks formed at three sites in the Ross Sea region by walking along a set route a set number of times, and observing changes in the nature of the surface. A clear walking track formed in as few as 20 passes on soft fine-textured materials and impacts were non-linear, with most impacts occurring in the initial stages of the trampling experiment (Campbell and others 1998a).

The Ross Sea region of Antarctica offers a range of outstanding natural features of interest to visitors. The recreational walking tracks on the ice-free southern tip of Hut Point Peninsula, and the walking track to a lookout over Scott's Terra Nova Hut at Cape Evans, are popular with visitors to Ross Island. Personnel working in the vicinity of Scott Base and McMurdo Station are able to access the nearby walking tracks during their recreational periods. The USAP promotes use of the walking tracks by way of information booklets for users of the Round Observation Hill and Up Observation Hill walking tracks (close to McMurdo Station) The booklets provide information on the geology and the views on the track. The Ross Island walking tracks are visible in the landscape; however, little is known about the effects of visitor use on soil physiochemical characteristics.

The objectives of this study were to investigate:

- The number of people using the Ross Island recreational walking tracks;
- The impact human trampling has on the soil physiochemical properties of the walking tracks;
- and impacts in varying local environments

Study area

Environmental setting and history

Ross Island is dominated by basaltic volcanoes (Mount's Erebus, Bird, and Terror) with the foot-slopes near the coasts comprised of lava fields and scoria cones. The study investigated five walking tracks at two localities on Ross Island: four walking tracks around the Hut Point Peninsula (the Scott Base to McMurdo Station, Up Observation Hill, Round Observation Hill, and Crater Hill summit, walking tracks), and one walking track on Wind Vane Hill, Cape Evans (Fig. 1). Cape Evans is a small, triangular-shaped ice-free area in the southwest of Ross Island, 10 km southeast of Cape Royds and 22 km northwest of Hut Point.

The five walking tracks occurred on gently undulating to steep lava flows, and were formed on weakly weathered (and comparatively young) scoriaceous basalt- dominated till and scoriaceous basalt bedrock. Soils at each locality are classed as Typic Haplorthels (Soil Survey Staff 2010) and contained ice-cemented permafrost. Soils were generally coarsely textured, loose, and alkaline with very low organic matter contents (Campbell and Claridge 1987; Balks and others 2002; Aislabie and others 2004). The surface deposits and soils were unweathered (weathering stage 1 of Campbell and Claridge 1975), and salt stage 1 (Bockheim 1997), indicative of their comparatively young age. The mean annual air temperature at the study localities was approximately -16° C (*from* USDA, Natural Resources and Conservation Center http://soils.usda.gov/survey/smst/antarctica/ScottBase/2010/); however during the continuous daylight of the summer months, air temperatures were within the range of -7 to +10° C, and surface soil temperatures can reach 20° C (Balks and others 2002). Ross Island soils have a subxerous moisture regime (wet for short periods during snow thaw) and are subject to moderate snowfalls (an average of seven snow fall events per month during summer (Campbell and others 1998b). Wind activity is a driver of surface processes; however, in late spring and summer, liquid melt-water occurs which facilitates a range of weathering, leaching, erosion, and freeze-thaw processes.

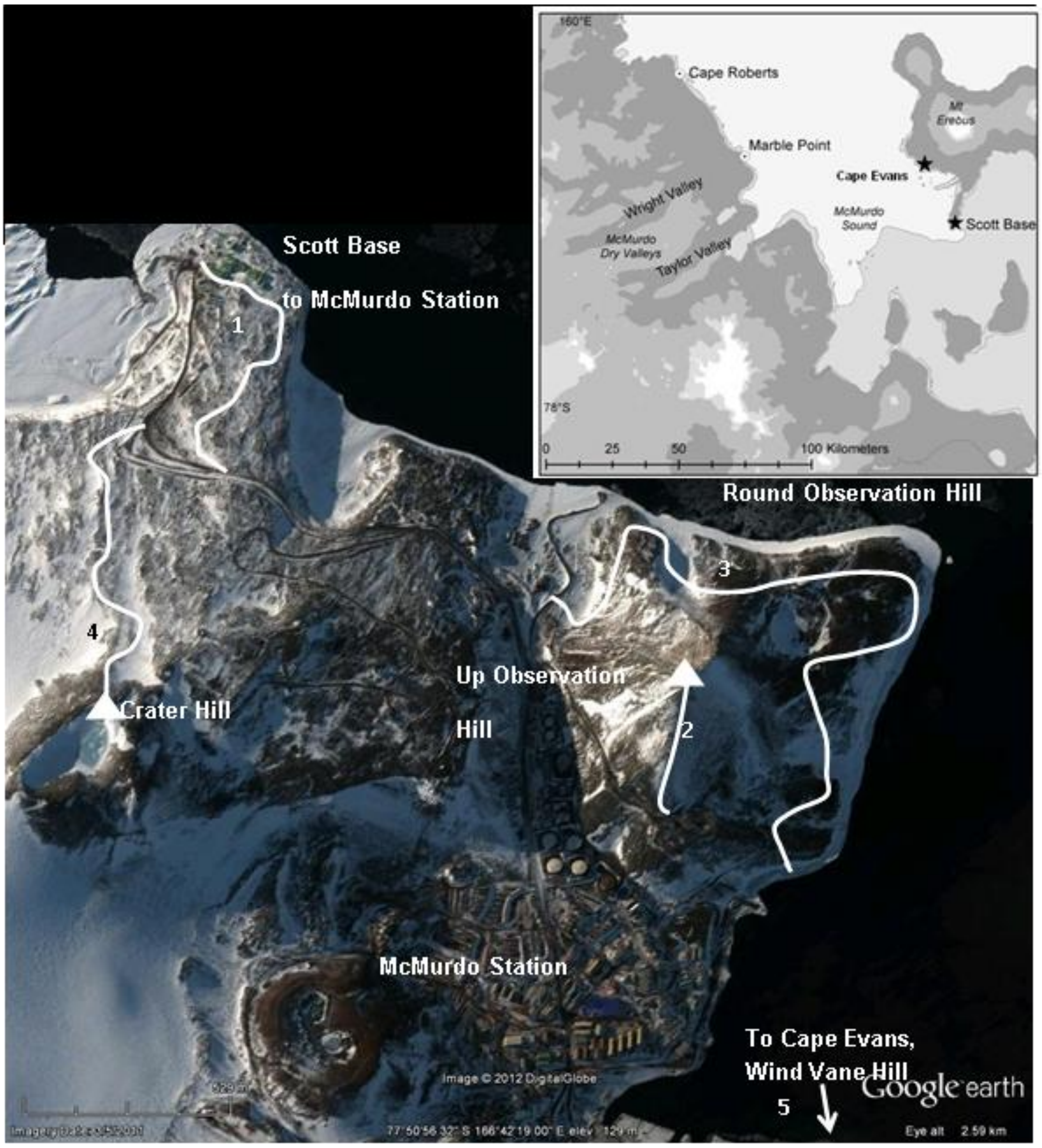

Fig. 1. Map showing the location of the Ross Island recreational walking tracks. 1 = Scott Base to McMurdo Station walking track; 2 = Up Observation Hill walking track; 3 = Round Observation Hill walking track; 4 = Crater Hill summit walking track; 5 = Wind Vane Hill walking track, 22 km north at Cape Evans.

Occupation of Hut Point Peninsula began in 1902 with the arrival of Scott's Discovery Expedition (Tin and others 2009). The ice-free southern tip of the peninsula is occupied by New Zealand's Scott Base (est. 1957) and the United States of America's McMurdo Station (est. 1956). Permanent and continuous occupation of the area has occurred since the late 1950s (Kennicutt II and others 2010). Antarctica's largest station, McMurdo Station, has a winter population of about 200 and has a capacity for 1,100 people in summer (Tin and others 2009). Nearby Scott Base has a winter population of about 10, and can accommodate about 85 people in the summer (Waterhouse 2001).

Visitor attractions

Observation Hill is a topographic high between McMurdo Station and Scott Base (Figs. 1, 2a). The first ascents of Observation Hill occurred about 1902 by members of Scott's Discovery Expedition. Scott's team's daily ascent of Observation Hill as they waited for their leader to return from the South Pole in 1912 would have initiated the development of present day 'Up Observation Hill' walking track.

Cape Evans is the site of Scott's Terra Nova Hut (est. 1911); the largest of the historic huts. The first ascent of Wind Vane Hill is likely to have occurred during Scott's first visit to Cape Evans around 1902 (Fig. 2c). Nowadays the Wind Vane Hill track is used by tourists visiting Scott's Terra Nova hut, and staff of USAP and NZAP. The walk between Terra Nova hut and the Wind Vane Hill lookout takes approximately 5 minutes.

Walking routes around Observation Hill (Fig. 2a,b), and the short-cut walking track between Scott Base and the road to McMurdo Station (Fig. 2d), are likely to have been first walked in the late 1950s during construction of Scott Base and McMurdo Station. An effort was made in the late 1990s-early 2000s to formalise the Scott Base to McMurdo Station walking track to keep people to one route. Large stones were cleared off the track and repositioned along the track margins to make a clearly defined walking track. Prior to that the whole area between Scott Base and the vehicle road to McMurdo Station was trampled, and multiple branches of informal tracks had formed. The route between Scott Base and the road to McMurdo Station takes approximately 10 minutes.

The Up Observation Hill and Round Observation Hill walking tracks comprise the 'Ross Island Trail System', which was opened officially on 27 December 2006. Prior to the official opening there were several informal tracks around Observation Hill. USAP staff used shovels to form an identifiable track and flagged cairns at locations where additional markers were required (J. Heil, Contractor, United States Antarctic Program, personal communication, 3 May 2012). The Up Observation Hill walk takes between 20-30 minutes one-way; and the Round Observation Hill loop walk 90-120 minutes return.

The Crater Hill summit route (Fig. 2e) had been walked for a number of decades; however in the summer of 2007/2008 a visiting New Zealand scout group formalised the route using marker flags from Scott Base to the summit of Crater Hill (J. Newman, Environmental Advisor to Antarctica New Zealand, personal communication, 3 May 2012). The Crater Hill track is regularly walked by NZAP participants. The Crater Hill summit route takes 60-90 minutes return.

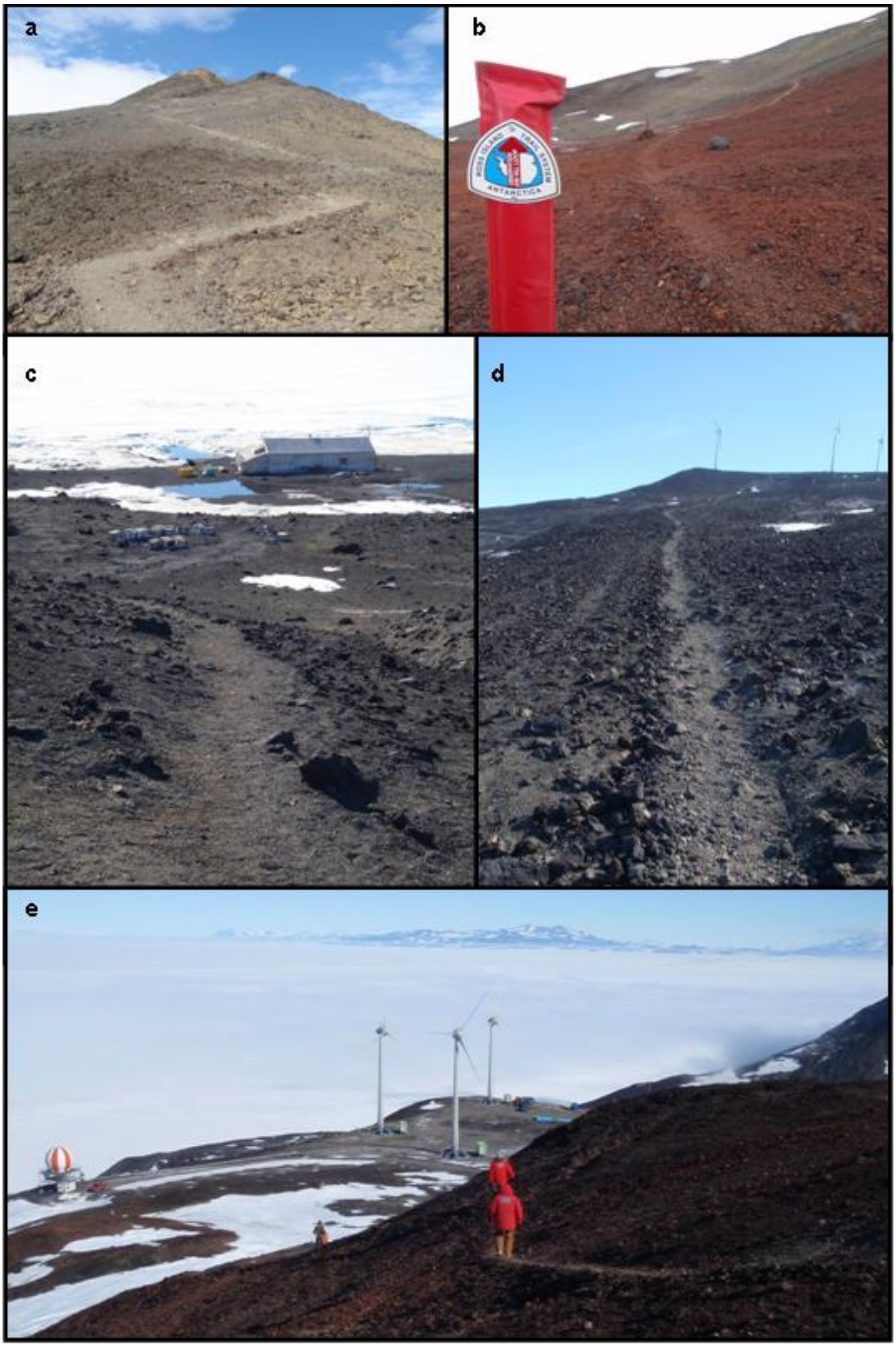

Fig. 2. Walking tracks in this study. (a) Up Observation Hill; (b) Round Observation Hill; (c) Wind Vane Hill, Cape Evans; (d) Scott Base to McMurdo Station road; (e) Crater Hill summit route.

Materials and methods

Infrared track counters

Infrared track counters (TRAFx, Canmore, Canada) were deployed to monitor visitor use over a two year period between the austral summers of 2008/2009 and 2009/2010. The monitor registers a pass-by event (i.e. a walker passing regardless of direction of travel) when the scope detects the warm moving object, the visitor count is recorded on the memory unit. Each pass-by event was date and time stamped accurate to the minute.

Track counters were installed in the first week of January 2009 at five walking tracks on Ross Island (Table 1). Track counters were hidden amongst mounds of rock material to prevent interference by track users (Figs. 3a, b). Care was taken to minimise counting errors by positioning the counters in areas out of direct sun strike, heavy snow accumulation, and at locations on the tracks where users were forced to walk in single-file. Counters were placed 1-3 m back from the track (well within the maximum detection distance of 6 m). A 1.5-second delay between counts was configured to ensure a single user could not be counted multiple times, or a slow user would not be double-counted. Data from the track counters were uploaded directly in the field onto a laptop via the TRAFx G3 Dock (TRAFx, Canmore, Canada), then imported into Microsoft Excel using the add-on TRAFx Reporter v7.1.

Table 1. Location of Ross Island track counters and general characteristics of the track counter site.

Track Counter	GPS location	Elevation (m)	Slope	Aspect	Dates of record
Hut Point Peninsula					
1. Scott Base-McMurdo Station	77° 50' 50.6" S, 166° 44' 52.0" E	77	3°	N	6.1.2009 - 31.1.2011
2. Up Observation Hill	77° 51' 04.5" S, 166° 41' 24.6" E	161	20°	SW	6.1.2009 - 31.1.2011
3. Round Observation Hill	77° 51' 07.7" S, 166° 42' 19.0" E	72	2°	NNE	7.1.2009 - 31.1.2011
4. Crater Hill Summit Track	77° 50' 38.7" S, 166° 45' 14.3" E	144	10°	NE	12.1.2009 - 15.1.2010
Cape Evans					
5. Wind Vane Hill	77° 38' 13.1" S, 166° 25' 09.3" E	15	15°	E	9.1.2009 - 31.1.2011

Track counters were calibrated by a series of tests and via direct observation in the field on two separate occasions in December 2009 and January 2010. Direct observations were recorded over an hour on a weekend day at each of the track counter locations (except at the Wind Vane Hill track due to inaccessibility) to check the accuracy of the automated visitor count. The calibration exercise was repeated approximately 6 weeks later. Visitor counts matched with direct observations on both occasions. It is possible that two people walking less than 1.5 seconds apart were counted as one. We therefore consider our results as best estimates of minimum counts. People using tracks that were one-way, up-and-back were counted twice. In this paper we report the track counter data as the number of passes on the track i.e. the number of counts, as our focus is the impacts which are a function of the number of passes along a track, and irrespective of the actual number of users.

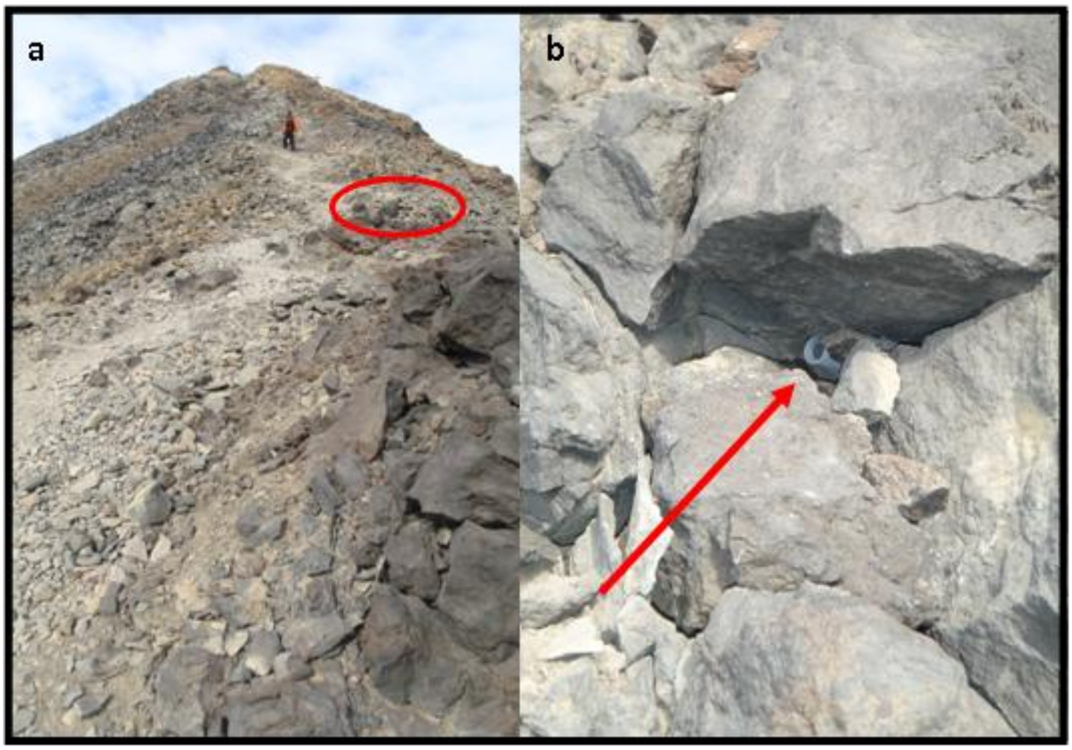

Fig. 3. The Up Observation Hill track counter (a) location of TRAFx counter (oval); (b) TRAFx track counter scope discretely hidden amongst rock (arrow).

Track survey

Impact indicators

A survey was undertaken where the extent and severity of selected impact indicators were assessed at three representative locations along each track. Evidence of track incision and track widening were measured and recorded in year one and year two to assess cumulative impacts from track use. Track incision was measured as the current incision below the original surface (i.e. the mean distance measured along a perpendicular transect of the walking track, including incision measurements of the middle and sides of the track).

As the study area is free of macro-vegetation, track width was defined as the area visibly affected by trampling (track incision), and with a visible colour difference between the track and surrounding undisturbed material. Track width and track incision were measured together at 15 locations along each track (5 replicates at the lower, less unconfined part of the track; 5 replicates at the upper, better confined part of the walking track; and 5 replicates at a mid-way point along the track, at the infrared track counter), and repeated in year two at the same sites, relocated using GPS.

Soil sampling

In 2009/2010 soil samples (about 500 g) were collected at depths of 0 to 2 cm and 2 to 5 cm at each of the walking tracks, and adjacent relatively undisturbed areas. Soil sampling took place at the track counter, 1 m down-track of the counter, and 3 m down-track of the counter. Where the substrate was not too rocky, soil bulk density measurements were undertaken using the sand replacement technique at the track counter and nearby control (two replicates at each). Soil samples were analysed for water content then air-dried and sieved to <2 mm size. Samples were analysed for soil pH, electrical conductivity (EC), and total phosphorus using standard methods (Blakemore and others 1987). Total organic carbon and nitrogen were determined in a LECO FP 2000 analyser at 1050°C (LECO, St Joseph's, Michigan).

Statistical analysis

Paired, two-tailed T-tests (Microsoft Excel v. 2007) were used to determine if there was a statistical difference between track width and incision values in year one and year two of the investigation. T-tests were also used to determine if soil physiochemical characteristics were statistically different between the walking track and adjacent control sites. The R^2 statistic was calculated to determine the relationship between track width, incision, track slope, and the number of passes recorded on the individual walking tracks.

Results

Track use monitoring

Over the 2-year monitoring period (Table 1) the total number of passes recorded on the Scott Base to McMurdo Station walking track were 5084; 10936 on the Up Observation Hill track; 3561 on the Round Observation Hill track; 693 on the Crater Hill summit track; and 2842 counts on the Wind Vane Hill track (Table 2). The Crater Hill track was monitored for only 52 weeks.

Annual counts (given as Year 1: calendar year from 1 Feb 2009 to 31 Jan 2010, and Year 2: calendar year from 1 Feb 2010 to 31 Jan 2011) are shown in Table 2. At all tracks the peak months were consistently November, December and January (Table 2; Fig. 4). In Year 1, track use in the summer months accounted for 67% of the total number of passes on the Scott Base to McMurdo Station track, 75% of the total counts on the Up Observation Hill track, 82% on the Round Observation Hill track, and 65% on the Wind Vane Hill Track. In Year 2 the proportion of total counts attributed to summer use increased at all tracks, to 84% at the Scott Base to McMurdo Station track, 86% at the Up Observation Hill track, 90% at the Round Observation Hill track, and 97% at the Wind Vane Hill track. The large increase in summer use at the Wind Vane Hill track can be attributed to the 2009 visitor season extending into the month of February and beginning in October in 2009, and starting later in 2010. Use declined at all tracks between late February and

March each year, and the Scott Base to McMurdo Station track was the only track regularly used over the winter (Fig. 4). Use began to rise again in October 2009 in Year 1, and early November 2010 in Year 2, again peaking in December and January of each year. There were differences in the level of weekday use, with the highest numbers of users recorded at the weekends and particularly on Sundays (Table 2). Other days when a high level of track use was recorded were Fridays and Saturdays..

Table 2. Track counter data showing the total number of passes between January 2009 and January 2011, total mean daily, peak daily, weekly and monthly counts, and mean daily counters during the summer months of November through January, on the five monitored Ross Island walking tracks.

Infrared Track Counter	**Scott Base-McMurdo Station**		**Up Observation Hill**		**Round Observation Hill**		**[4]Crater Hill**		**Wind Vane Hill**	
	Total	Summer	Total	Summer	Total	Summer	Total	Summer	Total	Summer
[1]Total Count	**5084**		**10936**		**3561**		**693**		**2842**	
[2]Annual Count Year 1 [3]Summer Count - '09-10	1562	1053	4666	3480	1135	936	693	-	1452	941
[2]Annual Count Year 2 [3]Summer Count - '10-11	2492	2096	4641	4013	1966	1767	-	-	1052	1024
Daily Mean Weekday:	5.5	16.5	13.6	26.1	3.9	13.5	2.6	4.7	3.7	11.7
Daily Mean Weekend:	9.8	28.6	16.7	31.4	6.7	22.1	5.2	4.4	4.9	17.6
Mean Monday	4.3	13.3	13.9	24.8	3.7	11.4	8.4	13.1	2.9	10.6
Mean Tuesday	6.4	19.2	17.7	32.6	3.5	10.5	2.0	3.0	8.4	24.2
Mean Wednesday	4.5	10.9	12.4	19.4	4.5	13.6	0.5	1.4	1	3.6
Mean Thursday	8.4	26.6	11.0	18.2	3.4	10.4	1.0	3.5	1.5	4.6
Mean Friday	4.0	12.5	12.9	18.4	4.6	14.6	0.9	2.6	4.6	16.0
Mean Saturday	6.7	20.9	15.3	38.7	6.7	20.1	1.5	5.4	3.8	13.5
Mean Sunday	12.9	36.3	18.2	52.8	6.7	22.3	8.9	3.4	6.1	21.7
Peak Month	Jan 2009 (1030)		Dec 2010 (1666)		Jan 2011 (767)		Jan 2009 (347)		Jan 2010 (483)	
Peak Week	13-19 Dec 2010 (236)		6-12 Dec 2010 (547)		22-28 Nov 2010 (180)		12-18 Jan 2009 (222)		21-27 Dec 2009 (373)	
Peak Day	28 Nov 2010 (96)		27 Nov 2010 (138)		28 Nov 2010 (74)		22 Sept 2009 (83)		22 Dec 2009 (373)	

[1]Total Count = total number of counts over the monitoring period, 6-12 Jan 2009 - 31 Jan 2011

[2]Annual Count Year 1 = Calendar year, 1 Feb 2009 - 31 Jan 2010; Annual Count Year 2 = Calendar year, 1 Feb 2010 - 31 Jan 2011

[3]Summer Count = 1 Nov - 31 Jan each year

[4]Crater Hill track counter in operation 12 Jan 2009 - 15 Jan 2010

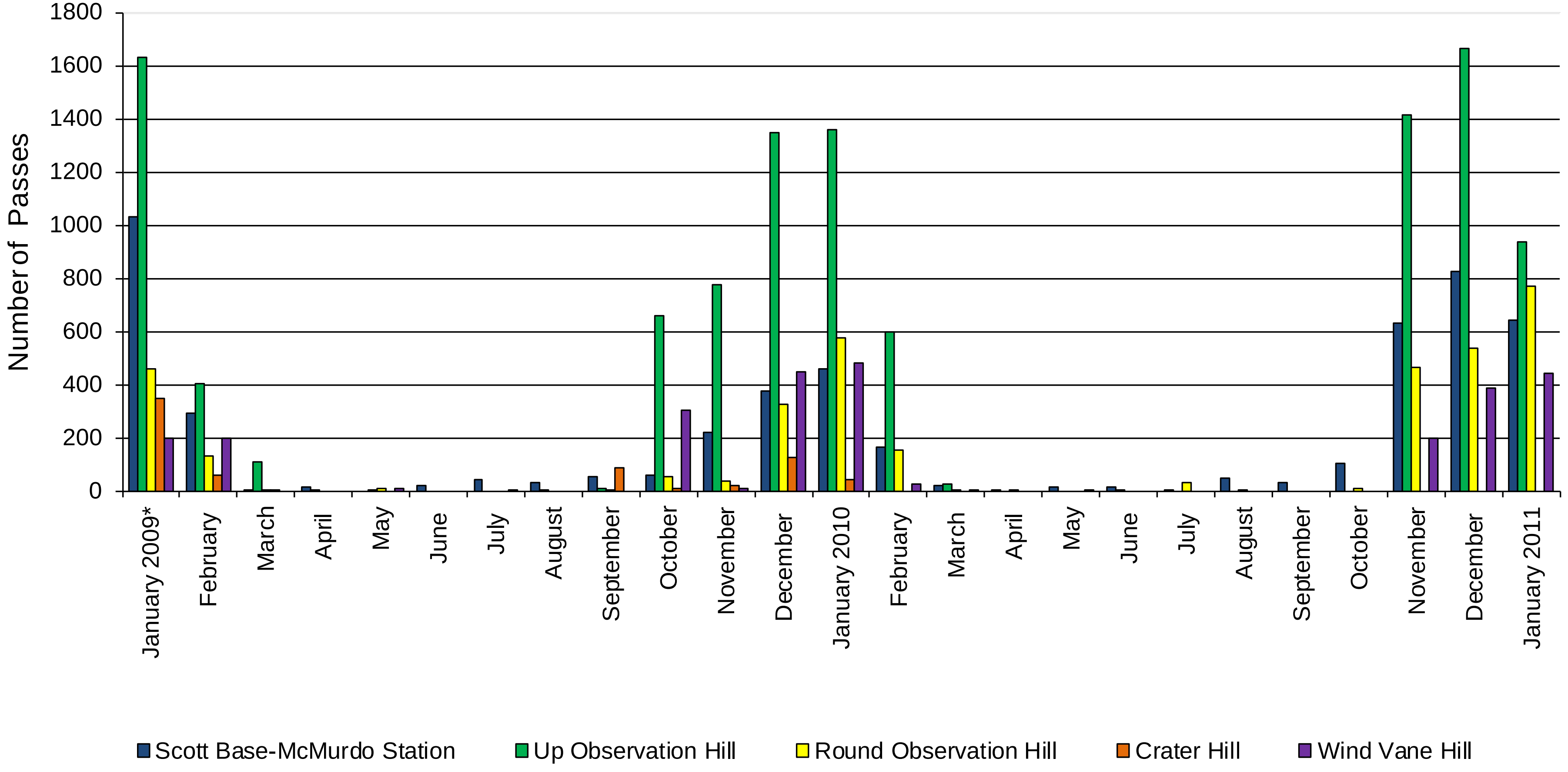

Fig. 4. Monthly counts at the five Ross Island walking tracks over the 2-year monitoring period, 6-12 Jan 2009 through 31 January 2011. *Incomplete data for January 2009 due to staggered installation of track counters.

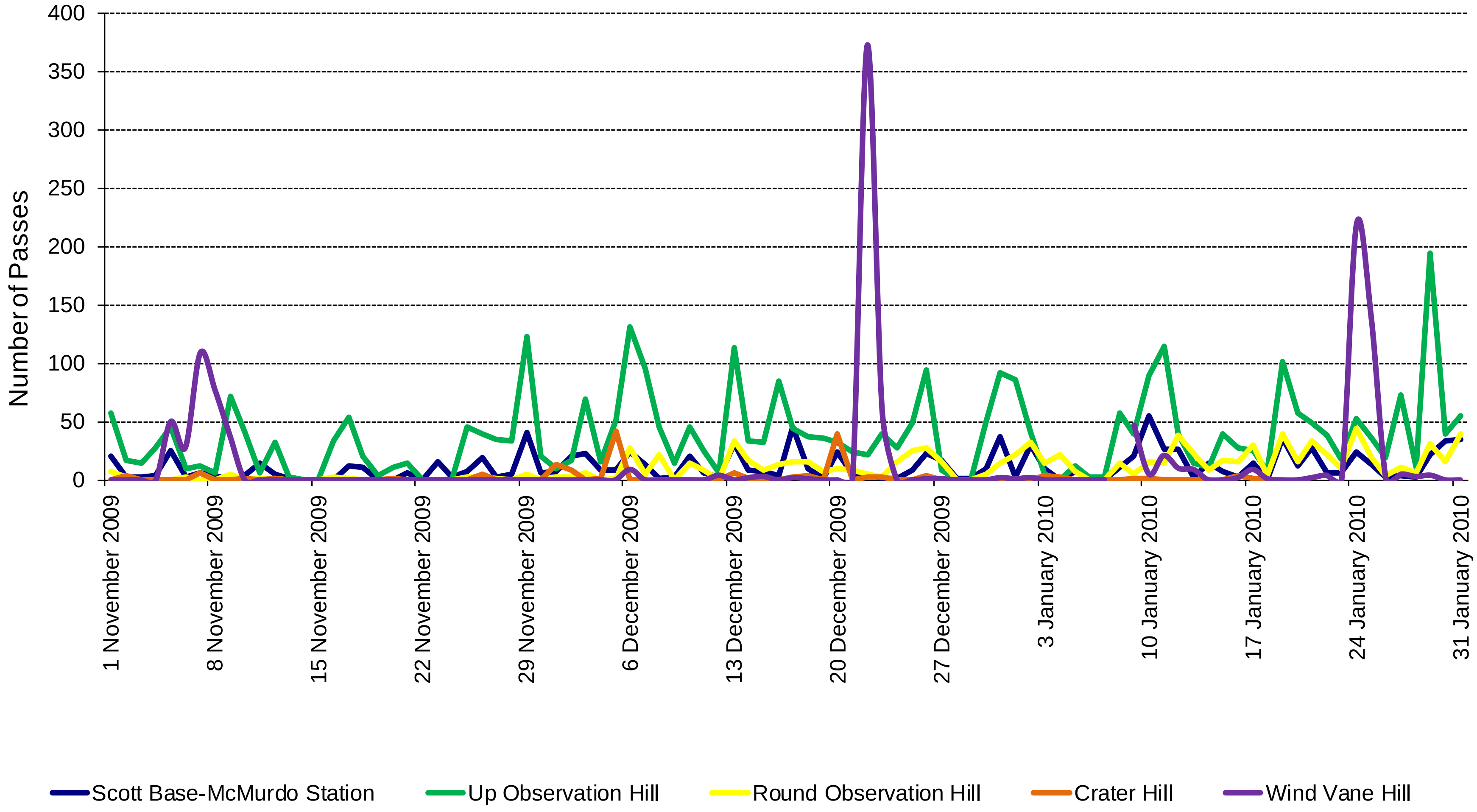

Fig. 5. Daily counts at the five Ross Island walking tracks during the 2009-2010 summer months, 1 November through to 31 January. *Wind Vane Hill peaks correspond to tourist ship visits on 22 December 2009 and 24 January 2010 (Table 3).

There were nine occasions during the 2-year monitoring period where counts at the Wind Vane Hill track exceeded 85 passes. The highest of these occurred on 22 December 2009 (373 passes) (Table 3). Early summer visitor number peaks in November and early December corresponded to recreation trips run for NZAP and USAP personnel (J. Newman, Environmental Advisor to Antarctica New Zealand, personal communication, 3 May 2012) (Fig. 5). Visitor number peaks occurring in late December, January, and February corresponded to Quark, Heritage, and Orion, expedition visits (Table 3) (tourism data *from* Antarctica New Zealand 2012).

Table 3. Peak days, track counter data, and visitor origin at the Wind Vane Hill walking track, Cape Evans.

Date	Track counter no. of passes	Visitor origin
24 February 2009	178	Heritage Expeditions (55 passengers)
7 November 2009	109	US/NZ personnel (Saturday)
22 December 2009	373	Quark Expeditions (122 passengers)
24 January 2010	219	Orion Expeditions (106 passengers)
14 November 2010	108	US/NZ personnel (Sunday)
21 November 2010	93	US/NZ personnel (Sunday)
28 November 2010	87	US/NZ personnel (Sunday)
20 December 2010	283	Quark Expeditions (120 passengers)
28 January 2011	94	Heritage in the Footsteps of Scott (59 passengers)

Track survey

Impact indicators

The Scott Base to McMurdo Station walking track was the widest of the five Ross Island walking tracks with a mean width of 1.23 m (average of Year 1 and Year 2), followed by the Round Observation Hill walking track at 1.21 m, and the Crater Hill walking track at 1.08 m wide (Table 4). The Wind Vane Hill (0.96 m) and Up Observation Hill (0.92 m) walking tracks were of a similar width. There was a significant change in track width across the two year monitoring period at the Crater Hill track and the lower Round Observation Hill track (Table 4). Track width increased in year two at lower, upper and track counter areas of the Crater Hill track ($p < 0.05$), and in the lower and less confined part of the Round Observation Hill track ($p < 0.05$).

Track incision ranged from 2 to 8 cm and there was little change in track incision over the monitoring period at all tracks except the Crater Hill walking track (Table 4). At the Crater Hill track counter site there was an increase ($p < 0.05$) in track incision from 5 cm below the original surface to 8 cm below the original surface in year two. The Round Observation Hill and Scott Base to McMurdo Station tracks have the lowest incision measurements (4 cm), whilst the Crater Hill upper track and upper part of the Up Observation Hill track had the highest, at 8 cm below the original surface. The average slope of the Scott Base to McMurdo Station track was 4°, Up Observation Hill track, 25°, the Round Observation Hill track, 2°, Crater Hill summit track, 12°, and the Wind Vane Hill track, 14° (Table 4).

Table 4. Track width, slope, and incision measurements of Ross Island recreational walking tracks, repeated over two consecutive years (summers of 2008/2009 and 2009/2010). Bolded values have p-values <0.05. *Width and incision measurements at the lower, upper, and track counter locations are means of five replicates.

		Year	Lower Track	Upper Track	Track Counter	Mean Std. Dev.	Overall Track Av.
SB to McM	**Track Width* (m)**	**Y1**	1.38	0.89	1.42	0.26	1.23
		Y2	1.40	0.85	1.45	0.29	1.23
	Track Incision* (m)	**Y1**	0.04	0.03	0.06	0.01	0.04
		Y2	0.04	0.04	0.06	0.01	0.04
	Track Slope (deg.°)		1-3	5-8	3	2.06	4
Up Observation Hill	**Track Width* (m)**	**Y1**	1.19	0.82	0.75	0.20	0.92
		Y2	1.21	0.81	0.75	0.21	0.92
	Track Incision* (m)	**Y1**	0.06	0.08	0.07	0.01	0.07
		Y2	0.07	0.08	0.07	0.01	0.07
	Track Slope (deg.°)		15-18	>35	20	10.20	25
Round Observation Hill	**Track Width* (m)**	**Y1**	**1.45**	1.20	0.94	0.22	**1.19**
		Y2	**1.50**	1.22	0.95	0.23	**1.22**
	Track Incision* (m)	**Y1**	0.03	0.03	0.04	0.01	0.04
		Y2	0.03	0.04	0.04	0.01	0.04
	Track Slope (deg.°)		1-3	1-3	2	0.78	2
Crater Hill	**Track Width* (m)**	**Y1**	**1.45**	0.64	**1.02**	0.34	**1.04**
		Y2	**1.55**	0.63	**1.15**	0.39	**1.11**
	Track Incision* (m)	**Y1**	0.02	0.07	**0.05**	0.02	0.05
		Y2	0.02	0.08	**0.08**	0.03	0.06
	Track Slope (deg.°)		2-5	20-25	10	8.47	12
Wind Vane Hill	**Track Width* (m)**	**Y1**	1.03	0.95	0.90	0.06	0.96
		Y2	1.05	0.95	0.92	0.07	0.97
	Track Incision* (m)	**Y1**	0.05	0.05	0.05	0.00	0.05
		Y2	0.05	0.05	0.05	0.01	0.05
	Track Slope (deg.°)		10-12	15-18	15	2.50	14

Soil sampling

Gravimetric water content was low to moderate and increased with depth from 1-7% at 0-2 cm to 2-12% at 2-5 cm depth (Table 5). The control samples of all tracks (except Wind Vane Hill), tended to have higher water contents than the track samples. Comparatively high moisture contents in the Round Observation and Up Observation Hill track and control sites were likely to be due to sampling taking place shortly after a snowfall event.

Soil samples were strongly alkaline (pH 8.4 – 9.7) and soil pH showed some increases with depth but was not consistent across all walking tracks. The Scott Base to McMurdo Station, Round Observation Hill, and Crater Hill walking tracks were more alkaline than the Wind Vane Hill and Up Observation Hill walking tracks.

Electrical conductivity (EC) was variable between tracks, controls, and with depth, and ranged between 0.04 mS/cm to 1.05 mS/cm (Table 5). EC was highest in the top 2 cm of all tracks and control samples and decreased with depth. EC was consistently higher in the top 2 cm of the control samples at four of the five walking tracks (ranging from 0.14 mS/cm to 1.05 mS/cm); with the exception of the Up Observation Hill walking track, where it was noted on sampling that natural salts were concentrated on the track and not the control.

The organic C content was low (0.02% to 0.11%) in all tracks and controls. There was no change in organic C within the top 5 cm of soil. Total N was consistently very low (0 – 0.02%) in all samples and depths. C:N ratios were low and ranged between 3 and 19. Track and control samples had similar C:N ratios, however, the Up Observation Hill track samples had higher C:N ratios (C:N of 19) compared with the adjacent control samples (C:N of 7). Total P ranged from 510 mg/kg to 1221 mg/kg and was highest in the Scott Base to McMurdo Station track and control, and lowest in the Up Observation Hill track and control. There was no consistent change in total P with depth, or difference between track and control samples. Soil dry bulk density ranged from 1.01 g/cm^3 to 1.74 g/cm^3 (Table 5).

T-tests showed no significant differences between the measured physiochemical properties of a track and adjacent control samples, except for bulk density ($p < 0.05$). The walking tracks had a higher dry bulk density than the adjacent control sites, except at Crater Hill where bulk density was about the same in the track and control (Table 5).

Table 5. Soil physiochemical characteristics at track counter sites on the Ross Island walking tracks. *EC = electrical conductivity. Measurements are the mean of three samples (at the track counter, 1 m and 3m down track of the counter).

Walking Track	Water Content (% dry wt)	Soil pH (water)	Soil EC* (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)	Bulk Density (g/cm^3)
Scott Base-McMurdo - Track								
0-2 cm	3.3	9.7	0.18	0.05	0.01	7	1156	
Standard Deviation	1.6	0.1	0.04	0.01	0.00	1	128	
2-5 cm	6.1	9.7	0.12	0.05	0.01	6	1117	1.32
Standard Deviation	1.0	0.0	0.00	0.00	0.00	0	72	0.08
Scott Base-McMurdo - Control								
Desert Pavement-2 cm	2.4	9.4	0.77	0.10	0.02	6	1131	
Standard Deviation	0.4	0.4	0.11	0.01	0.00	0	144	
2-5 cm	3.7	9.6	0.40	0.11	0.02	7	1221	1.01
Standard Deviation	0.5	0.1	0.01	0.01	0.00	0	129	0.09
Up Ob Hill - Track								
0-2 cm	3.5	8.9	0.22	0.03	0.00	18	510	
Standard Deviation	0.5	0.2	0.08	0.00	0.00	7	37	
2-5 cm	6.0	8.8	0.11	0.03	0.00	19	549	
Standard Deviation	0.9	0.1	0.01	0.00	0.00	12	92	-
Up Ob Hill - Control								
Desert Pavement-2 cm	6.7	8.5	0.04	0.08	0.01	7	703	
Standard Deviation	0.7	0.1	0.01	0.00	0.00	0	96	
2-5 cm	6.6	8.4	0.03	0.05	0.01	9	681	
Standard Deviation	0.7	0.0	0.00	0.00	0.00	0	114	-
Round Ob Hill -Track								
0-2 cm	7.1	9.0	0.04	0.03	0.00	8	899	
Standard Deviation	0.9	0.0	0.00	0.00	0.00	3	155	
2-5 cm	10.4	9.0	0.04	0.04	0.01	8	1068	1.74
Standard Deviation	0.6	0.0	0.00	0.00	0.00	2	110	0.21
Round Ob Hill - Control								
Desert Pavement-2 cm	7.7	9.6	0.28	0.05	0.01	8	1047	
Standard Deviation	0.1	0.0	0.00	0.01	0.00	1	100	
2-5 cm	11.7	9.3	0.10	0.05	0.01	9	1009	1.08
Standard Deviation	1.3	0.0	0.01	0.00	0.00	0	47	0.09
Crater Hill - Track								
0-2 cm	1.0	9.4	0.16	-	-	-	-	
Standard Deviation	0.0	0.0	0.01	-	-	-	-	
2-5 cm	3.0	9.5	0.09	-	-	-	-	1.51
Standard Deviation	0.1	0.0	0.01	-	-	-	-	0.10
Crater Hill - Control								
Desert Pavement-2 cm	1.9	9.6	1.05	-	-	-	-	
Standard Deviation	0.0	0.1	0.02	-	-	-	-	
2-5 cm	4.2	9.4	0.49	-	-	-	-	1.54
Standard Deviation	0.1	0.1	0.03	-	-	-	-	0.08
Wind Vane Hill - Track								
0-2 cm	2.8	9.1	0.16	0.02	0.01	3	763	
Standard Deviation	0.5	0.2	0.05	0.00	0.00	1	91	
2-5 cm	5.2	9.3	0.05	0.02	0.01	4	845	1.21
Standard Deviation	0.3	0.0	0.00	0.00	0.00	1	225	0.11
Wind Vane Hill - Control								
Desert Pavement-2 cm	1.9	9.2	0.14	0.01	0.00	3	669	
Standard Deviation	0.2	0.1	0.02	0.00	0.00	1	106	
2-5 cm	3.7	8.9	0.09	0.02	0.01	5	632	1.11
Standard Deviation	0.3	0.3	0.04	0.01	0.00	3	164	0.10

Discussion

Recreational walking track users

Annual data showed a higher number of users on all tracks in the 2010/2011 season, compared with the 2009/2010 season, which is likely the result of increased promotion of the walking tracks (and onlookers taking interest in the Crater Hill wind turbines installation) as well as an higher tourist numbers and increased national programme visits to Cape Evans (Table 2). Personnel working at Scott Base and McMurdo Station, number up to 1200 individuals over the summer months, were responsible for the majority of user counts at all tracks except the Wind Vane Hill walking track, where peaks corresponded to the arrival of tourist ships (i.e. 122 passengers from Quark Expeditions on 22 December 2009, Antarctica New Zealand 2012). Winter spikes in daily counts (e.g. on 9 July 2010 at the Round Observation Hill track) (Fig. 4) may represent an special event, such as a fun-run, organised by either base. Tourists also visited Scott Base, McMurdo Station, Discovery Hut, and walked up Observation Hill as part of their cruise itinerary. However, they are likely to have represented only a small proportion of the total user counts on the Observation Hill tracks. Tourists were not likely to have sufficient time to walk along the Crater Hill summit track, nor was it advertised by the tour operators.

All tracks, except the Scott Base to McMurdo Station track, showed a decrease in users over winter, coinciding with the absence of tourists and a decrease in the number of personnel working at Scott Base and McMurdo Station. Access was available to all tracks over the winter months, although both USAP and NZAP required users to travel in pairs and carry a radio, and the cold could have deterred some individuals. It is possible that some of the track counter sites were intermittently covered in snow over the winter months. Track counter sites were checked regularly by Scott Base winter science support and cleared if necessary.

Track characteristics

Track width and incision measurements showed tracks traversing flat or gently sloping surfaces, such as the Scott Base to McMurdo Station and Round Observation Hill tracks, tended to be wider ($R^2 = 0.85$), and have a smaller degree of track incision ($R^2 = 0.96$), compared with tracks on steeper slopes (Table 2). Past studies report that tracks with slopes of > 10 degrees are susceptible to erosion (Bratton and others 1979; Sun and Liddle 1993a,b; Marion and Olive 2006) as foot slippage on steep slopes causes track deepening (Sun and Liddle, 1993a). The Up Observation Hill walking track was the narrowest, and the level of track incision increased as the slope of the track increased from 15º in the lower reaches, to 20º at the mid-point (location of the track counter), and up to 35º in the upper reaches of the track (Table 4). Increased incision with increasing slope also occurred on the Crater Hill summit walking track ($p < 0.05$). On the longer established walking tracks, such as the Up Observation Hill and Scott Base to McMurdo Station tracks, track width and incision were consistent between year one and year two measurements, indicating that the walking tracks were in a steady state at time of sampling, and at the current intensity of use. The more recently flagged Round Observation Hill, and Crater Hill walking tracks, however, showed increases in track width at the lower, less confined reaches of the track, and in the case of the Crater Hill walking track, increases in track incision in year two of the study (Table 4).

We observed mountain bike skid marks on the Scott Base to McMurdo Station track and the Round Observation Hill walking track. Studies have shown that impacts from mountain bikes include track widening, erosion from skidding, linear rut development, and increased soil compaction (Wilson and Seney 1994; Chiu and Kriwoken 2003; Olive and Marion 2009; Pickering and others 2010). Although previous studies show no evidence of mountain bike impacts to soils being greater than the impacts of pedestrian traffic (Wilson and Seney 1994; Olive and Marion 2009), when ridden fast with heavy braking, on the relatively unconsolidated and bouldery material comprising Ross Island, and on steeper gradients, impacts may be greater than recreational walkers.

Moss and lichen were observed approximately 2 m off the Scott Base to McMurdo Station track and have also been observed on Crater Hill (J. Newman, Environmental Advisor to Antarctica New Zealand, personal communication, 3 May 2012). The current Crater Hill summit track crosses through a vegetated area of mosses and lichen and there has been recent disturbance to the vegetation.

Intensity of use relationships

Under the trampling intensities experienced on the Ross Island walking tracks there were no significant relationships between the number of users and measured impact indicators nor any differences in the soil physiochemical properties, except bulk density, between walking tracks and control sites. It is apparent that the slope of the terrain had the greatest influence on the track width and level of track incision, given that all sites comprise of similar scoriaceous basalt parent material. At all walking tracks, except the relatively recently established (and promoted) Crater Hill walking track and the lower less confined and also recently flagged Round Observation Hill walking track, there were no significant differences between the measured impact indicators in year two of the investigation implying that current user intensities are not causing cumulative impacts in the measured parameters. Differences in soil physiochemical properties between the tracks and controls fall within the natural spatial variability that is common to soils in the Ross Sea region. Bulk density measurements were consistently higher in the near surface soil on walking tracks than the adjacent control sites ($p < 0.05$), but there was no significant relationship between bulk density measurements and the number of track users.

Application and future research

Conservation management in Antarctica is a balance between the protection of natural and historic integrity of the site, while simultaneously allowing the use of the area for science, recreation, and tourism (Cessford and Thompson 2002). Campbell and others (1998a) showed that the unconsolidated nature of the Ross Sea region 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 levels of use. For this reason we recommend that recreational users should continue to use pre-existing tracks, and that the current tracks remain to concentrate visible impacts.

Given the vegetation found in the vicinity of the Crater Hill summit track, it may be advantageous to re-route the track away from the vegetation. The young age and minimal development of the lower part of the Crater Hill summit track, if abandoned, will quickly recover, aesthetically, to resemble the surrounding undisturbed landscape.

The walking tracks investigated in this study were limited to tracks on scoriaceous basalt parent material in relatively moist (by continental Antarctic standards) climatic conditions. In order to better understand cumulative physical and visual impacts it would be advantageous to carry out similar track assessment studies in areas under different climate regimes and parent materials.

Previous experimental trampling studies by Tejedo and others (2005, 2009) in the maritime Antarctic South Shetland Islands, and Campbell and others (1998a) in the vicinity of Scott Base and Lake Vanda in the McMurdo Dry Valleys, showed changes in the biophysical characteristics of soil (such as increased soil resistance to compression, and decreased arthropod abundance), and track width, and track surface colour, under increased trampling intensities. A complementary study into differences in microbial populations between walking tracks and adjacent undisturbed control sites would complement this research.

Conclusions

The objective of this research was an increased understanding of the number of people using the Ross Island recreational walking tracks, and to investigate the relationships between the number of users and track soil physiochemical and morphological characteristics.

Over the 2-year monitoring period 5084 passes were recorded on the Scott Base to McMurdo Station walking track, 2842 counts on the Wind Vane Hill walking track, 3561 on the Round Observation Hill walking track, 10936 passes were recorded on the Up Observation Hill track, and 693 counts were recorded on the Crater Hill summit walking track. Annual data showed higher counts on all tracks in the 2010/2011 season, compared with the 2009/2010 season, and that the highest frequency of visitors occurred on Sundays in the summer months, November through January. The Scott Base to McMurdo Station track is used continuously throughout the year. Peak daily counts at the Wind Vane Hill track coincided with the arrival of tourist ships, whereas Scott Base and McMurdo Station personnel were responsible for the peaks in traffic at the other four walking tracks in the vicinity of the stations.

There was no relationship between the number of passes on the track and the measured impact indicators indicating that higher usage of a formed track had little cumulative impact. Track width and incision were related to the slope of the terrain, with tracks traversing flatter areas generally wider ($R^2 = 0.85$) and less incised ($R^2 = 0.96$) than those traversing steeper hillsides. Soil sampling of walking tracks and adjacent control material revealed no significant differences between the measured soil physiochemical properties, except soil bulk density. An increase in soil bulk density ($p < 0.05$) was observed in the walking tracks compared with adjacent less disturbed control material and is likely to be a direct result of footfall causing compaction of the near surface soil.

Compared with other parts of the world the level of recreational use experienced on the Ross Island walking tracks is low. However, previous studies in the Ross Sea region have shown that due to the unconsolidated nature of the surface materials, it takes as little as 20 passes on a surface for a track to form. For this reason we recommend that recreational users should continue to use pre-existing tracks to concentrate visible impacts.

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References

Aislabie, J.M., M.R. Balks, J.M. Foght, and E.J. Waterhouse. 2004. Hydrocarbon spills on Antarctic soils: Effects and management. *Environmental Science & Technology* 38 (5): 1265-1274.

Antarctica New Zealand, 2012. Preliminary tourism data. Unpublished, Antarctica New Zealand.

Ayres, E., J.N. Nkem, D.H. Wall, B.J. Adams, J.E. Barrett, E.J Broos,. and R.A. Virginia. 2008. Effects of Human Trampling on Populations of Soil Fauna in the McMurdo Dry Valleys, Antarctica. *Conservation Biology* 22(6): 1544-1551.

Balks, M.R., R.F. Paetzold, J.M. Kimble, J. Aislabie, and I.B. Campbell. 2002. Effects of hydrocarbon spills on the temperature and moisture regimes of Cryosols in the Ross Sea region. *Antarctic Science* 14(4): 319-326.

Blakemore, L.C., P.L. Searle, and B.K. Daly. 1987. *Methods for chemical analysis of soils.* New Zealand Soil Bureau Scientific Report 80, Wellington, New Zealand.

Bockheim, J.G. 1997. Properties and classification of cold desert soils from Antarctica. *Soil Science Society of America Journal* 61(1): 224-231.

Bratton, S.P., M.G. Hickler, and J.H. Graves. 1979. Trail erosion patterns in Great Smoky Mountains National Park. *Environmental Management* 3: 431-445.

Campbell, I.B., and G.G.C. Claridge. 1975. Morphology and age relationships of Antarctic soils. In: Suggate, R.P., and M.M. Cresswell (editors). *Quaternary Studies*. Royal Society of New Zealand Bulletin 13: 87–88.

Campbell, I.B., and G.G.C. Claridge. 1987. *Antarctica: soils, weathering processes and environment.* Amsterdam: Elsevier (Developments in Soil Science 16). pp. 368.

Campbell, I.B., G.G.C. Claridge, D.I Campbell, and M.R. Balks. 1998a. The soil environment of the McMurdo Dry Valleys, Antarctica. *Antarctic Research Series* 72: 297-322.

Campbell, I.B., G.G.C. Claridge, D.I. Campbell, and M.R. Balks. 1998b. Soil temperature and moisture properties of cryosols of the Antarctic cold desert. *Eurasian Soil Science* 31(5): 542-546.

Cessford, G., and A. Thompson. 2002. Managing tourism in the New Zealand protected area system. *Parks* 12 (1): 26-36.

Chiu, L., and L. Kriwoken**.** 2003. Managing recreational mountain biking in Wellington Park, Tasmania, Australia. *Annals of Leisure Research* 6 (4). pp. 339-361.

Gremmen, N.J.M., V.R. Smith, and O.F.R. van Tongeren. 2003. Impact of trampling on the vegetation of subantarctic Marion Island. *Arctic Antarctic and Alpine Research* 35(4): 442-446.

Hammitt, W.E., and D.N. Cole. 1998. *Wildland recreation: ecology and management* (second edition). New York: John Wiley and Sons.

Hill, W.M., and C.M. Pickering. 2009. *Ecological impacts of walking tracks in protected areas and comparison of methods and indicators for assessment of track condition.* Technical Report. Sustainable Tourism CRC, Griffith University.

IAATO, 2011. Tourism statistics. http://iaato.org/tourism-statistics. Accessed 4 November 2011.

Kennicutt, M. C., A. Klein, P. Montagna, S. Sweet, T. Wade, T. Palmer, and G. Denoux. 2010. Temporal and spatial patterns of anthropogenic disturbance at McMurdo Station, Antarctica. *Environmental Research Letters* 5(3): 1-10.

Leung, Y-F and J.L. Marion. 2000. *Recreation impacts and management in wilderness: a state of knowledge review.* USDA FS Proceedings Rocky Mountains Research Station P–15– Vol 5.

Liddle, M.J. 1997. *Recreation ecology.* London: Chapman and Hall.

Marion, J.L., Y-F. Leung, and S. Nepal. 2006. Monitoring trail conditions: new methodological considerations. *The George Wright Forum* 2: 36–49.

Newsome, D., S.A. Moore, and R.K. Dowling. 2002. *Natural area tourism: ecology, impacts and management*. Sydney: Channel View Publications.

Olive, N.D., and J.L. Marion. 2009. The influence of use related, environmental, and managerial factors on soil loss from recreational trails**.** *Journal of Environmental Management*. 90: 1483-1493.

Pickering, C.M., W Hill, D. Newsome, and Y-F. Leung. 2010. Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. *Journal of Environmental Management* 91:551-562.

Scott, J.J., and J.B. Kirkpatrick. 1994. Effects of human trampling on sub-Antarctic vegetation of Macquarie Island. *Polar Record* 30: 207–220.

Soil Survey Staff, 2010. *Keys to soil taxonomy*(tenth edition). United States Department of Agriculture, Natural Resources Conservation Service, Washington, D.C.

Sun, D., and M.J. Liddle. 1993a. A survey of trampling effects on vegetation and soil in eight tropical and subtropical sites. *Environmental Management* 17 (4): 497-510.

Sun, D., and M.J. Liddle. 1993b. Plant morphological characteristics and resistance to simulated trampling. *Environmental Management* 17 (4): 511-521.

Tejedo, P., A. Justel, E. Rico, J. Benayas, and A. Quesada. 2005. Measuring impacts on soils by human activity in an antarctic special protected area. *Terra Antarctica* 12: 57–62.

Tejedo, P., A. Justel, J. Benayas, E. Rico, P. Convey, and A. Quesada. 2009. Soil trampling in an Antarctic Specially Protected Area: tools to assess levels of human impact. *Antarctic Science* 21(3): 229-236.

Tin, T., Z.L. Fleming, K.A. Hughes, D.G. Ainley, P. Convey, C.A. Moreno, and I. Snape. 2009. Impacts of local human activities on the Antarctic environment. *Antarctic Science* 21(1): 3-33.

United States Department of Agriculture, 2010. Scott Base climate station statistics. http://soils.usda.gov/survey/smst/antarctica/ScottBase/2010/. Accessed 12 May 2012.

Waterhouse, E.J. (editor). 2001. *Ross Sea Region 2001: a State of the Environment Report for the Ross Sea Region of Antarctica.* New Zealand Antarctic Institute, Christchurch.

Wilson, J.P., and J.P. Seney. 1994. Erosional impact of hikers, horses, motorcycles, and off-road bicycles on mountain trails in Montana. *Mountain Research and Development* 14(1), 77-88.

Additional Notes:

A preliminary investigation into the differences in microbial community structure between the Ross Island walking tracks and adjacent undisturbed control sites has been undertaken using microbial DNA profiling by terminal restriction fragment length polymorphism (TRFLP) (methods described in Chapter 6).

Provisional ordination results indicate there may be some clustering of TRFs within the ordination space by treatment (i.e. track versus control), however it is neither simple nor consistent between tracks and between site differences in significant soil parameters seem to have an overriding effect on TRF clustering.

8 DISCUSSION AND CONCLUSIONS

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8.1 Introduction

Under the broad aim of investigating impacts and soil recovery following physical soil disturbance due to human activity, five research objectives were addressed in this thesis. The principal findings of each thesis chapter are summarised below. This chapter closes with a synthesis including a discussion of the management implications arising from this thesis, environmental management applications that have already resulted, the limitations of my study, and recommendations for further research.

8.2 Summary of main conclusions

8.2.1 Environmental Impact Assessment effectiveness (Chapter 3)

Objective one was to investigate the effectiveness of the current Environmental Impact Assessment (EIA) system with respect to managing the effects of visitor activity in the Ross Sea region of Antarctica. Objective one was met by investigating five case studies, whereby the present state of the sites were assessed using visual site assessment methods (modified from Campbell et al. 1993 and Kiernan & McConnell, 2001), and a comparison was made between the predicted impacts set forth in the EIA and the actual impacts on the ground. All five case studies demonstrated a high level of consistency between EIA-predicted impacts and actual impacts, appropriate remediation of sites post-event, and follow-up monitoring. Additional key findings are listed below.

- The greatest benefit of the EIA system is raising environmental awareness (or the obligation to abide by EIA promises of keeping away from a sensitive area, for example). On the exterior the EIA process may appear superficial with a lot of generic form-filling, however, while relatively short on detail they are sufficient in motivating visitors to take responsibility for their “footprint” on the environment.

- The Loop Moraine field camp site illustrated the differences in recovery rates of confined tracks and randomly trampled sites. Where the EIA impacts were predicted to be ‘less than minor and transitory’, evidence of the campsite itself was undetectable, but the well-used tracks to and from the campsite were visible five years on.
- Cleanup practices were of a high standard. Where the raking out of tracks, redistribution of disturbed stones, and careful backfilling of excavations, had occurred, former occupation was almost undetectable. At the Loop Moraine field camp, in hindsight the group may have chosen to either rake out formed tracks, or walk to their experimental sites and the toilet facilities in a random and widespread fashion, avoiding the formation of confined walking tracks.
- The VISTA (Visitor Site Assessment Scheme) implemented by Antarctica New Zealand, attempts to address cumulative impacts and provide ongoing monitoring in the Taylor Valley Visitor Zone by building baseline information on recovery between tourist seasons. VISTA photo-replication revealed that the colour contrast between the walking tracks and the adjacent control persisted between seasons, however, was less pronounced after the site had a winter to recover; implying that some surface recovery occurs between tourist seasons.
- EIA follow-up investigations are often a neglected element of the EIA process. Effort should be made to systematically carry out evaluations on a regular basis to ensure the EIA process is effective.

8.2.2 Desert Pavement Recovery Assessment method (Chapter 4)

Objective two was to develop a reproducible, field-based method to assess desert pavement recovery following physical disturbance. To meet this objective a simple Desert Pavement Recovery Assessment method (DPRA) was formulated (Chapter 4), and moves beyond previous methods that assess the degree of impact (Campbell et al. 1993). The DPRA is based on a set of 11 criteria which were identified to change as a pavement recovers. The DPRA method was tested on 54 disturbed sites in the Ross Sea region, across a variety of parent materials, landforms, and climates. The key outcomes are summarised below.

- Eleven morphological features (termed recovery criteria), were identified to change over time as a desert pavement recovers from disturbance, and included: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development.
- Recovery criteria were assigned a severity rating on a scale from zero to four, and the Mean Recovery Index (MRI) of the site was calculated relative to an equivalent control. Overall recovery stages were defined as recently or highly disturbed (MRI of 0-24%), incipient pavement (MRI of 25-49%), intermediate recovery (MRI of 50-74%), advanced recovery (MRI of 75-99%), and indistinguishable from control site (MRI = 100%).
- Fifty of the 54 sites investigated were in an intermediate or higher stage of desert pavement recovery (i.e. MRI > 50%), 30 sites were in an advanced stage of recovery (i.e. MRI > 75%), and four sites were indistinguishable from adjacent control sites (MRI = 100%).
- Five recovery criteria proved the most useful in determining the Mean Recovery Index of the sites investigated. They were: embeddedness of surface clasts, impressions of removed clasts, % overturned clasts, armouring per m^2, and colour contrast between the disturbed and control desert pavement sites.

- Active surfaces, such as gravel beach deposits, aeolian sand, and alluvial fan deposits, recovered relatively quickly and had higher MRIs, whereas less active sites of higher intensity disturbances, such as the bulldozed tracks at Marble Point had lower MRIs, and showed only intermediate recovery 20 to 30 years after disturbance.
- Sites where desert pavements had been disturbed by randomly dispersed footprints, recovered to be undetectable (MRI = 100%) within five years, whereas sites with formed tracks resulting from repeated trampling, had lower MRIs (MRI = 82%).
- Raking to re-contour tracked areas, such as the ice-free storage area at Cape Roberts, led to an advanced stage of desert pavement recovery within 10 years (MRI = 91%).
- The DPRA field-based method provided reproducible methods that give semi-quantitative results for assessing environmental impacts of human activities. The method was formulated to be a tool which can be used to advance environmental management in the Ross Sea region of Antarctica and allow different operators to have a reasonably replicable outcome.

8.2.3 Visual recovery following foot and vehicle traffic (Chapter 5)

Objective three was to investigate the visual recovery of the desert pavement following impacts from human trampling and vehicle traffic (Chapter 5). Objective three was two-fold; the second aim was to address the long-standing question: what has the greatest visual impact, single file pedestrian movements which form a "track" or footprints being spread randomly over a wider area. To meet objective three previously disturbed and nearby control sites were assessed using comparative photo-records, and two field-based techniques: the Visual Site Assessment of Campbell et al. (1993), and the Desert Pavement Recovery Assessment (Chapter 4). Contrary to previous researchers who concluded that most visual disturbances persist in the landscape for decades to potentially hundreds of years (Campbell & Claridge, 1987; Campbell et al. 1993, 1998a), overall extent of visual surface recovery from the physical impacts of foot and vehicle traffic was higher than anticipated. Key findings are listed below.

- Eleven of the 12 study sites (all except the Taylor Valley Visitor Zone walking track) had a Mean Recovery Index (MRI) greater than 50%. Sites showing the greatest visual differences in desert pavement compared to an undisturbed control were the steep walking track in the Taylor Valley Visitor Zone (MRI = 39%) and the 1957/58 bulldozer cut surface at Marble Point (MRI = 51%). Highest MRIs were: the former tent site at the Loop Moraine (MRI = 100%, indistinguishable from the control site) and the vehicle track crossing periodically saturated ground at Marble Point (MRI = 98%).
- Concentrating activity on more resilient parent materials, such as bouldery or bedrock surfaces, like those at the former Vanda Station site (MRI = 90%), and the Vanda *Rocky* treading trial site (MRI = 96%), lessens visible impacts to the environment.
- Walking in patterned ground cracks (as is practised by visitors to the Taylor Valley Visitor Zone) minimised impacts on stable desert pavement surfaces and should be undertaken where practicable;
- Formed walking tracks, such as the tracks at the Loop Moraine, and Vanda treading trial tracks, remained visible in the landscape due to the persistence of larger rocks and loose material concentrated at the outer margins of the walking track. However, randomly dispersed footprints on surfaces were often recovered to be undetectable within five years.
- Widespread, dispersed trampling around one-off campsites is recommended to minimise the overall visible impact in the medium term.
- At steep sloped sites, and sites where repeated visits occur, such as the Taylor Valley Visitor Zone, the use of a single confined walking track is recommended.
- Site remediation activities, including replacing larger moved stones back in their original positions, ensuring that surface stones are

placed with the weathered side up, and raking of gravel sand-sized displaced materials, can all be effective at enhancing the rate and degree of visual surface recovery.

- Remedial activities such as raking should only be carried out on areas that have been disturbed already, where there is gravelly sand materials which lack a strongly developed desert pavement.
- Consideration must be given to ensure that the overall environmental effects of the remediative activities do not cause more impact than they cure, particularly with respect to potential impacts on microbial communities.

8.2.4 Changes to bacterial community structure following simulated soil surface disturbance (Chapter 6)

Objective four was to investigate the short-term effects of human disturbance on soil bacterial community structure at an experimental site near Scott Base (Chapter 6). Three blocks, each comprising an undisturbed control, and an area disturbed by removing the top 2 cm of soil, were sampled over a time series (Day 0, 7, 14, 21, and 35), and the bacterial community structure was determined using microbial DNA profiling by terminal restriction fragment length polymorphism (TRFLP). Key findings are listed below.

- 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.
- TRFLP analysis revealed that the soil replicate blocks supported distinct bacterial communities; and the composition of communities reflected the different spatial variability in soil physiochemical properties of the blocks.
- Soil electrical conductivity ($R^2 = 0.55$) and soil pH ($R^2 = 0.67$) strongly correlated with TRFLP patterns and can be inferred as the most important factors controlling bacterial composition at the study site.

- Our data highlights the importance of local scale heterogeneity in structuring soil bacterial communities, and that distinct communities are possible within 2 m of one another, and within the same landscape unit.
- Given the current knowledge of the drivers of bacterial community structure, i.e. soil EC, soil pH, and soil moisture content, we expect a disturbance of sufficient intensity to affect those properties mentioned, will cause a shift in bacterial community structure, over and above the time frame measured in this experiment.
- A more rigorous follow-up investigation incorporating DNA and RNA-based analyses over a time frame of 2-3 years would lead to a greater understanding of the effects of soil disturbance on bacterial communities.

8.2.5 Ross Island recreational walking tracks (Chapter 7)

Objective five was to investigate the number of people using the Ross Island recreational walking tracks, and examine the relationships between the numbers of users, track morphological characteristics, and soil physiochemical properties (Chapter 7). In order to meet objective five infrared track counters were installed on five walking tracks on Ross Island. On each monitored walking track, track width and track incision, were measured, and soil sampling in the vicinity of the track counter and an adjacent control site was undertaken. Two years of data were obtained from each walking track with outcomes summarised below.

- Between January 2009 and January 2011 5084 passes were recorded on the Scott Base to McMurdo Station walking track, 2842 on the Wind Vane Hill walking track, 3561 on the Round Observation Hill walking track, 10936 on the Up Observation Hill track, and 693 on the Crater Hill summit walking track (one year record on Crater Hill).
- Annual data showed higher counts on all tracks in the 2010/2011 season, compared with the 2009/2010 season, and the highest

frequency of visitors occurred on Sundays in the summer months, November through January.

- The Scott Base to McMurdo Station track was used throughout the year.
- Peak daily counts at the Wind Vane Hill track coincided with the arrival of tourist ships, whereas Scott Base and McMurdo Station personnel were responsible for the peaks in traffic at the other four walking tracks in the vicinity of the stations.
- There was no relationship between the number of passes on the track and the measured impact indicators indicating that higher usage of a formed track had little cumulative impact.
- Track width and track incision were related to the slope of the terrain, with tracks traversing flatter areas generally wider ($R^2 = 0.85$) and less incised ($R^2 = 0.96$) than those traversing steeper hillsides.
- Soil sampling of walking tracks and adjacent control material revealed no significant differences between the measured soil physiochemical properties, except soil bulk density. An increase in soil bulk density ($p < 0.05$) was observed in the walking tracks compared with adjacent less disturbed control material and is likely to be a direct result of footfall causing compaction of the near surface soil.

8.2.6 Surface processes affecting surface recovery

The mechanisms for desert pavement recovery were similar to the drivers of desert pavement formation (see 2.3.1), including agents such as wind, the intermittent supply of water, and freeze-thaw action (Campbell and Claridge, 1987; Haff and Werner, 1996; McFadden et al. 1987). 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), was likely to be the primary driver of desert pavement recovery at the study sites (Bockheim 2010; Campbell and Claridge, 1987; Campbell et al. 1998a). The midday heating a dry soil surface and microtopography of the soil surface are known to influence wind strength (Hillel, 1998) and therefore the inputs of energy available to regenerate disturbed surfaces.

Of the study sites, wind action in valley floors and low ridge sites, such as the Loop Moraine, former Vanda Station, Vanda experimental treading trial sites, and the Taylor Valley Visitor Zone sites in the McMurdo Dry Valleys, assisted in the rehabilitation of the desert pavement. At most sites wind is likely to be the instigator in the first stages of formation of an incipient desert pavement. In instances where we had records of low level disturbance, such as impacts from the tent sites at the Loop Moraine field site in the Wright Valley, wind action is likely to have resulted in natural infilling of footprints, sorting of surface materials to re-create 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 several disturbed sites, such as the Loop Moraine walking-tracks, Marble Point bulldozer tracks, or diffuse the "indentation" visible across the walking tracks at the Loop Moraine and the Vanda Fan treading trial site.

The intermittent supply of moisture may have assisted in desert pavement recovery at some of the study sites. Disturbances occurring in the moist coastal climatic zones of Marble Point, the vicinity of Scott Base, Cape Evans, and Cape Roberts, are moistened by occasional summer snowfalls and spring snow thaw. Subsequent repetitive freeze-thaw action may have also aided recovery, and over time, jostled surface clasts into a more embedded position in the desert pavement surface and along with windblown material infilled the impressions of removed clasts. In the drier, central mountain climatic zones, such as in the McMurdo Dry Valleys, further from the coast, moisture available for soil surface processes is less, and recovery was generally not as advanced as equivalent intensity disturbances in moister areas.

The rate and extent of desert pavement recovery at the sites investigated were attributed to the active surface processes mentioned above, in combination with factors including the intensity of the initial disturbance, parent material, and also the restoration and remediation efforts undertaken at the site (Chapters 4 and 5).

8.3 Synthesis and management implications

Over the course of this research we sought out examples of "worst case scenarios" of past physical disturbances, where the mode, intensity, and timing of disturbance, were all well constrained. The longevity of the former physical disturbance was investigated through visual site assessments (Campbell et al. 1993, Chapters 3 and 5) and through application of a new pavement recovery method (Chapters 4 and 5). Individual results depended on the intensity of the disturbance, age and characteristics of the parent material, and the environmental conditions of the site. When we consider the extent of human impacts in the Ross Sea region it is important to stand back and consider the timing, size, and scale of impacts. The ice-free area visited by humans, relative to the Antarctic continent as a whole, is small and impacts occur as isolated pockets amongst largely unimpacted and pristine Antarctic wilderness. While impacting a small portion of the total area, there have, however, been numerous cases of human-induced physical disturbances to parts of the Ross Sea region. The most intense and long-lasting visible impacts occurred around the current and former research bases (Chapters 4 and 5) in the late 1950s through to the 1970s (Campbell & Claridge 1987; Webster et al. 2003; Kennicutt II et al. 2010). After which the environmental footprint of stations such as Scott Base and McMurdo Station on Ross Island have remained static or decreased (Kennicutt II et al. 2010), as environmental accountability , enhanced environmental management, and environmental awareness, increased (Chapters 3 and 5). Sites, such as the former Vanda station, were once highly impacted areas and would have been criss-crossed with vehicle and walking tracks. Yet, removed with some retrospective restoration and left to the rehabilitative action of active surface processes, it is now only the high intensity disturbances visible in the landscape. All national programme personnel and visitors to Antarctica must now plan all activities and limit adverse impacts on the Antarctic environment and associated ecosystems (Chapter 6) under the Annex I and II of the 1991 ratified Protocol on Environmental Protection to the Antarctic Treaty. 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 as my research has shown, there is a high level of consistency between EIA-predicted impacts and actual impacts on the ground (Chapter 3).

What it means to protect wilderness and aesthetic values comes into question at the Taylor Valley Visitor Zone. We can assume from the studies by Summerson and Bishop (2012) that most visitors to the Canada Glacier would agree that the existing confined tracks, which are a clear visual component of the landscape and are carried over year-to-year, detracts from the wilderness and aesthetic value of the Canada Glacier. It is then a question of which is better: (a) to let the current site with lower wilderness values and lower aesthetic values recover and to choose a less vulnerable site for visitors to view a glacier, such as an area where movements are focussed on resilient bedrock; or (b) to continue to visit the current site and to keep impacts minimal by using existing walking tracks.

Dissemination of the insights gained from investigations into the recoverability of different parent materials in the Ross Sea region (Chapters 3-5 and Appendix 1) will allow national programme environmental managers to inform project leaders and visitors of the vulnerabilities and resilience of the areas they are working in. Chapter 5 showed that in some instances, such as one-off campsites, the visual impacts associated with widespread trampling are recoverable to pre-disturbance condition within a few years. Whereas at sites where repeated visits are likely to occur, such as tourist sites (Chapter 5 and Appendix 2) and well-used recreational walking tracks (Chapter 7), visible tracks form quickly due to the unconsolidated nature of many Ross Sea region surface materials (Campbell et al. 1993; 1998a) and increased usage of the formed tracks does not add greatly to impacts (Chapter 7). As a result, recreational users should continue to use pre-existing tracks, and the current tracks remain to concentrate visible impacts. This research can contribute to better informed decisions regarding site selection, impact mitigation, and remediation measures, whereby many of the soil impacts caused by low intensity soil disturbance activities could be avoided, through educating visitors of the longevity of impacts and recovery capabilities of the landscapes they are visiting.

A significant challenge to environmental managers in the Ross Sea region is monitoring the disturbance history of sites used by a variety of visitors and national programmes. A high level of coordination is required and Antarctica New Zealand has taken steps by implementing the VISTA scheme at sites such as the Taylor Valley Visitor Zone. The baseline data that is currently being collected in the Taylor Valley Visitor Zone and other frequently visited sites is important as it provides information against which cumulative impacts can be assessed in the future. I recommend that the Crater Hill summit track and surrounds be monitored for any signs of increased physical disturbance, particularly if use of the summit track is publicised to the McMurdo Station personnel (few USAP personnel currently use the walking track).

8.4 Environmental management applications of this work

Over the course of two field seasons in the Ross Sea region we were asked to assist Antarctica New Zealand (New Zealand's Crown Entity responsible for developing, managing, and executing New Zealand Government activities in Antarctica) with two projects: 1) A request for an amendment to Antarctic Heritage Trust's Initial Environmental Evaluation for restoration of Scott's Terra Nova Hut at Cape Evans (Appendix 1); and 2) An investigation into the current state of the environment at the Canada Glacier Tourism Zone [now known as the Taylor Valley Visitor Zone] (Appendix 2).

We investigated the impacts of relocating the Antarctic Heritage Trust field camp from West Beach to Home Beach, a site closer to their workplace (Appendix 1). The report concluded that there were no physical differences between the West Beach and Home Beach sites, and both camp locations were sites of previous disturbance. Complete visible recovery of Home Beach, formerly the site of the Greenpeace World Park Base, indicated that active surface processes (i.e. wind, melt-water, and waves) on the unconsolidated and unweathered gravelly-sand beach deposits would be expected to aid in the recovery of any field camp disturbance to pre-disturbance condition within a year or two; presuming buildings were removed and the site restored as much as possible. Our report contributed to the Ministry of Foreign Affairs and Trade, Antarctic Policy Unit, sanctioning the relocation of the Antarctic Heritage Trust field camp at Cape Evans, to Home Beach.

The second report (Appendix 2) was utilised by Antarctica New Zealand in the revision process of the Taylor Valley Visitor Zone (formerly Canada Glacier Tourism Zone) Management Plan. A number of recommendations were adopted at the June 2011 SCAR Antarctic Treaty Consultative Meeting in Buenos Aires, including changing the Taylor Valley Visitor Zone boundaries to avoid moist soils and mossy patches at the terminus of the Canada Glacier.

8.5 Limitations of this study

Fieldwork in Antarctica always has limitations due to time and logistic constraints. We undertook two successful field campaigns and obtained valuable data. Nevertheless limitations of this study included:

- Age and weathering stage of the surfaces investigated

The study sites investigated were disturbed surfaces of weathering stages 1 through to 2. We did not include examples of older, more weathered sites, with weathering stages 3 through to 6. Older surfaces predominantly occur at high elevations and nearer the polar plateau, are typically more strongly weathered, and thus more vulnerable to disturbance (Bockheim, 2010; Campbell & Claridge, 1987; Campbell et al. 1998b). Most of the areas impacted by humans occur at lower elevations, in the valley floors and near the coast, and we have a good representation of the younger surfaces in this study. Further work is warranted to investigate the rehabilitative capability of older highly weathered surfaces (although there are far fewer examples of existing major disturbances available on these sites).

- Statistical analysis and need for larger data sets

Simple exploratory data analysis, including two-way ANOVA, were undertaken during the development of the Desert Pavement Recovery Assessment method to look at the relationships between the Mean Recovery Index and variations in parent material, climate, time since disturbance, and severity of disturbance. Despite what we know about the rate of landscape recovery in the Ross Sea region, there were no apparent statistical relationships. We also looked at a multivariate approach and sought advice from a statistical advisor at the University of Waikato but found the dataset too small with insufficient numbers of observations in all combinations to produce a useful principle components analysis.

The logistics limitations, lack of historic information on disturbed sites, and necessarily opportunistic nature of fieldwork in Antarctica meant we lacked a statistically balanced range of disturbances (surface age, level of intensity, length since disturbance etc.). A problem encountered in the field was that we could only assess the severely impacted sites (where impacts were visibly long lasting), as the less impacted sites >10 years old had recovered and were therefore not visible in the landscape. There are no accurate records of location or degree of impacts for sites which had minor disturbance 10 to 50 years ago. Currently the New Zealand Antarctic Programme (as do many others) requires that visitors give GPS coordinates for all camping locations, and experimental sites. Precise location information will improve the ability to revisit and assess sites and accumulate data on the recoverability of sites over time.

8.6 Recommendations for further research

The following areas are suggested for further investigation.

- Extend the Desert Pavement Recovery Assessment method for application to other parts of the Antarctic continent and high Arctic environments.
- Incorporate RNA-based analyses into an extended (2-3 years) investigation into the effects of soil disturbance on bacterial communities. RNA-based analyses might better reflect changes in metabolically active community structure.
- Using a range of different modes and intensities of physical disturbance, investigate previously disturbed sites around the Ross Sea region and examine whether the microbial community in disturbed soils is structured differently than that in adjacent undisturbed soils.
- Investigate any differences in Environmental Impact Assessment effectiveness across national programmes.
- Use remotely sensed data (satellite data and aerial photographs) to spatially depict the extent of, and temporal changes in, impacted areas.

- The Environmental Domains Analysis (Morgan et al. 2007; Morgan, submitted) is a systematic environmental classification framework that allows similar environments to be grouped based on the location's environmental character regardless of their geographic location. There is potential to add information on human impacts and resilience into the Antarctic Environmental Domains Analysis system.
- Extend the collection of cumulative effects baseline data, such as the data collected for the Antarctica New Zealand VISTA scheme, to other frequently visited sites in the Ross Sea region. The Crater Hill summit track, a newly flagged track, for instance, may experience increased traffic over time. Cumulative impacts research needs to be maintained so national programmes are able to monitor any changes that might be occurring.

8.5 Conclusions

A field-based method was developed that can be used to assess desert pavement recovery. The Desert Pavement Recovery Assessment method is based on a set of recovery criteria identified to change over time as a surface recovers. The method allows the user to categorise the relative stage of pavement recovery of a disturbed surface along a continuous spectrum of desert pavement rehabilitation. The method can be added to the repertoire of tools available to environmental managers, giving repeatable, semi-quantitative results for assessing impacts of human activities on the soil surface; which can be used to assess how a site is recovering over time.

Using visual site assessment methods and desert pavement recovery assessments I concluded that the extent of visual surface recovery from the physical impacts of foot and vehicle traffic was higher than sometimes reported. Many of the visual soil impacts can be avoided, or remedied, if field parties are aware of the recovery capabilities of the areas they are working in. Concentrating activity on young, active, and readily recoverable surfaces, or resilient bedrock, is recommended. At some sites walking tracks remained visible in the landscape (due to surface recontouring and larger clasts concentrating along track margins), whereas at one-off campsites, footprints from dispersed trampling were undetectable within five years. For steep slopes and sites where repeated visits occur, use of a single track is recommended. At sites where visually obvious impacts were remediated, visible evidence of former occupation was almost undetectable.

Infrared track counters recorded the number of users on five Ross Island walking tracks. There was no relationship between the number of passes on the track and the measured impacts, indicating that higher usage of a formed track had little cumulative impact. Rather, measured impacts were a function of track slope. An increase in soil dry bulk density, was observed in the walking tracks compared with adjacent less disturbed control material.

There was no significant shift in short-term bacterial community structure over a 35 day sampling period in response to removal of the top 2 cm of soil at an experimental site near Scott Base. Local scale (< 2 m) heterogeneity in soil electricity conductivity and soil pH correlated with differences in bacterial community structure. Further investigation to determine longer term (2-3 years) changes to microbial community structure in response to soil disturbances needs to be undertaken.

An investigation into the effectiveness of Environmental Impact Assessments at five case studies revealed a high standard of environmental management. At most sites Environmental Impact Assessment-predicted impacts were in agreement with the impacts observed. Site remediation practices were effective, post-event monitoring undertaken, and consequently, when assisted by active surface recovery processes, visual site recovery was high. Investigations showed that the Environmental Impact Assessment process effectively raised awareness, thus motivating visitors to take responsibility for their activities. Effort should be made to carry out comparisons between impacts predicted in Environmental Impact Assessments and the eventual outcomes on a regular basis to ensure the Environmental Impact Assessment process is effective.

9 REFERENCES

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Reference list includes all references cited in this document, including the research papers.

Abaza, H., Bisset, R., & Sadler, B. 2004. Environmental Impact Assessment and Strategic Environmental Assessment: Towards an Integrated Approach. UNEP.

Adlam, L.S., Balks, M.R., Seybold, C.A., & Campbell, D.I. 2010. Temporal and spatial variation in active layer depth in the McMurdo Sound Region, Antarctica. *Antarctic Science* 22(1), 45-52.

Aislabie, J. 1997. Hydrocarbon-degrading bacteria in oil-contaminated soils near Scott Base, Antarctica. *In* W. B. Lyons, C. Howard-Williams & I. Hawes (ed.), *Ecosystem Processes in Antarctic Icefree Landscapes*, A.A. Balkema, Rotterdam, Netherlands, pp 253-258.

Aislabie, J., McLeod, M., & Fraser, R. 1998. Potential for biodegradation of hydrocarbons in soil from the Ross Dependency, Antarctica. *Applied Microbiology and Biotechnology,* 49(2), 210-214.

Aislabie, J, Foght, J, & Saul, D. 2000. Aromatic hydrocarbon-degrading bacteria from soil near Scott Base, Antarctica. *Polar biology* 23, 183-188.

Aislabie, J., Fraser, R., Duncan, S., & Farrell, R. L. 2001. Effects of oil spills on microbial heterotrophs in Antarctic soils. *Polar Biology* 24(5), 308-313.

Aislabie, J.M., Balks, M.R., Foght, J.M., & Waterhouse, E.J. 2004. Hydrocarbon spills on Antarctic soils: effects and management. *Environmental Science and Technology* 38(5), 1265-1274.

Aislabie, J.M., Chhour, K.L., Saul , D.J., Miyauchi, S., Ayton, J., Paetzold, R.F., & Balks, M.R. 2006a. Dominant bacteria in soils of Marble Point and Wright Valley, Victoria Land, Antarctica. *Soil Biology and Biochemistry* 38, 3041-3056.

Aislabie, J.M., Saul, D.J., & Foght, J.M. 2006b. Bioremediation of hydrocarbon-contaminated polar soils. *Extremophiles* 10, 171–179.

Aislabie, J.M., Duggan, S., & Barker, G.M. 2008. Relation between soil classification and bacterial diversity in soils of the Ross Sea region, Antarctica. *Geoderma* 144, 9-20.

Aislabie, J.M., Bockheim, J., McLeod, M., Hunter, D., Stevenson, B. & Barker, G.M. 2011. Microbial biomass and community structure changes along a soil development chronosequence near Lake Wellman, southern Victoria Land. *Antarctic Science* 24, 154-164

Aislabie, J.M., Ryburn, J., Gutierrez-Zamora, M.L., Rhodes, P., Hunter, D., Sarmah, A.K., Barker, G.M. & Farrell, R.L. 2012. Hexadecane mineralization activity in hydrocarbon-contaminated soils of Ross Sea region Antarctica may require nutrients and inoculation. *Soil Biology and Biochemistry* 45(0), 49-60

Al-Farraj, A. 2008. Desert pavement development on the lake shorelines of Lake Eyre (South), South Australia. *Geomorphology*, 100(1-2), 154-163. doi: DOI 10.1016/j.geomorph.2007.10.029.

Al-Farraj, A., & Harvey, A.M. 2000. Desert pavement characteristics on wadi terrace and alluvial fan surfaces: Wadi Al-Bih, UAE and Oman. *Geomorphology,* 35(3-4), 279-297.

Antarctica (Environmental Protection) Act 1994. Public Act 1994 No. 119. Act is administered by the Ministry of Foreign Affairs and Trade, New Zealand.

Antarctica New Zealand. 2009. *VISTA Update and Review: Visitor Site Monitoring in the Ross Sea region*. Antarctica New Zealand, Christchurch, New Zealand.

Antarctica New Zealand. 2011. *Statement of Intent 2011-2014*. The New Zealand Government.

Antarctica New Zealand. 2011. *Historic hut and Cape Roberts visitor statistics*, unpublished. Antarctica New Zealand, Christchurch, New Zealand.

Antarctica New Zealand, 2012. *Preliminary tourism data for the seasons 2008-2011*. Unpublished. Antarctica New Zealand, Christchurch, New Zealand.

Ayres, E., Nkem, J.N., Wall, D.H., Adams, B.J., Barnett, J.E., Broos, E.J, Parsons, A.N., Powers, L.E, Simmons, B.L., & Virginia, R.A. 2008. Effects on human trampling on populations of soil fauna in the McMurdo Dry Valleys, Antarctica. *Conservation Biology* 22(6), 1544-1551.

Ayres, E., Nkem, J.N., Wall, D.H., Adams, B.J., Barnett, J.E., Simmons, B.L., Virginia, R.A. & Fountain, A.G. 2010. Experimentally increased snow accumulation alters soil moisture and animal community structure in a polar desert. *Polar Biology* 33, 897-907.

Balks, M.R., Campbell, D.I., Campbell, I.B. & Claridge, G.G.C. 1995. *Interim results of 1993-94 soil climate, active layer and permafrost investigations at Scott Base, Vanda and Beacon Heights, Antarctica.* University of Waikato, Antarctic Research Unit Special Report 1, 64 pp.

Balks M.R., Paetzold, R., Kimble, J.M., Aislabie, J. & Campbell, I.B. 2002. Effect of hydrocarbon spills on temperature and moisture regimes of Cryosols in the Ross Sea region, *Antarctic Science,* 14(4), 319-326.

Ball B.A, Barrett J.E, Gooseff M.N, Virginia R.A, Wall D.H. 2011. Implications for meltwater pulse events for soil biology and biogeochemical cycling in a polar desert. *Polar Reseach* 30: 14555

Ball B.A, Virginia R.A 2012. Meltwater seep patches increase heterogeneity of soil geochemistry and therefore habitat suitability. *Geoderma* 189-190: 652-660

Barrett, J.E., Virginia, R.A., Wall, D.H., Parsons, A.N., Powers, L.E. & Burkins. M.B. 2004. Variation in biogeochemistry and soil biodiversity across spatial scales in a polar desert ecosystem. *Ecology* 85, 3105–3118.

Barrett, J.E., Virginia, R.A., Hopkins, D.W., Aislabie, J., Bargagli, R., Bockheim, J.G., Campbell, I.B., Lyons, W.B., Moorhead, D.L., Nkem, J.N,. Sletten, R.S., Steltzer, H., Wall, D.H. & Wallenstein, M.D. 2006a. Terrestrial ecosystem processes of Victoria Land, Antarctica. *Soil Biology and Biochemistry* 38, 3019–3034.

Bastmeijer, K., & Ricardo, R. 2004. Regulating Antarctic Tourism and the Precautionary Principle. *American Journal of International Law* 98, 763-781.

Belbin, L. 1991. Semi-strong hybrid scaling, a new ordination algorithm. *Journal of Vegetation Science* 2, 491–496.

Bergstrom, D., & Chown, S.L. 1999. Life at the front: history, ecology and change on southern ocean islands. *Trends Ecology Evolution* 14, 472–477.

Billi, D. & Potts, M. 2002. Life and death of dried prokaryotes. *Research in Microbiology* 153, 7–12.

Blakemore, L.C., Searle, P.L., & Daly, B.K. 1987. *Methods for Chemical Analysis of Soils*. New Zealand Soil Bureau Scientific Report 80, Wellington, New Zealand.

Blanchette, R. A., Held, B. W., Jurgens, J. A., Aislabie, J., Duncan, S., & Farrell, R. L. 2004. Environmental pollutants from the Scott and Shackleton expeditions during the 'Heroic Age' of Antarctic exploration. *Polar Record* 40(213), 143-151.

Bockheim, J.G. 1997. Properties and classification of Cold Desert soils from Antarctica*.* *Soil Science Society of America Journal* 61, 224-231.

Bockheim, J.G. & McLeod, M. 2006. Soil formation in Wright Valley, Antarctica since the late Neogene. *Geoderma* 37, 109–116.

Bockheim J.G. 2010. Evolution of desert pavements and the vesicular layer in soils of the Transantarctic Mountains. *Geomorphology* 118, 433-443.

Bölter, M. 1995. Distribution of bacterial numbers and biomass in sols and on plants from King George Island (Arctowski Station, Maritime Antarctica). *Polar Biology* 15, 115-124.

Bratton, S.P., M.G., Hickler, & Graves, J.H. 1979. Trail erosion patterns in Great Smoky Mountains National Park. *Environmental Management* 3: 431-445.

Bray, J.R. & Curtis, J.T. 1957. An Ordination of the Upland Forest Communities of Southern Wisconsin. *Ecological Monographs* 27, 325-349.

Brinkmann M, Pearce D.A, Ott S. 2007. The cyanobacterial community of polygon soils at an inland Antarctic nunatak. *Polar Biology* 30:1505-1511

British Antarctic Survey, 2005. *Antarctic Factsheet Geographical Statistics*. British Antarctic Survey, Cambridge, UK. 4p.

Broadbent, N.D. 1994. An archaeological survey of Marble Point, Antarctica. *Antarctic Journal* 19, 3-6.

Broadbent, N.D. 2009. From Ballooning in the Arctic to 10,000-Foot Runways in Antarctica: Lessons from Historic Archaeology. *In*: Krupnik, I, Lang, M.A, Miller, S.E. (eds), *A Selection from Smithsonian at the Poles. Contributions to International Polar Year Science*, Washington D.C.

Broady, P.A. 1981. The Ecology of Sublithic Terrestrial Algae at the Vestfold Hills, Antarctica. *British Phycological Journal,* 16(3), 231-240.

Bromley, M. 1994. *The climate of Scott Base 1957-1992*. National Institute of Water and Atmospheric Research Report 94-002:1-20.

Cameron, R.E, & Devaney, J.R. 1970. Antarctic Soil Algal Crusts: Scanning Electron and Optical Microscope Study. *Transactions of the American Microscopical Society* 89(2), 264-273.

Campbell, I.B. & Claridge, G.G.C. 1969. A classification of frigic soils-the zonal soils of the Antarctic continent. *Soil Science* 107, 75–85.

Campbell, I.B. & Claridge, G.G.C. 1975. Morphology and age relationships of Antarctic soils. *In* Suggate, R.P. & M.M. Cresswell, (eds.), *Quaternary Studies. Royal Society of New Zealand Bulletin* 13, 87–88.

Campbell, I.B. & Claridge, G.G.C. 1987. *Antarctica, soils, weathering processes and environment*, Elsevier, New York, 368 pp.

Campbell, I.B., Balks, M.R. & Claridge, G.G.C. 1993. A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record* 29(171), 321-328.

Campbell, I.B., Claridge, G.G.C., & Balks, M.R. 1994. The effects of human activities on moisture content of soils and underlying permafrost from the McMurdo Sound region, Antarctica. *Antarctic Science* 6(3), 307-314.

Campbell, I.B., Claridge, G.G.C., & Balks, M.R. 1998. Short- and long-term impacts of human disturbances on snow-free surfaces in Antarctica. *Polar Record* 34(188), 15-24.

Campbell, I.B., Claridge, G.G.C., Campbell, D.I. & Balks, M.R. 1998a. Soil temperature and moisture properties of Cryosols of the Antarctic Cold Desert. *Eurasian Soil Science* 31(5), 600-604.

Campbell, I.B., Claridge, G.G.C., Campbell, D.I. & Balks, M.R. 1998b. The soil environment of the McMurdo Dry Valleys, *In*: John C. Priscu (ed.), *Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica*, Antarctic Research Series 72, 297-322.

Campbell, I.B. & Keys, J.R. 1993. *Cape Roberts Comprehensive Environmental Evaluation – a survey of the soils and vegetation*. Unpublished report, 9p.

Cannone, N., Wagner, D., Hubberten, H.W. & Guglielmin, M. 2008. Biotic and abiotic factors influencing soil properties across a latitudinal gradient in Victoria Land, Antarctica. *Geoderma* 144, 50-65.

Cary, S.C., McDonald, I.R., Barrett, J.E., & Cowan, D.A. 2010. On the rocks: the microbiology of Antarctic Dry Valley soils. *Nature Reviews Microbiology,* 8(2), 129-138. doi: Doi 10.1038/Nrmicro2281.

Cessford, G. & Thompson, A. 2002. Managing tourism in the New Zealand protected area system. *Parks* 12(1), 26-36.

Chiu, L. & Kriwoken, L. 2003. Managing recreational mountain biking in Wellington Park, Tasmania, Australia. *Annals of Leisure Research* 6(4), 339-361.

Chong, C.W., Dunn, M.J., Convey, P., Tan, G.Y.A., Wong, R.C.S. & Tan, L.K.P. 2009. Environmental influences on bacterial diversity of soils on Signy Island, maritime Antarctic. *Polar Biology* 32(11), 1571-1582.

Chong, C.W., Pearce, D.A, Convey, P. &. Tan, I.K.P. 2012. The identification of environmental parameters which could influence soil bacterial community composition on the Antarctic Peninsula - a statistical approach. *Antarctic Science*. Doi:10.1017/S0954102012000028.

Chowdhury, N., Marschner, P. & Burns, R. 2011. Response of microbial activity and community structure to decreasing soil osmotic and matric potential. *Plant and Soil* 344(1-2), 241-254.

Chown, S.L. & Convey, P. 2007. Spatial and temporal variability across life's hierarchies in the terrestrial Antarctic. *Philosophical Transactions of the Royal Society* B362, 2301-2331.

Chwedorzewska, K.J. & Korczak, M. 2010. Human impact upon the environment in the vicinity of Arctowski Station, King George Island, Antarctica. *Polish Polar Research* 31(1), 45-60.

Claridge, G.G.C. 1965. The clay mineralogy and chemistry of some soils from the Ross Dependency, Antarctica. *New Zealand Journal of Geology and Geophysics* 8(2), 186-220.

Claridge, G.G.C., Campbell, I.B., Powell, H.K.J., Amin, Z.H., & Balks, M.R. 1995. Heavy metal contamination in some soils of the McMurdo Sound region, Antarctica. *Antarctic Science* 7(9)-14.

Claridge, G.G.C., Campbell, I.B., & Balks, M.R. 1999. Movement of salts in Antarctic soils: experiments using lithium chloride. *Permafrost and Periglacial Processes* 10, 223-233.

Cockell, C.S., Mckay, C.P., 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. *Journal of Photochemistry and Photobiology B-Biology,* 90(2), 79-87.

Codling, R .1995. The Precursors of Tourism in the Antarctic. *In* Hall, C.M. & Johnston, M. (eds), *Polar Tourism - Tourism in the Arctic and Antarctic Regions.* Wiley, Brisbane, pp. 167-177.

Committee for Environmental Protection. 2005. Guidelines for Environmental Impact Assessment in Antarctica, Resolution 4. *CEP Handbook*, 2007.

Convey, P. 2006. Antarctic climate change and its influences on terrestrial ecosystems. *In*: D.M. Bergstrom, P. Convey and A.H.L. Huiskes (eds), *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator.* Springer, Dordrecht, pp. 253–272.

Cooke, R.U. 1970. Stone Pavements in Deserts. *Annuals of the Association of American Geographers* 60, 560-577.

Cooke , R.U. & Warren, A. 1973. *Geomorphology in Deserts*, UCL Press, London, 309p.

Cowan, D.A., Russell, N.J., Mamais, A. & Sheppard, D.M. 2002. Antarctic Dry Valley mineral soils contain unexpectedly high levels of microbial biomass. *Extremophiles* 6, 431-436.

Cowie, J. 2001. *Cape Roberts Project K001: Clean up phase*. Antarctica New Zealand Logistics Report, Antarctica New Zealand, Christchurch, New Zealand.

Csonka, L.N. 1989. Physiological and genetic responses of bacteria to osmotic stress. *Microbiology and Molecular Biology Reviews* 53(1), 121–147.

De Villiers, M. 2008. Review of recent research into the effects of human disturbance on wildlife in the Antarctic and sub-Antarctic region. *In:* Human disturbance to wildlife in the broader Antarctic region: a review of findings. *Working Paper 12 for XXXI Antarctic Treaty Consultative Meeting*, Kiev, Ukraine, 2–13 June 2008.

Delille, D. & Delille, B. 2000. Field observations on the variability of crude oil impact on indigenous hydrocarbon-degrading bacteria from sub-Antarctic intertidal sediments. *Marine Environmental Research* 49(5), 403-417.

Delille, D., Coulon, F. & Pelletier, E. 2007a. Long-term changes of bacterial abundance, hydrocarbon concentration and toxicity during a biostimulation treatment of oil-amended organic and mineral sub-Antarctic soils. *Polar Biology* 30(7), 925-933.

Delille, D., Pelletier, E. & Coulon, F. 2007b. The influence of temperature on bacterial assemblages during bioremediation of a diesel fuel contaminated subAntarctic soil. *Cold Regions Science and Technology* 48(2), 74-83.

Deprez, P.D., Arens, M. & Locher, H. 1999. Identification and assessment of contaminated sites at Casey Station, Wilkes Land, Antarctica. *Polar Record* 35, 299-316.

Doran, P.T., Priscu, J.C., Lyons, W.B., Walsh, J.E., Fountain, A.G., McKnight, D.M., Moorhead, D.L., Virginia, R.A., Wall, D.H., Clow, G.D., Fritsen, C.H., McKay, C.P. & Parsons, A.N. 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415, 517-520.

Edwards, D.D., McFeters, G.A. & Venkatesan, M.I. 1998. Distribution of *Clostridium perfringens* and fecal sterols in a benthic coastal marine environment influenced by the sewage outfall from McMurdo Station, Antarctica. *Applied and Environmental Microbiology* 64, 2596–2600.

Engelen A, Convey P, Hodgson DA, Worland MR, Ott S. 2008. Soil properties of an Antarctic inland site: implications for ecosystem development. *Polar Biology* 31:1453-1460

Ferguson, S.H., Franzmann, P.D., Revill, A.T., Snape, I. & Rayner, J.L. 2003. The effects of nitrogen and water on mineralisation of hydrocarbons in diesel-contaminated terrestrial Antarctic soils. *Cold Regions Science and Technology* 37 (2), 197–212.

Ferguson, S.H., Powell, S.M., Snape I., Gibson, J.A.E. & Franzmann, P.D. 2008. Effect of temperature on the microbial ecology of a hydrocarbon-contaminated Antarctic soil: implications for high temperature remediation. *Cold Regions Science and Technology* 53, 115–129.

Foght, J., Aislabie, J., Turner, S., Brown, C.E., Ryburn, J., Saul, D.J. & Lawson, W. 2004. Culturable bacteria in subglacial sediment and ice from two Southern Hemisphere glaciers. *Microbial Ecology* 47, 329–340.

Fox, A.J. & Cooper, P.R. 1994. Measured properties of the Antarctic Ice Sheet, derived from the SCAR digital database. *Polar Record*. 30, 201-204.

Freckman, D.W. & Virginia, R.A. 1997. Low diversity Antarctic soil nematode communities: distribution and response to disturbance. *Ecology* 78, 363-369.

Ganzert, L., Lipski, A., Hubberten, H.W. & 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. *Microbiology Ecology* 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 Research and Management* 21, 211-227.

Green, T.G.A., Seppelt, R.D. & Schwarz, A.M.J. 1992. Epilithic lichens on the floor of the Taylor Valley, Ross Dependency, Antarctica. *Lichenologist* 24, 57-61.

Greenpeace. 1986. *Greenpeace Antarctic Programme: Environmental Assessment for 1986-97 season*. Greenpeace International, Amsterdam.

Greenpeace. 1991a. *Initial environmental evaluation, removal of World Park Base, Cape Evans*. Greenpeace International, Amsterdam.

Greenpeace. 1991b. *Greenpeace 1990-1991 Antarctic expedition report*. Greenpeace International, Amsterdam.

Greenpeace. 1992. *Greenpeace 1991-1992 Antarctic expedition report.* Greenpeace International, Amsterdam.

Greenpeace. 1993. *The Greenpeace report of the Antarctic environmental impact monitoring programme at World Park Base 1991-1992*. Greenpeace International, Amsterdam.

Greenpeace. 1994a. *Greenpeace 1992-1993 Antarctic expedition report*. Greenpeace International, Amsterdam.

Greenpeace. 1994b. *World Park Base Antarctica 1987-1992: treading lightly: a minimal impact Antarctic station*. Greenpeace International, Amsterdam.

Greenpeace. 1997. *Greenpeace 1996-1997 Antarctic expedition report.* Greenpeace International, Amsterdam.

Gremmen, N.J.M., Smith, V.R. & van Tongeren, O.F.R. 2003. Impact of trampling on the vegetation of subantarctic Marion Island. *Arctic Antarctic and Alpine Research* 35(4), 42-446.

Griffiths, R.I., Whiteley, A.S,. O'Donnell, A.G. & Bailey, M.J. 2003. Influence of depth and sampling time on bacterial community structure in an upland grassland soil. *FEMS Microbiology Ecology* 43, 35-43.

Grosse, G., Romanovsky, V.E., Jorgenson, T., Walter, A.K, Brown, J. & Overduin, P.P. 2011. Vulnerability and feedbacks of permafrost to climate change. *Eos Trans. AGU* 92(9), 73-74.

Haff, P.K., Werner, B.T. 1996. Dynamical processes on desert pavements and the healing of surficial disturbances. *Quaternary Research* 45, 38-46.

Hale, M.E. 1987. Epilithic Lichens in the Beacon Sandstone Formation, Victoria Land, Antarctica. *Lichenologist* 19, 269-287.

Hammitt, W.E., & Cole, D.N. 1998. *Wildland recreation: ecology and management* (second edition). New York: John Wiley and Sons.

Harris, C.M. 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.

Harris, R.F. 1981. Effect of water potential on microbial growth and activity. *In*: Parr, J.F., Gardner, W.R. & Elliott, L.F. (eds). *Water potential relations in soil microbiology*. American Society of Agronomy, Madison, Wisconsin, USA.

Haskell, T.R., Kennett, J.P. & Prebble, W.M. 1965. Geology of the Brown Hills and Darwin Mountains, southern Victoria Land, Antarctica. *Transactions of the Royal Society of New Zealand* 2(15), 231–248.

Hayward, J., Macfarlane, M.J., Keys, J.R. & Campbell, I.B. 1994. *Decommissioning Vanda Station, Wright Valley, Antarctica: Initial Environmental Evaluation, March 1994*.

Hemmings, A.D. & Roura, R. 2003. A square peg in a round hole: fitting impact assessment under the Antarctic Environmental Protocol to Antarctic tourism. *Impact Assessment and Project Appraisal* 21(1), 13-24.

Hill, W.M. &. Pickering, C.M. 2009. *Ecological impacts of walking tracks in protected areas and comparison of methods and indicators for assessment of track condition.* Technical Report. Sustainable Tourism CRC, Griffith University.

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

Hofstee, E.H., Campbell, D.I., Balks, M.R. & Aislabie, J. 2006. Groundwater characteristics at Seabee Hook, Cape Hallett, Antarctica. *Antarctic Science* 18(4), 487-495.

Hogg, I.D., Cary, S.C., Convey, P., Newsham, K.K., O'Donnell, A.G., Adams, B.J., Aislabie, J., Frati, F., Stevens, M.I. & Wall, D.H. 2006. Biotic interactions in Antarctic terrestrial ecosystems: Are they a factor? *Soil Biology & Biochemistry* 38(10), 3035-3040.

Hopkins D.W, Sparrow A.D, Novis P.M, Gregorich E.G, Elberling B, Greenfield L.G. 2006b. Controls on the distribution of productivity and organic resources in Antarctic dry valley soils. *Proc R Soc London Ser B* 273:2687-2695

Hughes, K.A. 2004. Reducing sewage pollution in the Antarctic marine environment using a sewage treatment plant. *Marine Pollution Bulletin* 49(9-10), 850-853.

Hughes, K.A. & Thompson, A. 2004. Distribution of sewage pollution around a maritime Antarctic research station indicated by faecal coliforms, Clostridium perfringens and faecal sterol markers. *Environmental Pollution* 127(3), 315-321.

Hughes, K.A. 2010. How committed are we to monitoring human impacts in Antarctica? *Environmental Research Letters* 5(4), 3p.

Hughes, K.A. & Convey, P. 2010. The protection of Antarctic terrestrial ecosystems from inter- and intra-continental transfer of non-indigenous species by human activities: A review of current systems and practices. *Global Environmental Change-Human and Policy Dimensions* 20(1), 96-112.

Huston, S.M. & Waterhouse, E.J. (eds.). 2002. *Ross Sea Region 2001: The next steps. Proceedings of a workshop to build on the first Antarctic state of the environment report, Victoria University of Wellington 28–29 May 2002*. Antarctica New Zealand, Christchurch, New Zealand.

Kennedy, A.D. 1993. Water as a limiting factor in the Antarctic terrestrial environment—a biogeographical synthesis. *Arctic Antarctic Alpine Research* 25, 308–315

Kennicutt, M.C., Klein, A., Montagna, P., Sweet, S., Wade, T., Palmer, T., & Denoux, G. 2010. Temporal and spatial patterns of anthropogenic disturbance at McMurdo Station, Antarctica. *Environmental Research Letters* 5(3), 1-10.

Kerry, E. 1993. Bioremediation of Experimental Petroleum Spills on Mineral Soils in the Vestfold Hills, Antarctica. *Polar Biology* 13(3), 163-170.

Keys, J.R., & Williams, K. 1981. Origin of Crystalline, Cold Desert Salts in the Mcmurdo Region, Antarctica. *Geochimica Et Cosmochimica Acta* 45(12), 2299-2309.

Keys, J.R, Barrett, P., Cooper, A., Davey, F., McFarlane, M., Preston, D., Pyne, A. & Webster, B, 1994. *Final Comprehensive Environmental Evaluation: Antarctic Stratigraphic Drilling East of Cape Roberts in Southwest Ross Sea, Antarctica, prepared and written for the International Steering Committee for Environmental Protection.* Department of Conservation, New Zealand.

Kiernan, K. & McConnell, A. 2001. Land surface rehabilitation research in Antarctica. *Proceedings of the Linnean Society of New South Wales* 123, 101-118.

Kormos C.F and Locke H. 2008. Introduction. In C.F. Kormos (ed.): A handbook on international wilderness law and policy. Pp.3_29. Golden, CO: Fulcrum Publishing.

Kyle, P.R. 1981. Mineralogy and Geochemistry of a Basanite to Phonolite Sequence at Hut Point Peninsula, Antarctica, Based on Core from Dry Valley Drilling Project Drillholes 1, 2 and 3. *Journal of Petrology* 22(4), 451-500.

Lauber, C.L., Hamady, M., Knight, R. & Fierer, N. 2009. Pyrosequencing-based assessment of soil pH as a predictor of soil community structure at the continent scale. *Applied and Environmental Microbiology* 75, 5111-5120.

Leung, Y-F. & Marion, J.L. 2000. *Recreation impacts and management in wilderness: a state of knowledge review.* USDA FS Proceedings Rocky Mountains Research Station P–15– Vol 5.

Liddle, M.J. 1997. *Recreation ecology*. London, Chapman and Hall.

Macdonald, C.A., Campbell, C.D., Bacon, J.R. & Singh, B.K. 2008. Multiple profiling of soil microbial communities identifies potential genetic markers of metal-enriched sewage sludge. *FEMS Microbiology Ecology* 65, 555–564.

Macdonald, C.A., Thomas, N., Robinson, L., Tate, K.R., Ross, D.J., Dando, J. & Singh, B.K. 2009. Physiological, biochemical and molecular responses of the soil microbial community after afforestation of pastures with Pinus radiata. *Soil Biology and Biochemistry* 41(8), 1642-1651.

Marion, J.L., Leung, Y-F. & Nepal, S. 2006. Monitoring trail conditions: new methodological considerations. *The George Wright Forum* 2, 36–49.

McCraw, J.D. 1967. Some Surface Features of McMurdo Sound Region Victoria Land Antarctica. *New Zealand Journal of Geology and Geophysics* 10(2), 394-417.

McCune, B. & Mefford, M.J. 2011. *PC-ORD. Multivariate Analysis of Ecological Data*. *Version 6.04* MjM Software, Gleneden Beach, Oregon, U.S.A.

McFadden, L.D., Wells, S.G. & Jercinovich, M.J. 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, Ph.D. Thesis, University of Waikato, New Zealand. 219 pp.

Mear R. & Swan R. 1987. *In the footsteps of Scott*. Jonathan Cape, London. 306p.

Mielke, P.W. 1984. Meteorological applications of permutation techniques based on distance functions. *In*: Krishanaiah, P.R. & Sen, P.K. (eds.), Handbook of Statistics. North-Holland,Amsterdam, pp. 813– 830.

Moorhead, D.L., Barrett, J.E., Virginia, R.A., Wall, D.H. & Porazinska, D. 2003. Organic matter and soil biota of upland wetlands in Taylor Valley, Antarctica. *Polar Biology* 26, 567–576.

Morgan, F., Barker, G., Briggs, C., Price, R. & Keys, H. 2007. *Environmental domains of Antarctica: Version 2.0 final report*. Landcare Research New Zealand Contract Report: LC0708/055.

Morgan, F. submitted. Lines in the Ice: Classifying Antarctica. *In* Liggett, D. & Steel, G. (eds.) *Exploring Linkages between Environmental Management and Value Systems: The Case of Antarctica*. Christchurch: Gateway Antarctica.

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*. Washington, DC, American Geophysical Union. pp. 389–400.

Newman, J. 2009. *Most visited tourist sites in the Ross Sea region, 2005-2009.* Unpublished data. Antarctica New Zealand, Christchurch, New Zealand.

Newsome, D., Moore, S.A. & Dowling, R.K. 2002. *Natural area tourism: ecology, impacts and management*. Sydney, Channel View Publications.

Niederberger, T., McDonald, I.R., Hacker, A.L., Soo, R.M., Barrett, J.E., Wall, D.H. & Cary, S.C. 2008. Microbial community composition in soils of Northern Victoria Land, Antarctica. *Environmental Microbiology* 10, 1713–1724.

Nkem, J.N., Virginia, R.A., Barrett, J.E., Wall, D.H. Li, G. 2006. Salt tolerance and survival thresholds for two species of Antarctic soil nematodes. *Polar Biology* 29, 643-651.

Norbek, K.J. & Blomberg, A. 1998. Amion acid uptake is strongly affected during exponential growth of *Saccharomyces cerevisiae* in 0.7 M NaCl medium. *FEMS Microbial Letters* 158, 121-126

Nowlan, L. 2001. *Arctic Legal Regime for Environmental Protection.* IUCN, Gland, Switzerland and Cambridge, UK and ICEL, Bonn, Germany. xii + 70 pp.

Olive, N.D. & Marion, J.L. 2009. The influence of use related, environmental, and managerial factors on soil loss from recreational trails. *Journal of Environmental Management* 90, 1483-1493.

O'Neill, T.A., Balks, M.R, López-Martínez, J. & McWhirter J. 2012. 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. *Journal of Environmental Management* 112:415-428.

O'Neill, T.A., Balks, M.R, López-Martínez, J. 2013. Soil Surface Recovery from Vehicle and Foot Traffic in the Ross Sea region of Antarctica. *Antarctic Science* doi:10.1017/S0954102012001125..

O'Neill, T.A., Balks, M.R. & López-Martínez, J. 2012. 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. Berlin-Heildelberg-New York: Springer.

O'Neill, T.A., Balks, M.R., & López-Martínez, J. in press. Ross Island recreational walking tracks: relationships between soil physiochemical properties and use. *Polar Record*.

O'Neill, T.A., Balks, M.R., Stevenson, B., López-Martínez, J., Aislabie, J. & Rhodes, P. in press. The short-term effects of surface soil disturbance on soil bacterial community structure at an experimental site near Scott Base, Antarctica**.** *Polar Biology*.

Pickering, C.M., Hill, W., Newsome, D. &. Leung, Y-F. 2010. Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. *Journal of Environmental Management* 91, 551-562.

Pointing, S.B., Chan, Y., Lacap, D.C., Lau, M.C.Y., Jurgens, J.A. & Farrell, R.L. 2009. Highly specialized microbial diversity in hyper-arid polar desert. *Proceedings of the National Academy of Sciences of the United States of America* 106(47), 19964-19969.

Powell, S.M, Ferguson, S.H., Bowman J.P, & Snape, I. 2006. Using real-time PCR to assess changes in the hydrocarbon-degrading microbial community in Antarctic soils during bioremediation. *Microbial Ecology* 52, 523–532.

Preliminary Environmental Evaluation K123. 2004. *Preliminary Environmental Evaluation for K123: Environmental Protection of Soils of the Ross Sea Region*, prepared for Antarctica New Zealand, June 2004.

Quade, J. 2001. Desert pavements and associated rock varnish in the Mojave Desert: How old can they be? *Geology* 29(9), 855-858.

Reich, R.J. 1980. The development of Antarctic tourism. *Polar Record* 20, 203-214.

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 Record* 40(212), 51-67.

Ruberto, L., Vazquez, S.C., & MacCormack, W.P. 2003. Effectiveness of the natural bacterial flora, biostimulation and bioaugmentation on the bioremediation of a hydrocarbon contaminated soil. *International Biodeterioration Biodegradation* 52, 115–125.

Ruberto, L., Vazquez , S.C., Lobalo , A. & MacCormack, W.P. 2005. Psychrotolerant hydrocarbon-degrading Rhodococcus strains isolated from polluted Antarctic soils. *Antarctic Science* 17, 47–56.

Santos, I.R., Silva, E.V., Schaefer, C.E., Albuquerque, M.R. & Campos, L.S. 2005. Heavy metal contamination in coastal sediments and soils near the Brazilian Antarctic Station, King George Island. *Marine Pollution Bulletin* 50(2), 185-194.

Saul, D., Aislabie, J., Brown, C., Harris, L. & Foght, J. 2005. Hydrocarbon contamination changes the bacterial diversity of soil from around Scott Base, Antarctica. *FEMS Microbiology Ecology* 53, 141-155.

Schimel, D.S. & Parton, W.J. 1986. Microclimatic Controls of Nitrogen Mineralization and Nitrification in Shortgrass Steppe Soils. *Plant and Soil* 93(3), 347-357.

Schimel, J., Balser, T.C. & Wallenstein, M. 2007. Microbial stress-response physiology and its implications for ecosystem function. *Ecology* 88(6), 1386-1394.

Schoeneberger, P.J., Wyosocki, D.A., Benham, E.C. & Broderson, W.D. (eds.), 2002. *Field book for describing and sampling soils, Version 2.0*. National Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.

Scott, J.J. & Kirkpatrick, J.B. 1994. Effects of human trampling on sub-Antarctic vegetation of Macquarie Island. *Polar Record* 30, 207–220.

Shanhun, FL et al. 2012. Abiotic processes dominate CO2 fluxes in Antarctic soils. *Soil Bio Biochem* 53:99-111

Sheppard, D.S., Campbell, I.B., Claridge, G.G.C. 1993. *Contamination in the Soils at Vanda Station.* Institute of Geological and Nuclear Sciences Report to Antarctica New Zealand (unpublished).

Sheppard, D.S., Campbell, I.B., Claridge, G.G.C., 1994. *Contamination of soils about Vanda Station, Antarctica*, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. Report 40/20.

Sheppard, D.S., Claridge, G.G.C. & Campbell, I.B. 2000. Metal contamination of soils at Scott Base, Antarctica. *Applied Geochemistry* 15, 513-530.

Singh, B.K., Nazaries, L., Munro, S., Anderson, I.C. & Campbell, C.D. 2006. Use of multiplex terminal restriction fragment length polymorphism for rapid and simultaneous analysis of different components of the soil microbial community. *Applied and Environmental Microbiology* 72, 7278–7285.

Smith, J.J., Ah Tow, L., Stafford, W., Cary, C. & Cowan, D.A 2006. Bacterial Diversity in three different Antarctic cold desert mineral soils. *Microbial Ecology* 51, 413-421

Smith, J.L., Barrett, J.E., Tusnady, G., Rejto, L. & Cary, S.C. 2010. Resolving environmental drivers of microbial community structure in Antarctic soils. *Antarctic Science* 22(6), 673-680.

Snape, I., Morris, C.E. & Cole, C.M. 2001. The use of permeable reactive barriers to control contaminant dispersal during site remediation in Antarctica. *Cold Regions Science and Technology* 32(2-3), 157-174.

Soil Survey Staff. 2002. *Keys to Soil Taxonomy (9th edition).* United States Department of Agriculture, Natural Resources Conservation Service, Washington, D.C.

Soil Survey Staff. 2010. *Keys to soil taxonomy (10th edition).* United States Department of Agriculture, Natural Resources Conservation Service, Washington, D.C.

Sparrow A.D, Gregorich E.G, Hopkins D.W, Novis P, Elberling B, Greenfield L.G. 2011. Resource limitations on soil microbial activity in an Antarctic dry valley. Soil Bio Biochem 75: 2188- 2197

Stallwood, B., Shears, J., Williams, P.A. & Hughes K.A. 2005. Low temperature bioremediation of oil-contaminated soil using biostimulation and bioaugmentation with a Pseudomonas sp. from maritime Antarctica. *Journal of Applied Microbiology* 99, 794–802.

Summerson R. & Bishop I.D. 2011. Aesthetic value in Antarctica: beautiful or sublime? *The Polar Journal* 1, 225_250.

Summerson R. & Bishop I.D. 2012. The impact of human activities on wilderness and aesthetic values in Antarctica. *Polar Research* 31: 1-21..

Sun, D. & Liddle, M.J. 1993a. A survey of trampling effects on vegetation and soil in eight tropical and subtropical sites. *Environmental Management* 17(4), 497-510.

Sun, D. & Liddle, M.J. 1993b. Plant morphological characteristics and resistance to simulated trampling. *Environmental Management* 17(4), 511-521.

Sutherland, D. 2002. *Lake Vanda Monitoring Report No. 7*. National Institute of Water and Atmospheric Research Ltd, prepared for Antarctica New Zealand.

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 Antarctica* 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. *Antarctic Science* 21(3), 229-236.

Tiao, G., Lee, C.K., McDonald, I.R., Cowan, D.A. & Cary, S.C. 2012. Rapid microbial response to the presence of an ancient relic in the Antarctic Dry Valleys. *Nature Communications* 3. doi: Artn 660 Doi 10.1038/Ncomms1645.

Tin, T., Fleming, L., Hughes, K.A., Ainsley, D.G., Convey, P., Moreno, C.A., Pfeiffer, S., Scott, J. & Snape, I 2009. Review: Impacts of local human activities on the Antarctic environment. *Antarctic Science* 21, 3-33.

Treonis, A.M., Wall, D.H. & Virginia, R.A. 1999. Invertebrate biodiversity in Antarctic dry valley soils and sediments. *Ecosystems* 2, 482-492.

Turnbull, I.M., Allibone, A.H., Forsyth, P.J. & Heron, D.W. 1994. Geology of the Bull Pass - St John‘s Range area, southern Victoria Land, Antarctica, scale 1:50000. Institute of Geological & Nuclear Sciences geological map 14. 1 sheet + 52p. Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited.

Ugolini, F.C. & Bockheim, J.G. 2008. Antarctic soils and soil formation in a changing environment: A review. *Geoderma* 144, 1-8.

Wall, D.H. & Virginia, R.A. 1999. Controls on soil biodiversity: insights from extreme environments. *Applied Soil Ecology* 13, 137-150.

Wall, D.H. 2007. Global change tipping points: above- and belowground biotic interactions in a low diversity ecosystem. *Philos Trans R Soc B Biol Sci* 362, 2291–2306.

Walworth, J., Reynolds, C.M., Rutter, A. & Snape, I. 2008. Landfarming. *In* Filler, D., Snape, I. & Barnes, D., (eds). *Bioremediation of petroleum hydrocarbons in cold regions.* Cambridge: Cambridge University Press, pp. 170–189.

Waterhouse, E.J. (ed). *Ross Sea Region 2001: a State of the Environment Report for the Ross Sea Region of Antarctica.* New Zealand Antarctic Institute, Christchurch, New Zealand.

Webster, J., Webster, K., Nelson, P. & Waterhouse, E. 2003. The behaviour of residual contaminants at a former station site, Antarctica. *Environmental Pollution* 123(2), 163-179.

Wellman, H.W. 1964. Delayed Isostatic Response + High Sea-Levels. *Nature* 202(493), 1322-1328.

Wichern, J., Wichern, F. & Joergensen, R.G. 2006. Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. *Geoderma* 137, 100-108.

Wilson, J.P. & Seney, J.P. 1994. Erosional impact of hikers, horses, motorcycles, and off-road bicycles on mountain trails in Montana. *Mountain Research and Development* 14(1), 77-88.

Wynn-Williams, D.D. 1990. Ecological aspects of Antarctic microbiology. *In*: Marshall, K.C. (ed.). *Advances in Microbial Ecology* 2, 71-146.

Xiao, X., Li, M., You, Z. & Wang, F. 2007. Bacterial communities inside and in the vicinity of the Chinese Great Wall Station, King George Island, Antarctica. *Antarctic Science* 19, 11-16.

Yergeau, E., Bokhorst, S., Huiskes, A.H.L., Boschker, H.T.S., Aerts, R. & Kowalchuk, G.A. 2007. Size and structure of bacterial, fungal and nematode communities along an Antarctic environmental gradient. *FEMS Microbiology Ecology* 59, 436-451.

Yergeau, E. & Kowalchuk, G. 2008. Responses of Antarctic soil microbial communities and associated functions to temperature and freeze-thaw cycle frequency. *Applied Microbiology* 10(9), 2223-2235.

Zabinski, C.A. & Gannon, J.E. 1997. Effects of recreational impacts on soil microbial communities. *Environmental Management* 21(2), 233-238.

Antarctic Treaty Consultative Meeting documents referenced:

SAT (Secretariat of the Antarctic Treaty) 1991. Protocol on environmental protection to the Antarctic Treaty. Accessed on the internet at http://www.ats.aq/documents/recatt/ Att006_e.pdf on 1 August 2012.

IAATO. 2010. IP 113 ATCM XXXIII: IAATO Overview of Antarctic Tourism: 2009-10 Season and Preliminary Estimates for 2010-11 and Beyond.

New Zealand, United Kingdom, United States. 2006. WP 34 ATCM XXIX: Ross Sea Protected Area Inspections.

ATCM. 2011. ATCM XXIV, Measure 10: Management Plan for Antarctic Specially Managed Area No. 2, McMurdo Dry Valleys, Southern Victoria Land. Available online: http://www.mcmurdodryvalleys.aq/images/asma2mpfull.pdf

Websites

Antarctica New Zealand. Environmental Impact Assessment. http://www.antarcticanz.govt.nz/environmentalstewardship/environmental-impact-assessment. Accessed 4 November, 2011.

Antarctic Treaty. 2011. Last updated May 2011, retrieved February 15, 2012, from http://www.ats.aq/e/ats_keydocs.htm

IAATO. 2011. Tourism statistics. http://iaato.org/tourism-statistics. Accessed 4 November, 2011.

IAATO 2012. Visitor guidelines. http://iaato.org/visitor-guidelines.
Accessed 4 November, 2011.

United States Department of Agriculture. 2010. Scott Base climate station statistics. http://soils.usda.gov/survey/smst/antarctica/ScottBase/2010/. Accessed 12 May 2012.

10 APPENDICES

APPENDIX 1

Home Beach vs West Beach report for Antarctica New Zealand

POTENTIAL IMPACTS AND RECOVERY OF SOIL FROM CAMPING ACTIVITIES AT CAPE EVANS, ANTARCTICA:

HOME BEACH vs WEST BEACH

Report prepared for Antarctica New Zealand

April 2009

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ABSTRACT

The ice-free regions of Cape Evans have been sites of human occupation, activity, and consequently disturbance, since the heroic era of Scott and others in the early 1900's.

The objectives of this report are to assess and compare the potential impacts of camp establishment at Home Beach (the proposal campsite for AHT) with those at the existing West Beach designated campsite. This study assesses the abilities of the materials of Home and West beaches to recover from impacts related to camping. There was also concern regarding the potential to remobilise any remaining hydrocarbons from a reported fuel spill at the site, should camping activity be allowed to resume in the area.

Home Beach and the designated campsite at West Beach are similar in terms of parent material, slope, environment and proximity to nesting skuas. The nature of the parent material at both sites is such that it favours relatively quick recovery from disturbances such as foot traffic.

Visual Site Assessment, Soil Vulnerability Indices and fuel spill investigations conclude that there is little or no evidence of former base activities. Both sites have relatively high recovery abilities due to their proximity to the sea, snow banks, sorting by the wind and snowmelt runoff, and also due to their relatively unweathered gravel composition, and recent age. There is evidence of patterned ground formation, another sign of a stable landscape.

The Home Beach environment has recovered from the impacts of the Greenpeace World Park Base site which is now difficult to identify. Future destabilization or remobilization of fuel spills is unlikely with no remaining hydrocarbon material identified. Greenpeace has set a fine standard in base removal and site remediation, as well as follow up monitoring of the Home Beach site.

Our investigations reveal no particular environmental impediments to establishing a short-term camp on Home Beach. However, we would be reluctant to see the longer-term designated campsite moved to Home Beach due to the visual impacts on the environs of Scott's Terra Nova Hut.

1. INTRODUCTION

The Antarctic Heritage Trust (AHT) are currently in the process of restoring Scott's Terra Nova Hut, Cape Evans, Ross Island, and have permit to do so until October 2013. AHT have applied to the Ministry of Foreign Affairs and Trade (MFAT), Antarctic Policy Unit, for a variation to approved activities in their current IEE, and Antarctica New Zealand have been asked to advise MFAT if there is likely to be any adverse impacts to the environment as a direct result of changes to the approved activities.

With the Cape Evans Management Plan up for review in 2010, AHT have requested to relocate their current campsite on West Beach (the current NZAP designated Cape Evans campsite) to Home Beach (former site of the Greenpeace World Park Base). AHT indicate that relocation to Home Beach will "reduce the walk to the work site by one third, increase efficiency and safety, and minimise tracking impacts".

Greenpeace established its *World Park Base* on Home Beach at Cape Evans, Ross Island (77° 38' S, 166° 24' E) in the austral summer of 1986/87 on the site of the *Footsteps of Scott Expedition* (including its hut, which was incorporated into the Greenpeace station) (Hemmings, 2005). The station was decommissioned, removed and the former site remediated in the austral summer of 1991/1992. Environmental monitoring of the site was carried out by Greenpeace in 1991/92, 1992/93 and 1995/1996.

Investigation of the site of the former Greenpeace base provides a good opportunity to assess the abilities of the materials in the area to recover from impacts related to camping. There was also concern regarding the potential to remobilise any remaining hydrocarbons from a reported fuel spill at the site, should camping activity be allowed to resume in the area.

The objectives of this report are to assess and compare the potential impacts of camp establishment at Home Beach (the proposal campsite for AHT) with those at the existing West Beach designated campsite.

2. SITE INFORMATION

Cape Evans is a small, triangular shaped, ice-free area in the south west of Ross Island, 10 kilometres south of Cape Royds and 22 kilometres north of Hut Point Peninsula on Ross Island. Cape Evans is a site of significant historic value, namely, Scott's Terra Nova Hut and associated artefacts within the vicinity, as well as other significant monuments such as the Cross on Wind Vane Hill, and it is the location of many early advances in the physical and biological sciences (Photo 1).

Photo 1: Location of current NZAP campsite at West Beach, and its proximity to North and South Bay, and Wind Vane Hill (observation point for Scott's Terra Nova Hut).

The ice-free area of Cape Evans is composed of basalt bedrock partially covered by till. West Beach (Photo 1) is currently the NZAP designated campsite, and site of the helo pad. There are currently four wannigans occupying the flat surface some 3 m from the shoreline. Both Home Beach (Photos 2 and 3) and West Beach (Photos 2 and 4) are active sandy gravel beaches, comprising uniform sub-angular gravels derived from scoriaceous basalt.

The former Greenpeace base site at Home Beach is on a raised beach terrace about 5 m above sea-level between low rock outcrops and the present beach. A small shallow lake, Skua Lake (Photo 2), and a small temporary stream that is the lake's outlet to the sea, are located 50 m to the south of the former base site. Similarly the current designated campsite at West Beach is about 3 m above sea-level, and both areas have soil profiles characterised by a surface of sub-angular pebbles, underlain by a 10-20 cm layer of single grained , poorly sorted, sandy gravel, and well sorted coarse sand (Roura, 2004, and this study). At both sites ice cement was between 30 and 40 cm depth on the 11th January 2009. The underlying material is basaltic bedrock, which crops out landward of the active and raised beaches at both sites.

Photo 2: Oblique view of North Bay showing current NZAP campsite at West Beach, former Greenpeace World Park Base site at Home Beach and their proximity to Scott's Terra Nova Hut. Note the large snowdrift between West Beach and Terra Nova Hut.

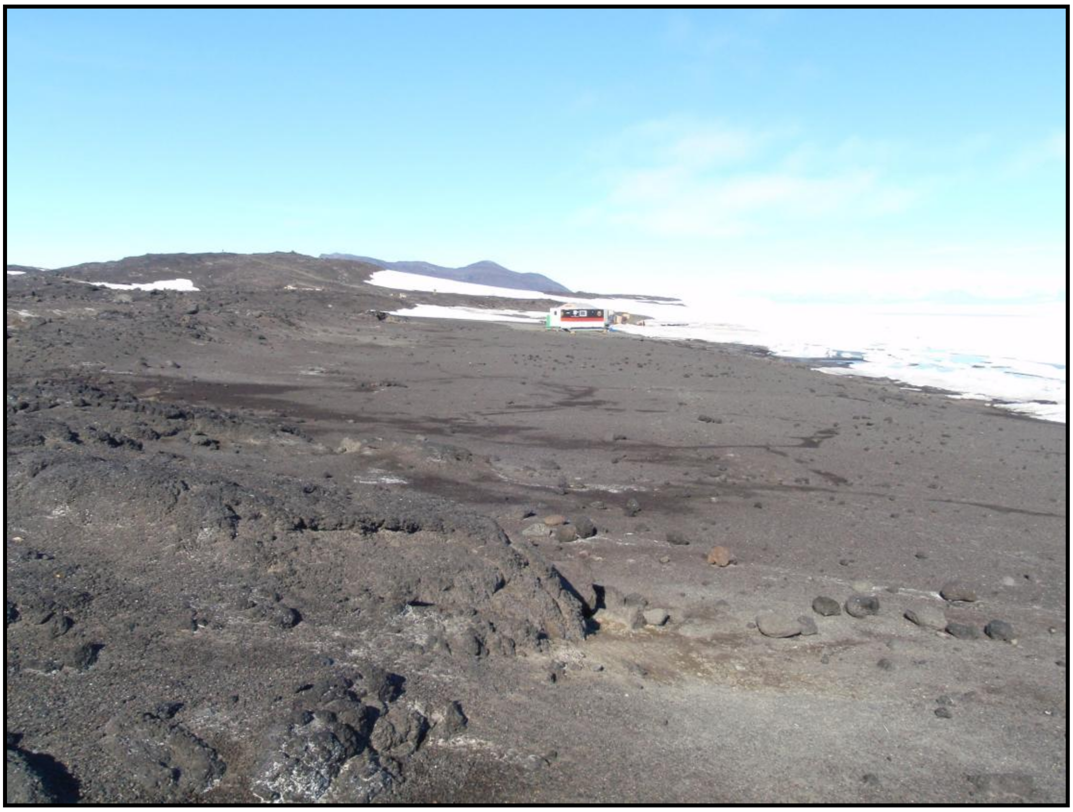

Photo 3: Home Beach site (11 January 2009). Photo is taken looking westwards towards the AHT temporary workshops, and Terra Nova Hut.

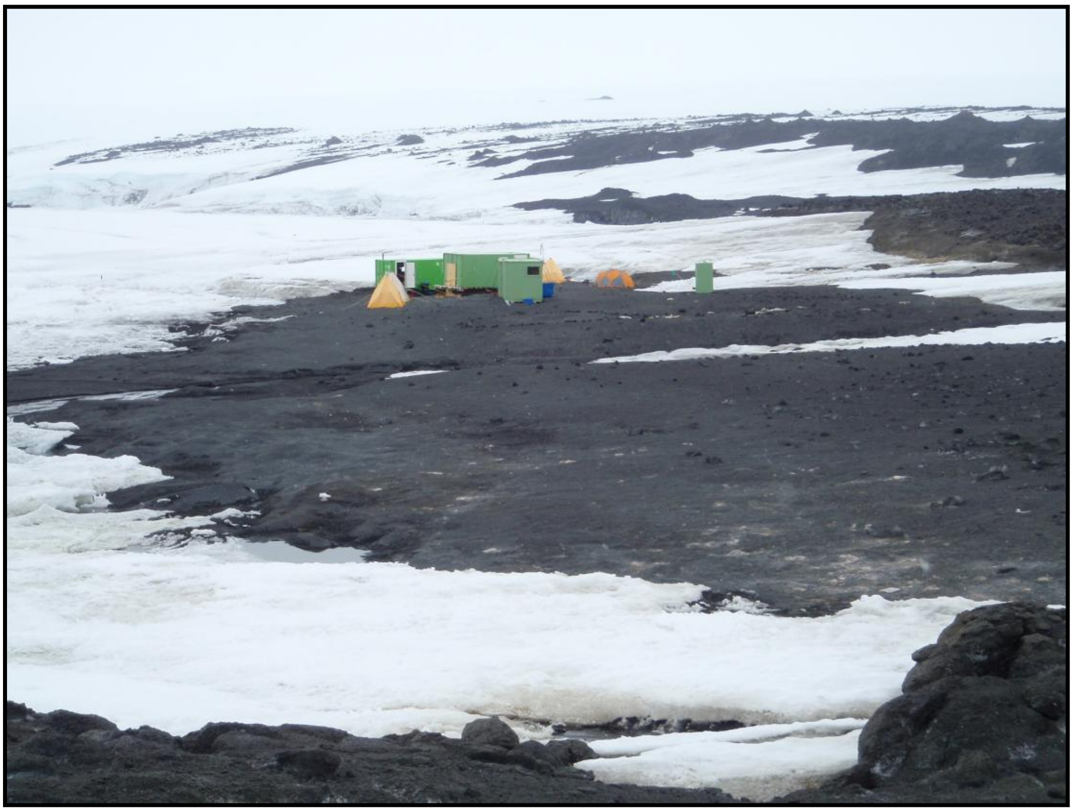

Photo 4: West Beach site (8 January 2009). Photo is taken from a rock outcrop at North Cape looking eastwards towards the Terra Nova Hut (not visible), Home Beach, and the Barne Glacier.

3. METHODOLOGY

Assessment of the present state of the Home Beach and West Beach sites were carried out. Photos and graphs were used as a means of locating the site of the former Greenpeace base, and the various geomorphological structures of the area were identified. Evidence of previous occupation was photo-documented, and GPS locations recorded for future site recovery studies. A detailed soil profile description, and bulk density measurements, along with soil sampling for further chemical and physical analysis was undertaken near the current location of the AHT workshops. Nine spade-width holes were dug to the depth of ice-cemented permafrost (approximately 40 cm below the surface) around the vicinity of the former fuel rack; and the “sniff test” conducted to check for any evidence of hydrocarbons.

- Visual Site Assessments and Soil Vulnerability Indexes:

A slightly modified version the Visual Site Assessment (VSA) method of Campbell *et al.*, (1993) was undertaken at two sites on Home Beach (an example of which has been included in Appendix 1). The Soil Vulnerability Index (SVI) of McLeod *et al.*, (in prep) was also implemented at both sites. The SVI provides a disturbance rating (over 10 boot imprints) and a recovery rating (governed by the nature of the parent material) of the soil. At each site 10 steps were tracked across the surface, imprints studied, and the number of nil versus partial breakthrough versus complete boot imprint breakthrough into the 2nd layer (horizon) of soil was counted and recorded. Based on the McLeod Index the relative susceptibility of the Home Beach and West Beach sites to damage from foot and vehicle traffic was determined.

- Soil sampling and description:

Sampling depths were dictated by depth to ice-cement, and included the desert pavement, underlying horizon/s, and the ice-rich horizon immediately above the ice-cemented permafrost. Two soil pits were excavated to a maximum dimension of 50 cm by 75 cm deep (or ice-cemented permafrost if shallower); and horizons set apart from one another on a ground sheet, described, sampled, and then backfilled in the correct order.

- Soil physical and chemical analyses:

Soil samples were analysed for water content in the lab facilities at Scott Base during the 2008/2009 field season. Further chemical analyses including pH, electrical conductivity, water soluble cations and anions will be undertaken at the MAF-accredited soils lab at Waikato University.

For further information on methods refer to K026 2008-2009 Field Season Immediate Science Report to Antarctica New Zealand.

4. RESULTS

4.1. Evidence of former Greenpeace World Park Base

4.1.1. Trace of former buildings

The main visible evidence of the former Greenpeace base was the unnatural gravel mounds associated with the removal of persistent snow drifts from the landward side of the building in the time of the former base (Photo 5), and the "unnaturally" placed cobbles and boulders on top of the raised beach surface (Photos 7 and 8). Overall there was little other evidence of the former base. There was no evidence of structures such as the drainage trench, SATCOM tower, or food storage hut. A lag gravel deposit has reformed over the entire site. To the trained eye, there is a faint trace of a corner of the main building (the side pointing to, and closest to, Scott's Hut) where the area was levelled and Greenpeace cut into the ridge that runs parallel to the shoreline (Photos 5 and 6).

Photo 5: Trace of former corner of main building and unnatural mounds of gravel likely to have resulted from clearing snow from behind the building.

Photo 6: Red lines indicate corner of the former main building. Note bag for scale.

4.1.2. Visual Site Assessments (VSA)

The VSA conducted on the raised beach surface showed no evidence of permafrost degradation in backfilled areas, no visual expressions of fuel spills on the surface, or remnants of walking tracks or drains, or any obvious differences in texture or surface colour when compared with nearby undisturbed beach surfaces. There is evidence of somewhat artificial looking boulders "placed" on the surface post-remediation (Photos 7 and 8), and also the odd nail or small (<10 cm long) piece of wood scattered across the surface. On an original undisturbed surface the artificial looking rocks would be incorporated into the pavement, sitting somewhere halfway embedded into the surface.

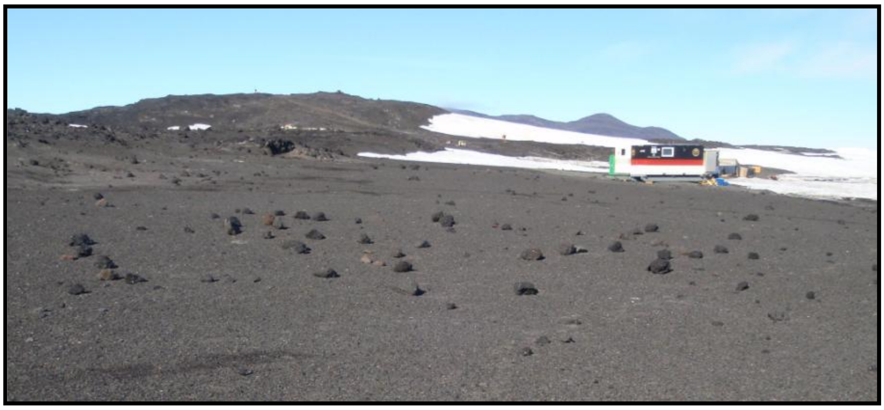

Photo 7: Home Beach site. Artificially placed boulders on the beach surface. Assumed to have been placed during Greenpeace remediation efforts.

Photo 8: Home Beach site. Unnatural boulders.

4.1.3. Former spill sites

Former spill sites were not visible. After careful determination of the location of the former fuel rack site, nine spade-width holes were dug. Holes were dug in hollows, and areas that we thought may have been infilled after spill contaminated soils were removed, and in sites that appeared darker on the surface, downhill from the location of the fuel storage site (Photo 3).

In eight of the nine holes ice-cemented permafrost was encountered at approximately 40 cm, and in the other site groundwater was encountered 45 cm below the surface. No hydrocarbon odour or presence was detected (Photo 9), and it is likely that after the initial volatilisation of lighter fuels, any remaining hydrocarbons from 1988 to 1992 base activity have subsequently washed laterally along the ice-cement interface, through the highly permeable beach gravels and been dispersed in the ocean. Groundwater at 45 cm is also a good indication of lateral flow, this again reinforces the impression that any remaining fuels would have likely been dispersed into the sea. Dark patches (Photo 3) on the surface were moist areas, likely to be the surficial expression of patterned ground polygons, thus reflecting an underground feature, and not associated with hydrocarbon spills.

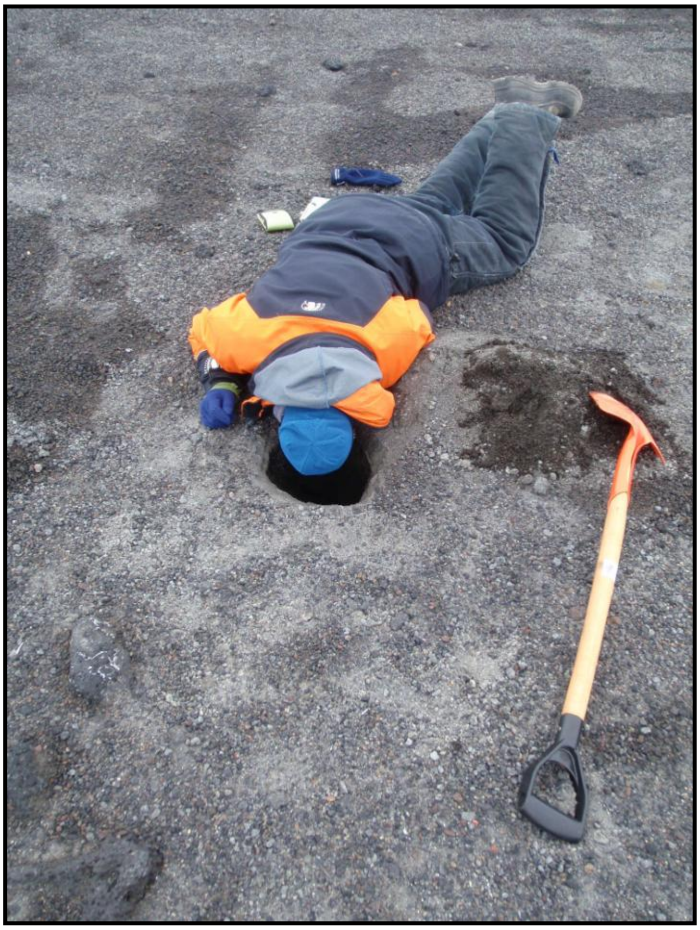

Photo 9: The “sniff” test. A quick test for hydrocarbon contamination. *Photographer*: Megan Balks.

4.1.4. Former tracks

There is faint evidence of a former track junction to the north east of the former Greenpeace base, north east of the fuel rack, which we believe to be the tracks that led to Greenpeace's climate station near "The Ramp" and the other, across past Skua Lake to South Bay. Only the first 10 m of the tracks are evident, but are not obvious to the untrained eye. We approximate their location by the presence of larger stones, cobbles and boulders being pushed to the outer edge of the former track – a common process as a result of repeated foot traffic (Photo 10).

Photo 10: Former tracks to "The Ramp" and South Bay.

The Home Beach site and the wetland and lake area behind is still infrequently traversed today, but not nearly as heavily trafficked as it would have been while Greenpeace inhabited the area. The occasional contemporary footprint was evident but we regard the site to be in a state of equilibrium.

4.1.5. Overall impacts of Greenpeace World Park Base

VSA, SVI and former fuel spill investigations conclude that there is little or no evidence of former base activities, which reflects the recoverability of the active landscape. Given that this is an active beach area, subject to wind, snow, and occasionally open-ocean, the surface pavement across the area has long since recovered. Furthermore, there is evidence of patterned ground formation, another sign of a stable landscape.

The lack of evidence of the former Greenpeace base at Home Beach is also a testament to the efforts Greenpeace put into the decommissioning operations, site remediation and post-remedial monitoring.

4.2. Route of existing and proposed walks

The walk from the existing West Beach campsite to Scott's Terra Nova Hut is shown in photos 11 through 13. The current route from West Beach causes minimal "tracking" as most of the traffic footprint is over a long-term snowbank surface (Photo 12).

Photo 11: The walk from West Beach campsite to Terra Nova Hut.

Photo 12: Across the snowbank towards Terra Nova Hut.

Photo 13: Back on terra firma – the heavily trafficked beach in front of Scott's Terra Nova Hut.

The proposed walk from the Home Beach campsite to Scott's Terra Nova Hut includes crossing a stream and is shown in photos 14 through 17.

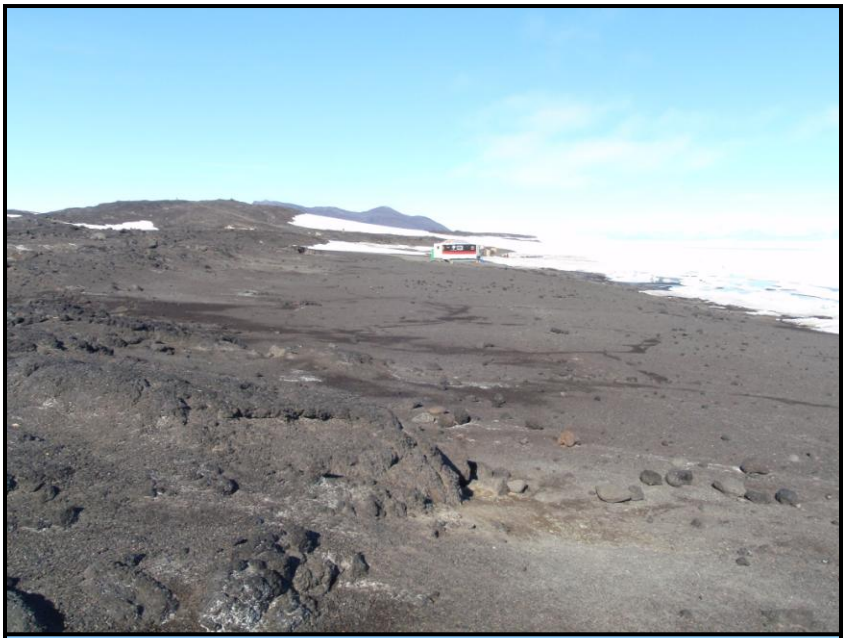

Photo 14: The walk from Home Beach to Terra Nova Hut.

Photo 15: The walk from Home Beach to Terra Nova Hut. Note: AHT workshops and stream.

Photo 16: The walk from Home Beach to Terra Nova Hut. Note: Stream crossing.

Photo 17: The walk from Home Beach camp to Terra Nova Hut. Note: red line shows route through a small snowbank between camp, AHT workshops and Scott's Hut.

The proposed walk from the Home Beach campsite to Scott's Terra Nova Hut includes crossing a stream and takes 3 to 5 minutes, whilst walking to the existing camp involves crossing a snowbank and takes 5 to 7 minutes.

5. DISCUSSION

The Home Beach and West Beach sites have been disturbed in the past, and are both active, resilient, readily recoverable surfaces. Both sites have relatively high recovery abilities due to their proximity to the sea, snow banks, sorting by the wind and snowmelt runoff, and also due to their relatively unweathered gravel composition, and recent age.

The Home Beach environment has recovered with the impacts at the Greenpeace World Park Base site now being difficult to identify. Future destabilization or remobilization of fuel spills is unlikely with no remaining hydrocarbon material identified. Greenpeace has set a fine standard in base removal and site remediation, as well as follow up monitoring of the Home Beach site.

In terms of parent material, slope, environment, proximity to nesting skuas, both Home Beach and the designated campsite at West Beach are similar (Photos 18 and 19). The nature of the parent material at both sites is such that it favours relatively quick recovery from disturbances such as foot traffic.

Photo 18: West Beach site. A heavily trafficked, yet highly active and readily recoverable, resilient beach surface.

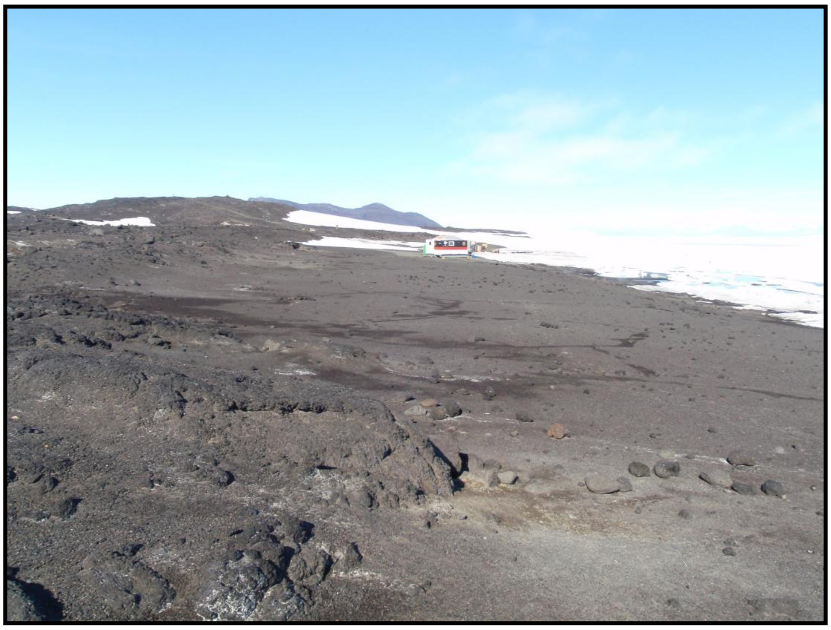

Photo 19: Home Beach site. Formerly heavily trafficked, now considered fully recovered, active, resilient beach surface.

We recommend that the Cape Evans Management Plan, current designated campsite, and current helo pad location, should remain at West Beach. We believe its present location is the best location to protect the visual integrity of Scott's Terra Nova Hut. Presently, landing at West Beach one gets an unobstructed view of Scott's Hut and the stunning vista of Mt Erebus in the background (Photo 20). From Scott's Hut and the lookout on Wind Vane Hill, the West Beach campsite is out of ones line of vision, whereas, we feel that a permanent relocation of the NZARP designated camp to Home Beach will detract from Scott's Terra Nova Hut, Mt Erebus, and the other artefacts within the ASPA.

If AHT were approved to move their campsite *temporarily* to Home Beach for the duration of their conservation and restoration project, it is our view, given the Greenpeace World Park Base experience and provided appropriate removal of camping equipment and appropriate remediation, a Home Beach campsite would recover quickly and within 5 years evidence of its presence would have largely disappeared.

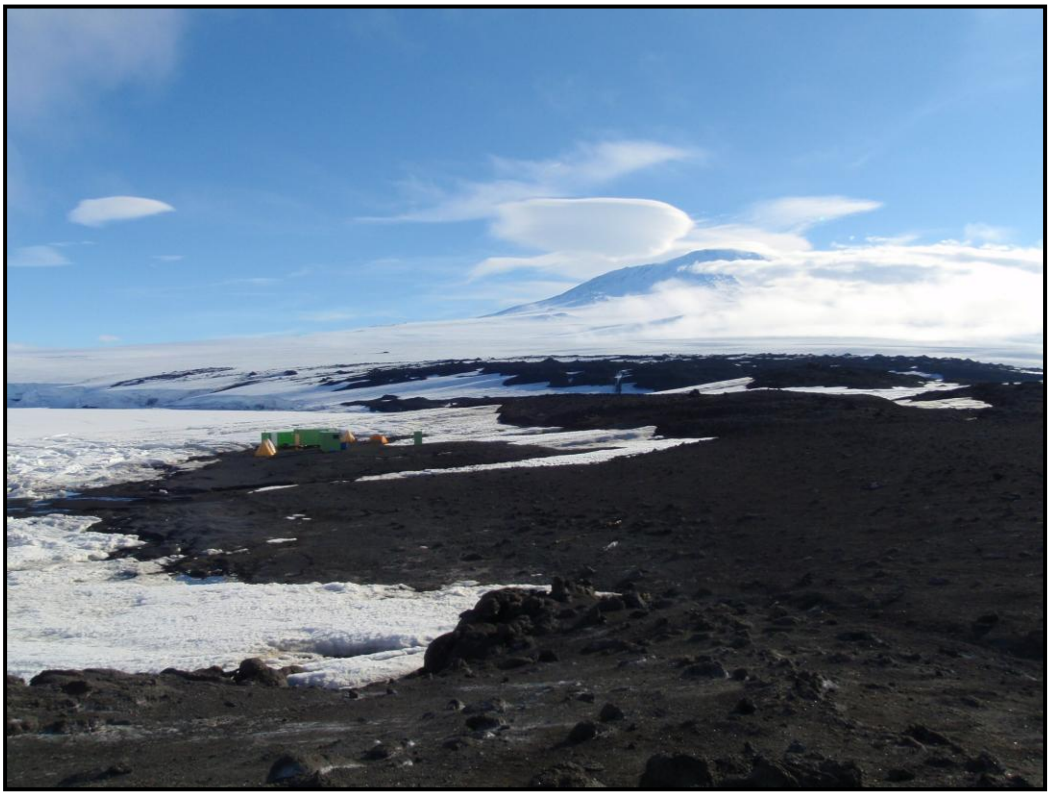

Photo 20: The current NZARP campsite and helo pad site. *Photographer*: Tanya O'Neill.

6. CONCLUSIONS

- Both Home Beach and West Beach are formed from recent scoriaceous basalt gravel beach deposits which are relatively unweathered, highly resilient surfaces.

- There are no physical differences between the Home Beach and West Beach sites; both are sites of previous disturbance.

- Due to active surface processes (wind, meltwater and waves) both sites are expected to recover within a year or two from trampling and other impacts associated with camp activity; presuming buildings are removed and the site restored as much as possible.

- We found no evidence of any remaining fuel spill at Home Beach and do not consider it a potential hazard for a campsite.

- Walking from the existing campsite to Scott's Terra Nova Hut is causing minimal "tracking" as most of the traffic footprint is over a long-term snowbank surface. The existing route from camp to work takes 5 to 7 minutes.

- Walking from Scott's Terra Nova Hut to the proposed Home Beach campsite includes crossing a stream and takes 3 to 5 minutes.

- We would be reluctant to see the longer-term designated campsite moved to Home Beach due to the visual impacts on the environs of Scott's Terra Nova Hut.

- We see no particular environmental impediments to establishing a short-term camp on Home Beach.

7. REFERENCES

Campbell, I. B., Balks, M. R., Claridge, G. G. C. 1993. A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record 29* (171), 321-328.

Hemmings, A. 2005. The Site of Greenpeace's World Park Base at Cape Evans Fourteen years after its Removal.

McLeod, M., Balks, MR., Hewitt, AE., Bockheim, JG. A rapid method to assess impact of foot trampling on ice-free soils of Wright Valley, Antarctica. *In prep.*

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 Record* 40 (212): 51-67.

Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., Broderson, W. D. (Eds.). 2002. Field Book for Describing and Sampling Soils, Version 2.0. National Soil Survey Center, Natural Resources Conservation Service, Lincoln, Nebreska. 228 pp.

Soil Survey Staff. 2006. Keys to Soil Taxonomy (10th Ed.). United States Department of Agriculture, Natural Resources Conservation Service, Washington D.C.

APPENDIX 1: Assessment criteria for visual evaluation of terrestrial environmental impacts, VSA modified from Campbell et al., 1993

Impact Assessment Criteria		Severity and Extent of Impacts (class)				Comments	Rating
		1	2	3	4		
A.	Disturbed surface stones	none visible (0)	few (<10)	many (10–25)	abundant (>25)		
B.	Impressions of removed rocks	none visible	just visible	distinct	fresh		
C.	Boot imprints	none visible	just visible	distinct	fresh		
D.	Visibly disturbed area	<5 m^2	5–10 m^2	20–100 m^2	>100 m^2		
E	Other surface impressions (e.g.shallow concavities from backfilled excavations)	none visible	weakly visible	distinct	very fresh		
F	Walking tracks	not visible	weakly defined	moderately defined	strongly defined		
G	Foreign objects	none visible (0)	few (<10)	some (10–25)	many (>25)		
H	Visible fuel spills	none visible	faintly distinguished	visible	very obvious		
I	Salt deposition	none visible	faintly distinguished	visible	abundant		
J	Biological disturbance	none visible	<1 m^2	1–5 m^2	>5 m^2		
K	Cumulative impact (scale 1–10)	disturbance not visible (0)	weakly evident (1–2)	clearly visible (3–5)	disturbed and very obvious (>5)		
L	Stratigraphic disturbance	negligible	within one unit	within two units	multiple units		
M	Morphological or textural change	negligible	just evident	moderate change	very obvious		
N	Rock cairns	none	rare or small	moderately common	very common		
O	Paint marks	none	rare or small	moderately obvious	very obvious		
P	Other	none	rare or small	moderately obvious	very obvious		
Site:					**Photo:**		

APPENDIX 2

Canada Glacier Tourism Zone (now Taylor Valley Visitor Zone), state of the environment report for Antarctica New Zealand

CANADA GLACIER TOURISM ZONE
Antarctica Specially Managed Area Two (ASMA 2)

STATE of the ENVIRONMENT

Report prepared for Antarctica New Zealand
April 2010

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ABSTRACT

The Canada Glacier Tourism Zone (CGTZ) is located directly in front of the Canada Glacier, a small polar glacier flowing southeast into the northern side of Taylor Valley, McMurdo Dry Valleys, Antarctica. Designated as a 'Tourism Zone' in 1995, the CGTZ is currently the only area in the McMurdo Dry Valleys where "tourism" may occur.

This report details our observations during a 3-hour visit to the CGTZ on the 30th of December 2009. Given the forthcoming review of the CGTZ Management Plan, the objectives of this report are to comment on the current state of the CGTZ, noting ground disturbance, areas of resilience and vulnerability, the tracking behaviour of the tourists (evidence of deviation from established tracks), and comment on any evidence of recovery between seasons.

Four specific sites were investigated using Visual Site Assessment, Soil Vulnerability Indices and Desert Pavement Recovery Assessment methods. Our observations and VISTA photo-replication suggest that the physical impacts of the tracks within the CGTZ persist between seasons. Distinct foot-prints are not evident, however an overall contrast in pavement colour between the track and adjacent undisturbed mixed till pavement was evident. We suggest there was some pavement recovery occurring between seasons, likely to be a function of wind and/or snow action, however, tracks remain due to larger clasts being concentrated on the outer margin of the track, where without remediation, they remain indefinitely.

We suggest that permanent low marker poles should be erected along the north-western boundary of the CGTZ at CG3, CG4, and CG5; between the Tourism Zone, pro-glacial ponds and the glacier. This will stop traffic wandering too close to the moist sediment near the pond margins, and minimise impacts to algae. The lower section of the CGTZ between the helo pad and foot of the Lookout hill should be clearly defined so tourism

operators and science programme visitors can easily locate the flagged route and to avoid multiple tracks forming. It is preferable to keep visitors to a single confined track in all areas of the TZ, following patterned ground cracks where possible, and particularly in the steeper sections of the Lookout hill. A single confined track will preserve the existing undisturbed desert pavement adjacent to current tracks, preserving the natural integrity of the landscape.

There was evidence of recent foot-prints between the CGTZ boundary and glacier (presumably from science personnel in the area). Thus we think it is advisable to discourage other visitors, such as science programme personnel, from walking along the CGTZ boundary, to avoid confusion within tourist groups as if tourists see others have walked outside the boundary they may wish to do so also. The implementation of permanent markers across the north-western boundary and between the helo pad and base of the Lookout hill will assist in this effort. General trampling around the vicinity of the helo pad had recovered well between the end of the previous tourist season and our visit.

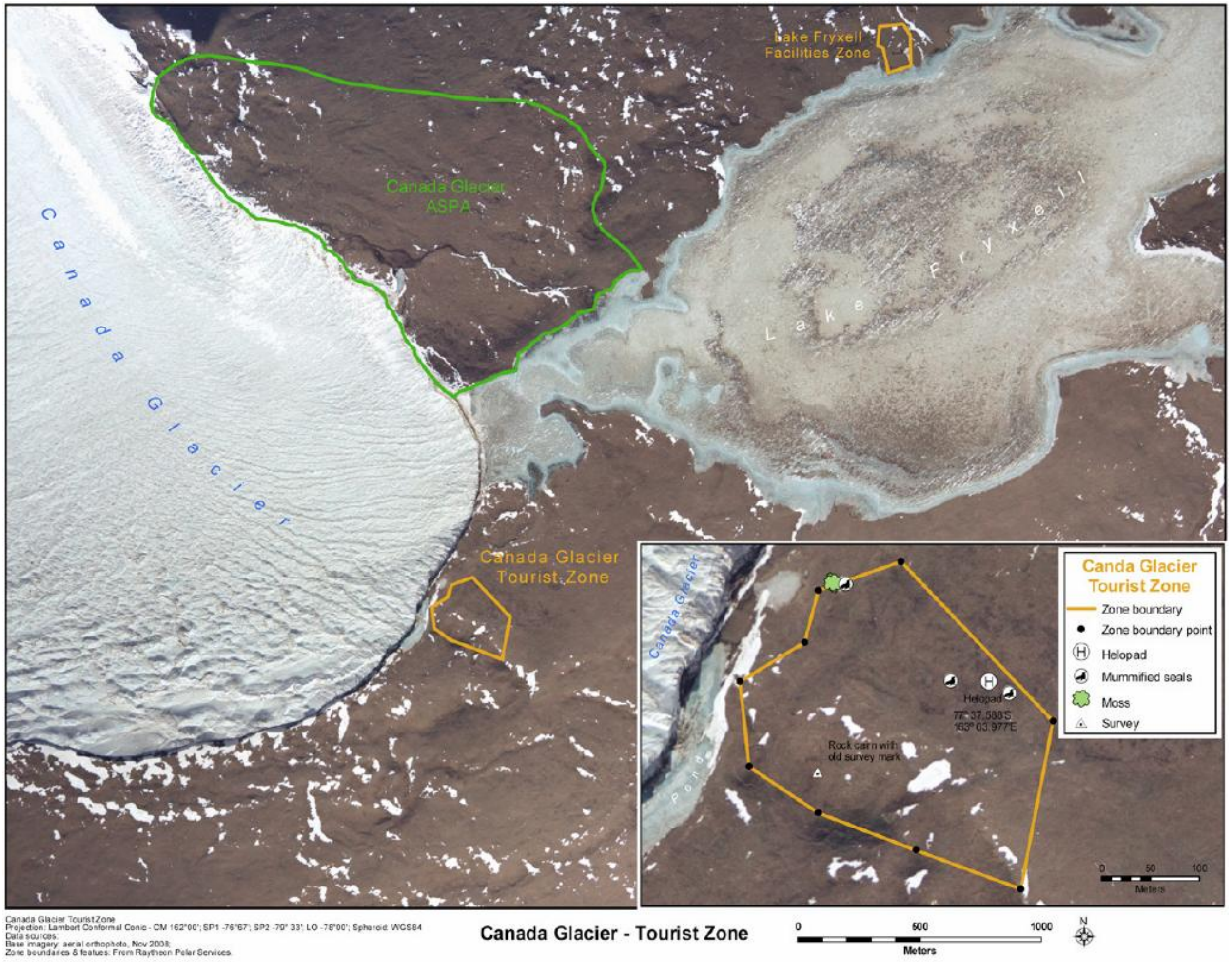
Overall the CGTZ is well managed, and it is clear that tourist operators go to great efforts to ensure their clients follow a single flagged track. Furthermore, the CGTZ provides an excellent 'Dry Valleys experience' for tourists as it is fairly typical of the environment with attractive glacier views and a prominent hilltop providing an excellent viewing platform.

1. INTRODUCTION

The McMurdo Dry Valleys are located in southern Victoria Land along the western coast of McMurdo Sound, southern Ross Sea, at approximately 77°S, 162°E. An area of approximately 15,000 km^2 is designated as an Antarctic Specially Managed Area (ASMA) to manage human activities in the valleys, for the protection of scientific, wilderness, ecological, and aesthetic values.

One specific site within the ASMA area, near the Canada Glacier (Figure 1 and 2), was further designated as a 'Tourism Zone' within the ASMA in 1995. The Tourism Zone is the only site in the Dry Valleys where "tourism" may occur, and was selected as a site where "safe and easy access and movement within the area can be reasonably assured with minimal impact to science activities or the environment" (ANZ, 2004b, p. 10). The ASMA management plan does not specify any particular limits on the numbers of tourists that can access the zone, but does provide a number of items of guidance to tour operators (Appendix 1).

Tourist cruises to the Ross Sea Region have, in recent years, started to visit the Canada Glacier Tourist Zone (CGTZ) as part of their regular itineraries. A total of 434 people have landed between the summers of 2006/2007 and 2008/2009; with 224 people visiting the site in the 2006/2007 season, 117 in the 2007/2008 season, and 93 in the 2008/2009 season. Average landing times are close to 9 hours (entire party). Research program activity also occurs at this site, with substantial USAP camps at nearby Lake Fryxell and Lake Hoare, so total visitor numbers are difficult to quantify. Access is only by helicopter as the Tourism Zone is approximately sixty kilometres from Scott Base and approximately forty kilometres from the nearest position that an ice-breaker can usually be positioned in McMurdo Sound. The tourism zone is approximately 350x300 m, dominated by a low (approximately 30 m high) hill, and is covered in gravely rocky till. A recent topographic map of the CGTZ, showing the boundary markers, helicopter landing pad, and features within the zone is shown below (Figure 2).



Canada Glacier Tourist Zone
Projection: Lambert Conformal Conic - CM 162°00'; SP1 -76°67'; SP2 -79° 33'; LO -78°00'; Spheroid: WGS84
Data sources:
Base imagery: aerial orthophoto, Nov 2008;
Zone boundaries & featues: From Raytheon Polar Services

Canada Glacier - Tourist Zone

Figure 1: Canada Glacier Tourism Zone and associated features. *Source*: Raytheon Polar Services.

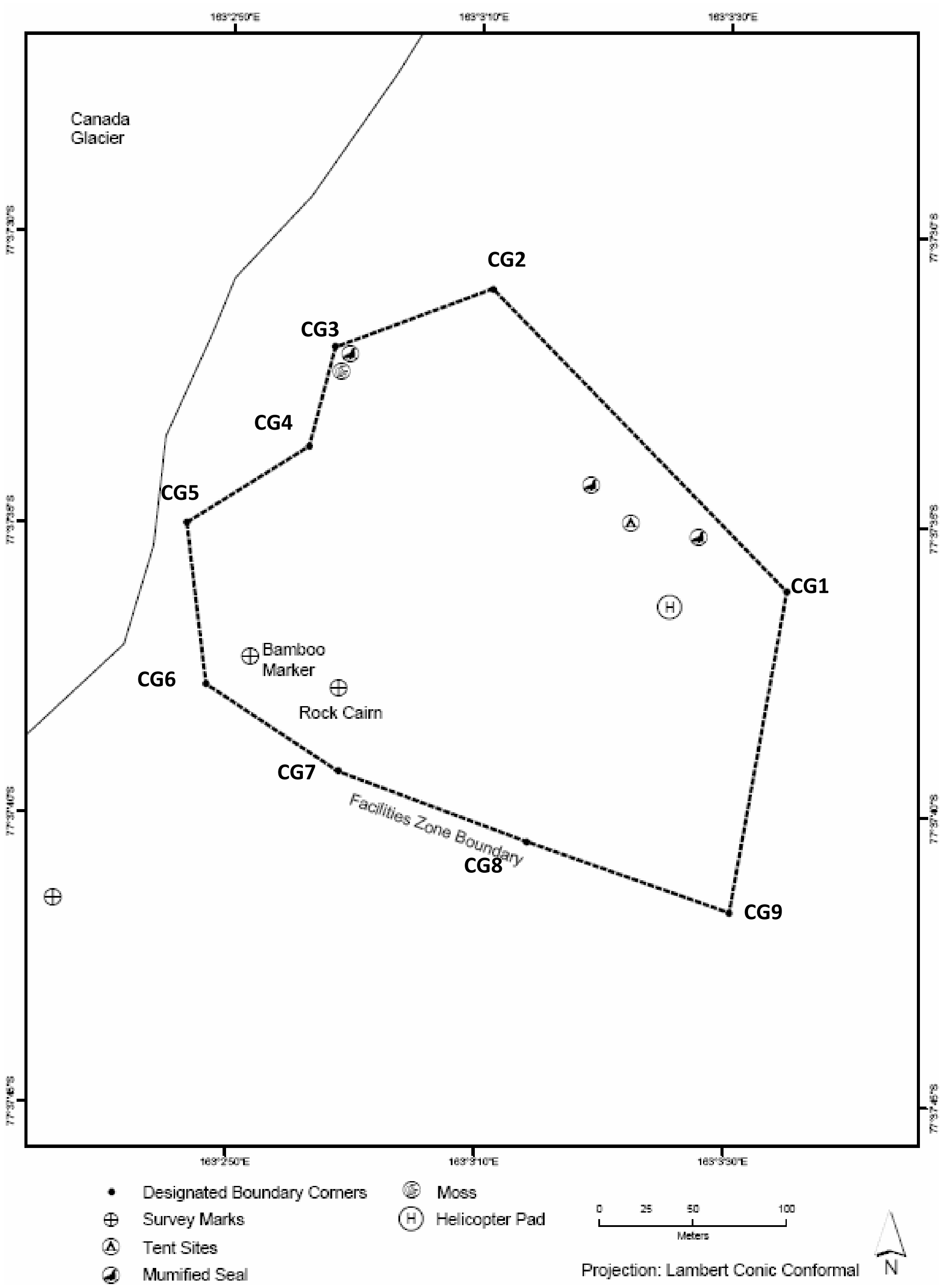


Figure 2: Canada Glacier Tourism Zone and associated features. CG1-9 are boundary markers. Source: Canada Glacier Tourism Zone Management Plan. ATCM, 2004.

Tourists are landed at a designated helicopter landing site and are then led by expedition guides around a roughly circular track that encompasses the more popular features of the zone (Antarctica New Zealand file notes, undated). Small guided groups explore a number of features including mummified seal carcases, a small patch of moss/lichen vegetation, the adjacent snout and pro-glacial lakes of the Canada Glacier (Photo 1), and walk to a lookout for a view of the glacier and wider area (Photo 2).

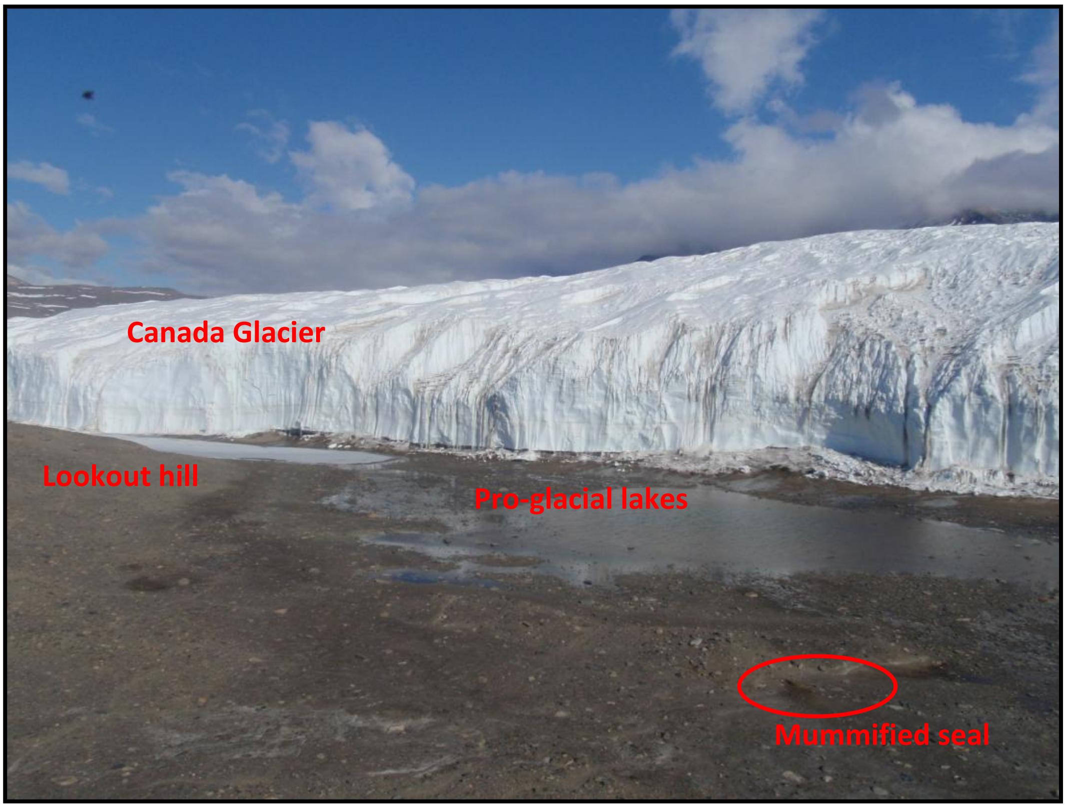


Photo 1: Canada Glacier Tourism Zone and associated features.

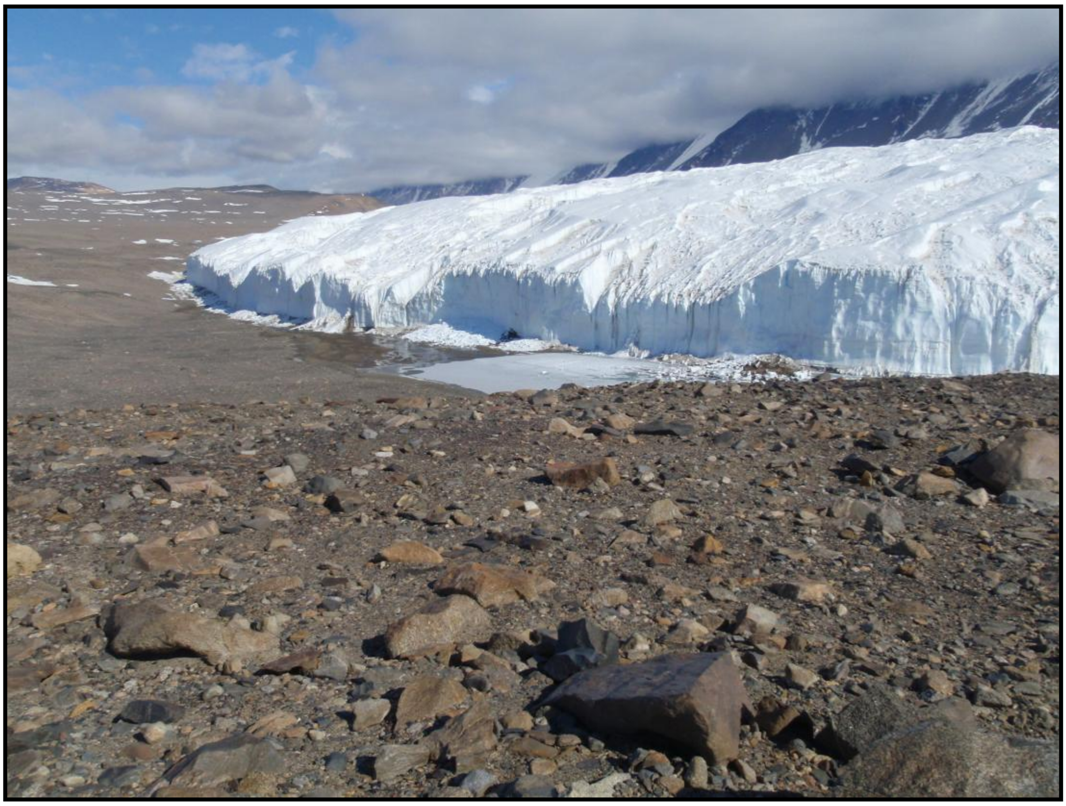


Photo 2: The view of the edge of the Canada Glacier from the Lookout.

This report details our observations during a 3-hour visit to the CGTZ on the 30th of December 2009. Given that the ASMA 2 (including the CGTZ) Management Plan is up for review in 2010, we were asked by the Environmental Management team of Antarctica New Zealand to comment on the current state of the Tourism Zone, noting ground disturbance, areas of resilience and vulnerability, the tracking behaviour of the tourists (evidence of deviation from established tracks), and comment on any evidence of recovery between seasons.

2. METHODS

Assessment of the impacts of human activity on the soil surface of the CGTZ was carried out using on-site observations, including: a set of replicable fixed point photos (VISTA, provided by Jana Newman, *Antarctica New Zealand*); Visual Site Assessments (VSA); Soil Vulnerability Indices (SVI); and Desert Pavement Recovery Assessments (DPRA). VSA, SVI, and DPRA were undertaken at four locations within the Tourism Zone, with impacts photo-documented, and GPS points recorded for future site recovery studies.

2.1 Visual Site Assessments and Soil Vulnerability Indices

A slightly modified version the VSA method of Campbell *et* al., (1993) was undertaken at four sites within the CGTZ (an example of which has been included in Appendix 2). The SVI of McLeod *et al*., (in prep) was also implemented at the four sites. The SVI provides a disturbance rating (over 10 boot imprints) and a recovery rating (governed by the nature of the parent material) of the soil. At each site 10 steps were tracked across the surface, imprints studied, and the number of nil versus partial breakthrough versus complete boot imprint breakthrough into the 2nd layer (horizon) of soil was counted and recorded. Based on the McLeod Index the relative susceptibility of the four sites to damage from foot and vehicle traffic was determined. The higher the SVI rating, the more vulnerable the site is to disturbance.

2.2 Desert Pavement Recovery Assessment

The DPRA system (Appendix 3) was formulated based on 13 distinguishing morphological features that change over time as the pavement re-establishes and stabilises (O'Neill *et al.,* in prep). Features included clast characteristics, such as embeddedness, impressions and attributes to describe clast characteristics (e.g. ventifacted, pitted); surface colour contrast; degree of deflation; varnish; pavement crust coherence and thickness; nature of pavement armour (packing and % of surface armoured); presence of salt coatings on rock undersides, as well as general surface stability (e.g. evidence of subsidence, melt, recent disturbance, and concentrations of salt).

The DPRA was applied to each site, and a relative % recovery for each parameter was calculated compared to a control or undisturbed equivalent surface. An overall Mean Recovery Index (MRI) was then assigned to each pavement surface, and is expressed as pavement Recovery Stage (RS) one through five (Table 1).

Table 1. Mean Recovery Index (MRI) and Recovery Stage (RS)

MRI (%)	Recovery Stage
0-24	Recently or highly disturbed
25-49	Incipient pavement
50-74	Intermediate recovery
75-99	Advanced recovery
100	Indistinguishable from control site

3. OBSERVATIONS:

3.1 Observations and concerns from previous Representatives:

Jana Newman, *Antarctica New Zealand, Environmental Officer*, in her summary of the Canada Glacier Tourism Zone, reported the following:

- There is obvious tracking at the site, most notably on the hills and around the helicopter landing site.
- Representative observations and VISTA photo-documentation have shown that the tracking at the site is quite persistent across seasons; although there seems to be some variability in the definition of the tracks, suggesting *some* recovery between visits.
- Minor tracking in the softer sediment around the margins of the pro-glacial ponds and terminus of the Canada Glacier have been noted.
- Ground disturbance associated with helicopter movement is evident, but minor and transitory.
- Cumulative effects of regular visitation (namely helicopter activity and foot-traffic) have been questioned.
- Past Representatives have also questioned the use of Confined tracks versus dispersed movement of visitors in relation to site recovery.

3.2 Observations at the CGTZ on 30th December 2009:

- Fresh helo skid marks were visible on the designated landing pad; although there was no evidence of wheel-marks, indicating it was likely that tourists had not yet visited in the 2009/2010 season. There was minor impact from helicopter activity.
- There are multiple tracks in the lower regions of the Tourism Zone between the helo pad and foot of the steeper part of the lookout hill. We suggest one clearly marked track to confine trafficking impacts.
- Indistinct foot-prints from the helo pad to the lower reaches of the track up the lookout hill; initially quite dispersed these become confined and follow natural patterned ground cracks up the gentle slope. Patterned ground cracks are naturally active parts of the

landscape, making last season's foot-prints on the lower confines of the hillslope, difficult to detect.

- Given the extensive foot-prints that would have occurred around the helo pad and emergency shelter area, season-to-season recovery is remarkably good; with old foot-prints in these well-trampled areas barely detectable. Our new foot-prints were however immediately evident.
- Tracking on the middle and upper sections of the lookout hill are more obvious due to the colour contrast between the tracks and adjacent undisturbed mixed till pavement. Track formation has resulted in the concentration of finer material in the middle of the track, and coarser (in this case often darker) clasts accumulating on the edges of the tracks.
- A single track is clearly attempted to be maintained up to the rock cairn on top of the hill. Minimal evidence of deviation from this track was observed.
- On the hilltop foot-prints are indistinct, although patches of finer material are evident, implying the area has been well-trampled. Areas showing little disturbance and a good armouring of pebble-sized clasts suggest the effect of wind and snow aids in the recovery of the hilltop between seasons.
- Towards the glacier-front a single track is enforced in the steeper declines; foot-prints and deeper foot-slip marks are obvious here. The track is narrow (average of 40 cm across) and well-defined to the bamboo marker pole, where the track widens slightly as the gradient of the slope decreases.
- VISTA photo-replication shows that the tracks within the CGTZ persist between seasons, remaining visible in the landscape. This is ultimately the result of the larger pavement clasts being pushed to the outer margin of the tracks where they remain indefinitely, even if the pavement within the track itself begins to recover.

- North-western boundaries between the pro-glacial ponds and the glacier-proper are ill-defined and there is evidence of wandering foot-prints (most likely 2009/2010 season research programme personnel) outside of boundaries between CG3 and CG4 (Figure 2). We were told that scientists are known to follow the pond edge whilst traversing between Lake Fryxell and Lake Hoare; this being the quickest route of least resistance, clearly bringing them outside CG3, CG4, and CG5.
- The grid coordinates for boundary marker CG1, as shown on the latest Raytheon topographic map of the Tourism Zone, are incorrect and the easting should be 163°03.556' E (CG1 = 77°37.609' S 163°03.556' E).
- As observers familiar with the McMurdo Dry Valleys we felt that the CGTZ provides an excellent 'Dry Valleys experience' for tourists as it is fairly typical of the environment with attractive glacier views and a prominent hilltop providing an excellent viewing platform.

4. SPECIFIC SITES

Four sites were investigated: 1) Lower track up to the Canada Glacier lookout, 2) Lookout on the hilltop, 3) Steep track to the terminus of the Canada Glacier, and 4) Low-lying soft, sand-rich site 10 m from pro-glacial lake and boundary CG3. The data are reported below for each site and interpretation of results is given in the following discussion. Full site description, VSA, SVI, and DPRA data is included in Appendix 4.

4.1 Lower Track up to the Lookout

The **Lower Track up to the Lookout** (see Appendix 4 for site details) is generally well confined and follows the natural patterned ground cracks up the gentle slope (Photo 3). The track was evident due to the paucity of large stones and faint residual indentations of foot-prints. However, the desert pavement surface had re-established providing a stable, natural surface. VSA, SVI, and DPRA investigations show the site is relatively resilient to trafficking, recovers well between seasons; and has a recovery stage of four, or relatively advanced recovery.

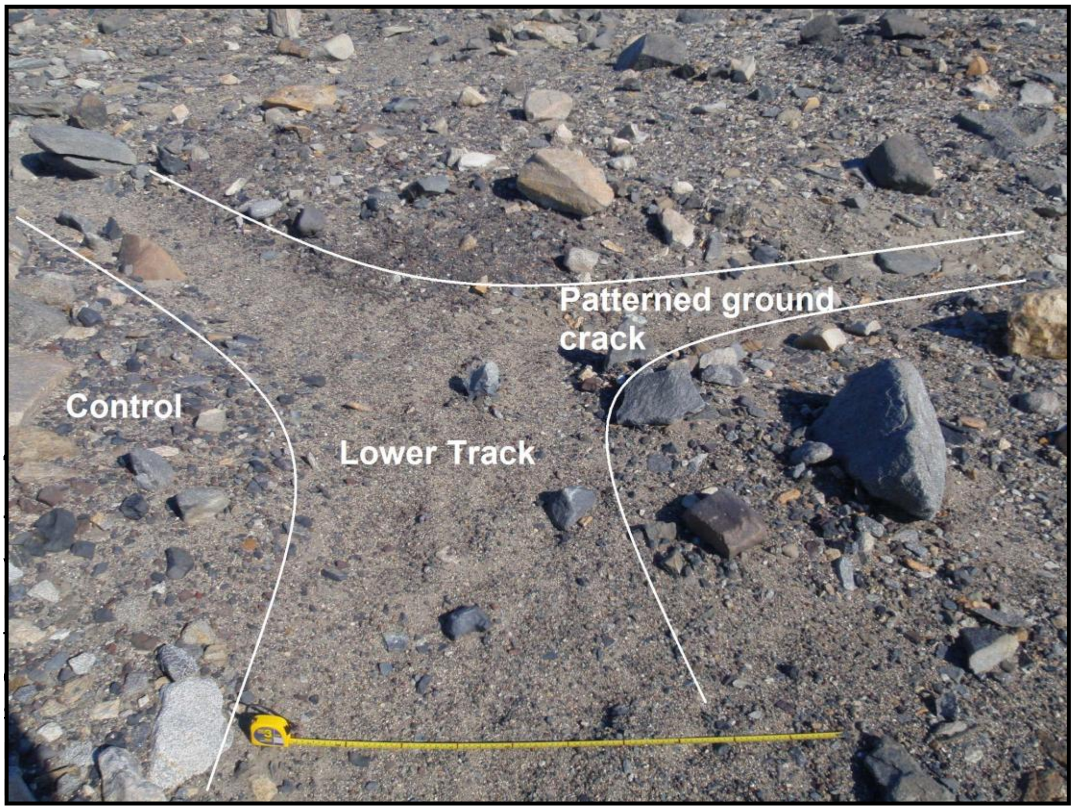


Photo 3: Lower Track up to the Canada Glacier Lookout. Note track follows natural patterned ground cracks. Marks on the tape measure an in 10 cm intervals.

4.2 Lookout

The **Lookout** (Appendix 4) is inevitability an area of widespread trampling as it is the main vantage point for views of the Canada Glacier. However, the area shows good surface pavement recovery, with a well armoured desert pavement and little evidence of residual foot-prints (Photo 2). Around the cairns there are patches of finer material (Photo 4), but overall surface recovery is likely to be attributed to wind and snow action between summer seasons. VSA, SVI, and DPRA investigations show the site is resilient to trafficking, recovers well between seasons; and has a recovery stage of four, or relatively advanced recovery.

Photo 4: Mixed till pavement at Canada Glacier Lookout.

4.3 Steep Track to terminus of Canada Glacier

The **Steep Track** (Appendix 4) from the Lookout to the Pro-glacial Lake Margin is one of the most vulnerable parts of the Tourism Zone. The steep gradient of the track and loose nature of the till materials, unavoidably results in greater visible impacts from foot-traffic, deeper print, and foot-scrape marks, and as a result, it is preferable that all visitors stay on a single confined track. Photos 5, 6 and 7 suggest deviation from the current track has occurred in the past, and that the pavement is capable of recovering from these one-off deviations; however, the use of a confined single track is advised. As visitors approach the bamboo marker pole the track widens as the gradient of the slope decreases. VISTA (Antarctica New Zealand Visual Site Assessment Scheme), VSA, SVI, and DPRA investigations show the site is vulnerable to the immediate and cumulative effects of foot-traffic, however, does show some recovery between seasons. The Steep Track site has a Mean Recovery Index of 42%, which equates to Recovery Stage 2-3, or Incipient-Intermediate Recovery.

Photo 5: Steep slope from Lookout to bamboo pole and Canada Glacier front. Note arrows show some previous trampling on either side of the track, and our own fresh foot-prints on the track.

Photo 6: Our fresh foot-prints on the steep track from Canada Glacier Lookout. Note: narrow width of track compared with the lower track up to the lookout and accumulation of large clasts along the margin of the track. Arrows show traces of old foot-prints faintly visible either side of the present day track.

Photo 7: Desert pavement on the steep track control site. The site shows signs of prior trampling but the desert pavement has recovered and is largely intact.

VISTA photo-replication was carried out at the **Steep Track** from the Lookout to the Pro-glacial Lake Margin. This involved replicating a key 'fixed point photo' using key marker points, in this case a bamboo marker pole, so changes in ground disturbance can be visually monitored between seasons. Photo point replication on the Steep Track showed that the physical impacts of the track within the CGTZ persist between seasons (Photo 8, 9 and 10).

Photo 8: 06/07 season, post-96 visitors (*Photo supplied:* Jana Newman)

Photo 9: 08/09 season,
pre-83 visitors (*Photo supplied:* Clayton-Greene)

Photo 10: 09/10 season, before first tourists (*Photo supplied:* Jeronimo Lopez-Martinez)

Distinct foot-prints from the previous summer season where 93 tourists landed (plus unknown numbers of science personnel) were not evident. Our new foot-prints were however clearly evident as were one set we interpreted as recently formed, probably by a local science research person traversing the area. An overall contrast in pavement colour between the track and adjacent undisturbed mixed till pavement was evident, and is carried over season-to-season (Photo 8, 9, and 10). The colour difference was predominately a result of the larger (and in this case darker) pavement clasts being pushed to the outer margin of the track, concentrated, where they remain for the foreseeable future, even if the desert pavement within the track itself begins to recover. It is important to note, however, photos 8 and 10 show that the colour contrast between track and control is much less pronounced after the site has had a winter to recover; implying recovery of the desert pavement does occur between tourist seasons.

4.4 Pro-glacial Lake Margin

The **Pro-glacial Lake Margin** (Photo 11 and Appendix 4) site is another vulnerable area within the CGTZ. The North-western boundary between the TZ, pro-glacial lakes and Canada Glacier-proper are ill-defined and there is evidence of wandering foot-prints outside of boundary markers CG2 and CG3 (Figure 2). Foot-prints were fresh and most likely a result of 2009-2010 season research programme personnel traversing between Lake Fryxell and Lake Hoare. We recommend the North-western boundary of the CGTZ be clearly marked to avoid visitors disturbing the susceptible pro-glacial lake margin; and that the National Programmes that currently work in the Taylor Valley communicate with and educate the importance of one rule for all visitors to the area. Tourists should not have one set of rules and National Programme personnel another as it will cause confusion and animosity. VSA, SVI, and DPRA investigations show this moist site would recover quickly from the effects of foot-traffic, however, ASMA 2 Guidelines for the Tourism Zone indicate that pond beds should be avoided.

Photo 11: Low-lying wet, sand-rich till site on the edge of the CGTZ, on margin of pro-glacial lake and CG3.

5. CONCLUSIONS

- The CGTZ provides an excellent 'Dry Valleys experience' for tourists as it is fairly typical of the environment with attractive glacier views and a prominent hilltop providing an excellent viewing platform. We were impressed with the overall management of the CGTZ; how well the site recovered between seasons; and it is clear that tourist operators go to great efforts to ensure their clients follow a single flagged track.

- VISTA photo-replication shows that the physical impacts of the tracks within the CGTZ persist between seasons. Distinct foot-prints were not evident; except for ours and one set we interpreted as recently formed, probably by a local science research person traversing the area. An overall contrast in pavement colour between the track and adjacent undisturbed mixed till pavement was evident; and due to the concentration of larger clasts being pushed to the outer margin of the track, where they remain for the foreseeable future.

- VISTA photo-replication shows that the colour contrast between track and adjacent control is much less pronounced after the site has had a winter to recover; implying desert pavement recovery does occur between tourist seasons

- Trampling is unavoidable around the helo pad, however there is evidence for good recovery of desert pavement between seasons.

- We suggest one clearly marked track (low cairns = natural rock of the area; or other low marker poles) between the helo pad and foot of the Lookout hill to confine trafficking impacts. If cairns are used it must be made clear to tourists that they are there for a purpose and building further cairns is unacceptable.

- A single track along pre-existing patterned ground cracks has generally been maintained up to the rock cairn on top of the hill. It was apparent that most visitors were staying on the track.

- On the hilltop 'Lookout' patches which lacked coarse fragments were evident, implying the area has been well-trampled. Overall the hilltop Lookout showed little disturbance and a good armouring of pebble-sized clasts suggest the effect of wind and snow aids in the recovery the site between seasons.

- A steep single track was formed between the Lookout and the glacier front. Our foot-prints and foot-slip marks were very distinct due to the steep decline of this track and loose nature of the till materials. A confined track is most appropriate on the steep surface.

- The North-western boundaries between the pro-glacial ponds and the Canada Glacier were ill-defined and there was evidence of wandering foot-prints outside of the boundaries between CG2 and CG3.

- Our observations suggest there was some recovery of the desert pavement between seasons, likely to be a function of wind and/or snow action, however tracks remain due to larger clasts being concentrated on the outer margin of the track, where, without remediation, they remain indefinitely.

6. RECOMMENDATIONS

The lower section of the CGTZ between the helo pad and foot of the Lookout hill should be clearly defined so tourism operators and science programme visitors can easily locate the flagged route and to avoid multiple tracks forming.

We suggest that permanent low marker poles should be erected along the north-western boundary of the CGTZ at CG3, CG4, and CG5; between the Tourism Zone, pro-glacial ponds and the glacier. This will stop traffic wandering too close to the moist sediment near the pond margins, and minimise impacts to algae.

Research by Campbell and others (1998) has shown that once a track has formed (within 20 or so passes) the cumulative impacts of larger numbers of people following the same track are minimal. Thus at this site we consider it preferable to keep visitors to a single confined track in all areas of the TZ, particularly in the steeper sections of the Lookout hill. A single confined track will preserve the existing undisturbed desert pavement adjacent to current tracks, preserving the natural integrity of the landscape.

For consistency we recommend all traffic within the CGTZ should stay on pre-existing tracks, following patterned ground cracks where possible. It is advisable to discourage all other visitors to the area (e.g. science programme personnel) from walking along the CGTZ boundary, as this will avoid confusion within tourist groups and between different operators. The implementation of permanent markers across the north-western boundary and between the helo pad and base of the Lookout hill will assist in the effort to minimize the human footprint in the CGTZ.

7. REFERENCES

Antarctica New Zealand, 2004, *"McMurdo Dry Valleys ASMA Manual"*, Antarctica New Zealand, Christchurch.

Campbell, I. B., Balks, M. R., Claridge, G. G. C. 1993. A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record 29* (171), 321-328.

Campbell, I.B., Claridge, G.G.C., Balks, M. R. 1998. Short- and long-term impacts of human disturbances on snow-free surfaces in Antarctica. *Polar Record 34(188)* 15-24.

McLeod, M., Balks, M. R., Hewitt, A. E., Bockheim, J. G. *in prep.* A rapid method to assess impact of foot trampling on ice-free soils of Wright Valley, Antarctica.

O'Neill, T. A., Balks, M. R., López-Martínez, J. *in prep.* A method for assessing the impact on, and recovery of, Antarctic Desert Pavements from human-induced disturbances.

APPENDIX 1:

Guidelines for the Tourism Zone

Special guidelines for activities within the Tourism Zone include that:

- Tourist movements in the Tourism Zone should be conducted in small, guided groups;
- Tour operators should ensure that footpaths in the Tourism Zone are clearly marked and that visitors stay on those routes. Markers used to mark tourist routes and sites of interest should be removed at the end of each visit;
- Tour expedition landings should be made at a landing site at 77.6358°S, 163.0656°E;
- Tents should only be established at the designated site and groups should not camp in the Tourism Zone except for reasons of safety;
- Stream and pond beds should be avoided. If streams must be crossed, designated crossing points including existing boulders should be used; and
- Activities planned for and conducted within the Zone should be in accordance with ATCM Recommendation XVIII-1.

The Tourism Zone is located in the Taylor Valley by the Canada Glacier. The boundary goes from a northernmost point by the Canada Glacier, southeast to a point northwest of a mossy area and nearby mummified seal, continuing southwest along the Canada Glacier, south to a point southwest of a bamboo marker, southeast to a point south of a rock cairn, southeast following high points encompassing the flat area of the Zone and a footpath to a point in the south, north continuing to parallel the footpath along elevated features in the landscape, northwest passing northeast of a mummified seal and the tent site and back to the original northernmost point by the Canada Glacier.

APPENDIX 2: Visual Site Assessment Form

Impact Assessment Criteria		Severity and Extent of Impacts (class)				Comments	Rating
		1	2	3	4		
A.	Disturbed surface stones	none visible (0)	few (<10)	many (10–25)	abundant (>25)		
B.	Impressions of removed rocks	none visible	just visible	distinct	fresh		
C.	Boot imprints	none visible	just visible	distinct	fresh		
D.	Visibly disturbed area	<5 m^2	5–10 m^2	20–100 m^2	>100 m^2		
E	Other surface impressions (e.g.shallow concavities from backfilled excavations)	none visible	weakly visible	distinct	very fresh		
F	Walking tracks	not visible	weakly defined	moderately defined	strongly defined		
G	Foreign objects	none visible (0)	few (<10)	some (10–25)	many (>25)		
H	Visible fuel spills	none visible	faintly distinguished	visible	very obvious		
I	Salt deposition	none visible	faintly distinguished	visible	abundant		
J	Biological disturbance	none visible	<1 m^2	1–5 m^2	>5 m^2		
K	Cumulative impact (scale 1–10)	disturbance not visible (0)	weakly evident (1–2)	clearly visible (3–5)	disturbed and very obvious (>5)		
L	Stratigraphic disturbance	negligible	within one unit	within two units	multiple units		
M	Morphological or textural change	negligible	just evident	moderate change	very obvious		
N	Rock cairns	none	rare or small	moderately common	very common		
O	Paint marks	none	rare or small	moderately obvious	very obvious		
P	Other	none	rare or small	moderately obvious	very obvious		
Site:					Photo:		

APPENDIX 3: Desert Pavement Recovery Assessment Form

	Desert Pavement Recovery Criteria	0 Highly Disturbed	1 Clearly Disturbed	2 Moderately Disturbed	3 Weakly Disturbed	4 Undisturbed
I	Embeddedness of surface clasts	none	few	some	most	all
II	Impressions of removed clasts	sharp/fresh	clear	distinct	faint	not visible
III	Degree of clast surface weathering (i.e ventifaction, pitting, polish)	unweathered	weakly weathered	moderately weathered	strongly weathered	very strongly weathered
IV	% overturned clasts	> 75%	50-75%	20-50%	1-20%	0%
V	Salt on underside of clasts - "10 cobble" test	0-20%	20-40%	40-60%	60-80%	80-100%
VI	Degree of development of salt coatings	not visible	weakly developed	moderately developed	strongly developed	very strongly developed
VII	Armouring ($1m^2$ test plot)	0-20%	20-40%	40-60%	60-80%	80-100%
VIII	Colour contrast (munsell unit difference)	very strong (>3)	strong (3)	moderate (2)	weak (1)	not visible (0)
IX	Evidence of subsidence and melt-out	prominent	distinct	faint	indistinct	not visible
X	Accumulation of salt on cut surfaces	abundant	common	some	rare	not visible
XI	Patterned ground development	not visible	indistinct	faint	distinct	prominent

APPENDIX 4:

Site Specific Visual Site Assessment, Soil Vulnerability, and Desert Pavement Recovery Assessment Data

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4.1 Lower Track up to the Lookout

Site number: TAO-10-25

Location: Lower Track up to the CG Lookout (Photo 3)

GPS: 77° 37' 35.3'' S, 163° 03' 18.6'' E

Elevation: 30 m

Site description: Lower confined track up to the CG Lookout; following patterned ground crack.

Parent material: Mixed till; dominated by Ferrar dolerite and Beacon sandstone.

Slope: 3 degrees

Track width: 80 to 100 cm.

Disturbance history: Present day access track to the glacier Lookout. Track has been in use since at least 1995. Last tourist use approximately 9 months prior to our visit, at the end of the 2008/2009 summer.

Visual Site Assessment:

Site	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	Q
Lower Track	4	1	3	4	2	1	4	1	1	1	1	4	4	4	1	1
Lower Track, control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Impact Assessment Criteria: A = disturbed surface stones; B = impressions of removed rocks; C = boot imprints; D = visibly disturbed area; E = surface colour difference; G = other surface impressions; H = walking tracks; I = foreign objects; J = visible fuel spills; K = salt deposition; L = biological disturbance; M = cumulative impact; N = stratigraphic disturbance; O = textural change; P = rock cairns; Q = paint marks. **Severity and Extent of Impacts**: rating of 1 is least disturbed/impacted, rating of 4 is severely disturbed/impacted.

Soil Vulnerability Index:

Lower Track - 10@1 = 100

Lower Track, control - 5@2, 1@1, 4@0 = 110

Desert Pavement Recovery Assessment:

Parameter	Lower Track control	Lower Track	% recovery
i	3	1	33.3
ii	4	4	100.0
iii	2.5	2.5	100.0
iv	4	1	25.0
v	4	3	75.0
vi	1.5	1.5	100.0
vii	4	3	75.0
viii	4	1	25.0
ix	0	0	100.0
x	0	0	100.0
xi	0	0	100.0
xii	0	0	100.0
xiii	3	3	100.0
MRI			**79.5**

Classification criteria: I = embeddedness; ii = impressions; iii = clast weathering; iv = % overturned clasts; v = salt undersides; vi = salt nature; vii = % armouring; viii = colour contrast; ix = crust integrity; x = crust thickness; xi = subsidence/melt; xii = salt accumulation; xiii = patterned ground development.

Mean Recovery Index (MRI) is 79.5%, which equates to Recovery Stage 4, or Advanced Recovery.

4.2 Lookout

Site number: TAO-10-26

Location: CG Lookout, near rock cairn (Photo 2)

GPS: 77° 37' 38.7'' S, 163° 03' 03.6'' E

Elevation: 53 m

Site description: Flat, top of the prominent CGTZ hill, CG Lookout.

Parent material: Mixed till pavement (Photo 4); dominated by Ferrar dolerite and Beacon sandstone.

Slope: 0 degrees; flat

Disturbance history: Present day viewpoint of the terminus of the Canada Glacier. Lookout has been in use since at least 1995.

Visual Site Assessment:

Site	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	Q
Lookout	4	2	3	4	3	1	4	1	1	1	1	4	2	3	3	1
Lookout, control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Impact Assessment Criteria: A = disturbed surface stones; B = impressions of removed rocks; C = boot imprints; D = visibly disturbed area; E = surface colour difference; G = other surface impressions; H = walking tracks; I = foreign objects; J = visible fuel spills; K = salt deposition; L = biological disturbance; M = cumulative impact; N = stratigraphic disturbance; O = textural change; P = rock cairns; Q = paint marks. **Severity and Extent of Impacts**: rating of 1 is least disturbed/impacted, rating of 4 is severely disturbed/impacted.

Soil Vulnerability Index:

Lookout - 7@1, 3@0 = 70

Lookout, control - 1@1, 9@0 = 10

Desert Pavement Recovery Assessment:

Parameter	Lookout control	Lookout	% recovery
i	3	2	66.7
ii	4	2	50.0
iii	2.5	2.5	100.0
iv	4	3	75.0
v	4	4	100.0
vi	2	2	100.0
vii	4	3	75.0
viii	4	1	25.0
ix	0	0	100.0
x	0	0	100.0
xi	0	0	100.0
xii	0	0	100.0
xiii	4	4	100.0
MRI			**84.0**

Classification criteria: I = embeddedness; ii = impressions; iii = clast weathering; iv = % overturned clasts; v = salt undersides; vi = salt nature; vii = % armouring; viii = colour contrast; ix = crust integrity; x = crust thickness; xi = subsidence/melt; xii = salt accumulation; xiii = patterned ground development.

Mean Recovery Index (MRI) is 84%, which equates to Recovery Stage 4, or Advanced Recovery.

4.3 Steep Track to terminus of Canada Glacier

Site number: TAO-10-27

Location: Steep slope from Lookout to bamboo pole (Photo 5)

GPS: 77° 37' 37.6'' S, 163° 02' 52.4'' E

Elevation: 76 m

Site description: Steep track from Lookout to the bamboo VISTA pole and terminus of the Canada Glacier.

Parent material: Mixed till (Photos 6 and 7); dominated by Ferrar dolerite and Beacon sandstone.

Slope: 20+ degrees; steep.

Track width: average 40 cm (Photo 6)

Disturbance history: Part of the present day circuit from the CG Lookout to the north-western boundary of the CGTZ and terminus of the Canada Glacier.

Likely that this track has been in use since at least 1995.

Visual Site Assessment:

Site	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	Q
Steep Track	4	2	4	4	4	1	4	1	1	1	1	4	4	4	1	1
Steep Track, control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Impact Assessment Criteria: A = disturbed surface stones; B = impressions of removed rocks; C = boot imprints; D = visibly disturbed area; E = surface colour difference; G = other surface impressions; H = walking tracks; I = foreign objects; J = visible fuel spills; K = salt deposition; L = biological disturbance; M = cumulative impact; N = stratigraphic disturbance; O = textural change; P = rock cairns; Q = paint marks. **Severity and Extent of Impacts**: rating of 1 is least disturbed/impacted, rating of 4 is severely disturbed/impacted.

Soil Vulnerability Index:

Steep Track **-** 6@1, 4@2 = 140

Steep Track, control **-** 8@1, 2@0 = 80

Desert Pavement Recovery Assessment:

Parameter	Steep Track control	Steep Track	% recovery
i	3	0	0.0
ii	4	1	25.0
iii	2.5	2.5	100.0
iv	4	0	0.0
v	4	0	0.0
vi	2	0	0.0
vii	3.5	0	0.0
viii	4	1	25.0
ix	0	0	100.0
x	0	0	100.0
xi	0	0	100.0
xii	0	0	100.0
xiii	3	0	0.0
MRI			**42.3**

Classification criteria: I = embeddedness; ii = impressions; iii = clast weathering; iv = % overturned clasts; v = salt undersides; vi = salt nature; vii = % armouring; viii = colour contrast; ix = crust integrity; x = crust thickness; xi = subsidence/melt; xii = salt accumulation; xiii = patterned ground development.

Mean Recovery Index (MRI) is 42%, which equates to Recovery Stage 2-3, or Incipient-Intermediate Recovery.

4.4 Pro-glacial Lake Margin

Site number: TAO-10-28

Location: Low-lying soft sand-rich site 10 m from pro-glacial lake and CG 3 (Photo 11).

GPS: 77° 07' 04.4'' S, 163° 02' 48.3'' E

Elevation: 39 m

Site description: Low-lying wet and soft sand-rich till site on the edge of the CGTZ, 10 m from pro-glacial lake and CG3.

Parent material: Mixed till and sand; dominated by Ferrar dolerite and Beacon sandstone.

Slope: 0 degrees; flat.

Disturbance history: Reasonably undisturbed site on the edge of the CGTZ. Some evidence of scattered foot-traffic, but no major traffic flow.

Visual Site Assessment:

Site	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	Q
CGTZ margin, near proglacial lake	1	1	2	2	1	1	1	1	1	1	1	2	1	1	1	1
Control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Impact Assessment Criteria: A = disturbed surface stones; B = impressions of removed rocks; C = boot imprints; D = visibly disturbed area; E = surface colour difference; G = other surface impressions; H = walking tracks; I = foreign objects; J = visible fuel spills; K = salt deposition; L = biological disturbance; M = cumulative impact; N = stratigraphic disturbance; O = textural change; P = rock cairns; Q = paint marks. **Severity and Extent of Impacts**: rating of 1 is least disturbed/impacted, rating of 4 is severely disturbed/impacted.

Soil Vulnerability Index:

CGTZ margin, near pro-glacial lake – 8@2, 2@0 = 160

Control - 8@2, 2@0 = 160

Desert Pavement Recovery Assessment:

Parameter	Control	CGTZ margin	% recovery
i	4	4	100.0
ii	4	4	100.0
iii	2	2	100.0
iv	4	4	100.0
v	0	0	100.0
vi	0	0	100.0
vii	3	3	100.0
viii	0	0	100.0
ix	0	0	100.0
x	0	0	100.0
xi	0	0	100.0
xii	0	0	100.0
xiii	0	0	100.0
MRI			**100.0**

Classification criteria: I = embeddedness; ii = impressions; iii = clast weathering; iv = % overturned clasts; v = salt undersides; vi = salt nature; vii = % armouring; viii = colour contrast; ix = crust integrity; x = crust thickness; xi = subsidence/melt; xii = salt accumulation; xiii = patterned ground development.

Mean Recovery Index (MRI) is 100%, which equates to Recovery Stage 5, or indistinguishable from an undisturbed site.

APPENDIX 3

Soil chemistry data for Ross Sea region sites

Soil pH, soil electrical conductivity, and soil water content of Ross Sea region sites

General Location	Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)
Cape Evans, Ross Island	Profile 1 - Disturbed site - DP (0-1 cm)	1	0.3	8.16	0.80
	Profile 1 - Disturbed site - H2 (1-15 cm)	2	0.4	8.16	0.75
	Profile 1 - Disturbed site - H3 (15-38 cm)	3	1.2	7.96	0.10
	Profile 2 - Undisturbed site - DP (0-1 cm)	4	0.3	7.50	0.72
	Profile 2 - Undisturbed site - H2 (1-14 cm)	5	0.4	7.90	0.15
	Profile 2 - Undisturbed site - H3 (14-50 cm)	6	2.0	7.25	0.04
	Profile 1 - Disturbed site - churned soil (0-15 cm)	7	0.4	7.55	0.26
	Jonno's fill	8	5.2	9.54	1.44
Crater Hill, Ross Island	Profile 3 - Nov 2008 disturbed site, near Turbine 2 - mound top (0-6 cm)	9	10.7	9.49	0.30
	Profile 3 - Nov 2008 disturbed site, near Turbine 2 - mound ice (6+ cm)	10	-	8.38	1.93
	Profile 4 - Nov 2008 disturbed site, near Turbine 2 - side mound top (0-8 cm)	11	3.5	9.40	0.31
	Profile 4 - Nov 2008 disturbed site, near Turbine 2 - side mound moist "H2" (8-28 cm)	12	7.3	9.55	0.11
	Profile 4 - Nov 2008 disturbed site, near Turbine 2 - salt on side mound (0-2 cm)	13	-	8.97	1.81
	Profile 4 - Nov 2008 disturbed site, near Turbine 2 - side mound ice (28+ cm)	14	-	8.44	0.53
	Profile 5 - Nov 2008 disturbed site - Turbine 2 pad - H1 (0-15 cm)	15	3.8	9.04	1.79
	Profile 5 - Nov 2008 disturbed site - Turbine 2 pad - H2 (20-25 cm)	16	8.4	9.74	0.45
	Profile 5 - Nov 2008 disturbed site - Turbine 2 pad - H3 (25-30 cm)	17	10.9	9.70	0.49
	Profile 5 - Nov 2008 disturbed site - Turbine 2 pad - salt (0-1 cm)	18	-	9.14	22.53
	Profile 6 - Nov 2008 recent cut, roadside opposite Turbine 2 - salt (0-2 cm)	19	-	10.02	35.27
	Profile 6 - Nov 2008 recent cut, roadside opposite Turbine 2 - cut surface (0-5 cm)	20	7.8	10.33	1.50
	Profile 6 - Nov 2008 recent cut, roadside opposite Turbine 2 - ice (5+ cm)	21	-	9.04	1.79
	Profile 7 - Nov 2008 recent cut+fill site, roadedge, near Turbine 2 - incipent DP (0-1 cm)	22	0.7	8.44	1.00
	Profile 7 - Nov 2008 recent cut+fill site, roadedge, near Turbine 2 - "H2" (1-20 cm)	23	1.5	8.53	1.04
	Profile 7 - Nov 2008 recent cut+fill site, roadedge, near Turbine 2 - "H3" (20-33 cm)	24	7.2	9.69	0.35
	Profile 8 - Nov 2008 recent cut+fill site (fill) behind Turbine 1 - incipent DP (0-3 cm)	25	1.7	8.66	1.90
	Profile 8 - Nov 2008 recent cut+fill site (fill) behind Turbine 1 - "H2" (3-25 cm)	26	7.0	9.70	0.21
	Profile 8 - Nov 2008 recent cut+fill site (fill) behind Turbine 1 - "H3" (25-38 cm)	27	7.4	9.75	0.31
	Profile 8 - Nov 2008 recent cut+fill site (fill) behind Turbine 1 - ice cemented "H5" (50-55 cm)	28	9.5	8.95	0.72
Scott Base, Ross Island	Recovering surface adj. to IR 1 (3 m from IR 1), SB to McMurdo Rd track (0-2 cm) (rep 1)	29	-	9.16	0.50
	Recovering surface adj. to IR 1 (3 m from IR 1), SB to McMurdo Rd track (0-2 cm) (rep 2)	30	-	9.28	0.69
	SB to McM Road shortcut track (0-2 cm) (rep 1)	31	-	9.72	0.35
	SB to McM Road shortcut track (0-2 cm) (rep 2)	32	-	9.51	0.10
	SB to McM Road shortcut track (0-2 cm) (rep 3)	33	-	9.51	0.28
	SB to McM Rd Track - IR1 site - 0-2 cm	34	1.7	9.53	0.28
	SB to McM Rd Track - IR1 site - 2-5 cm	35	4.7	9.62	0.16
	SB to McM Rd Control - IR1 site - desert pavement	36	-	-	-
	SB to McM Rd Control - IR1 site - 0-2 cm	37	1.1	9.78	0.37
	SB to McM Rd Control - IR1 site - 2-5 cm	38	2.3	9.82	0.26

Soil pH, soil electrical conductivity, and soil water content of Ross Sea region sites

General Location	Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)
Crater Hill, Ross Island	Crater Hill Summit track,lower unconfined Track - 0-2 cm	39	1.0	8.45	1.26
	Crater Hill Summit track,lower unconfined Track - 2-5 cm	40	2.1	8.52	0.99
	Crater Hill Summit track,lower unconfined Control - desert pavement	41	-	-	-
	Crater Hill Summit track,lower unconfined Control - 0-2 cm	42	1.8	8.25	2.30
	Crater Hill Summit track,lower unconfined Control - 2-5 cm	43	1.9	8.34	2.08
	Crater Hill Summit track, IR7 Track - 0-2 cm	44	1.0	9.41	0.16
	Crater Hill Summit track, IR& Track - 2-5 cm	45	3.0	9.48	0.09
	Crater Hill Summit track, IR7 Control - desert pavement	46	-	-	-
	Crater Hill Summit track,IR7 Control - 0-2 cm	47	1.9	9.63	1.05
	Crater Hill Summit track, IR7 Control - 2-5 cm	48	4.1	9.35	0.50
Scott Base, Ross Island	SB active layer disturbance site, disturbed 0-2 cm	49	2.6	9.67	0.14
	SB active layer disturbance site, disturbed 2-5 cm	50	4.5	9.66	0.07
	SB active layer disturbance site, salty disturbed 0-2 cm	51	5.9	8.39	1.64
	SB active layer disturbance site, salty disturbed 2-5 cm	52	7.8	8.76	0.86
	SB active layer disturbance site, disturbed FILL 2-5 cm	53	4.6	9.00	1.49
	Williams Field to McM pipeline, disturbed 0-2 cm	54	2.0	9.86	1.68
	Williams Field to McM pipeline, disturbed 2-5 cm	55	4.1	9.88	0.69
	Williams Field to McM pipeline, control, desert pavement	56	-	-	-
	Williams Field to McM pipeline, control 0-2 cm	57	1.9	9.05	3.82
	Williams Field to McM pipeline, control 2-5 cm	58	3.6	8.81	1.41
	Telecom cableway, disturbed 0-2 cm	59	0.8	9.89	0.21
	Telecom cableway, disturbed 2-5 cm	60	2.8	10.03	0.23
	Telecom cableway, control, desert pavement	61	-	-	-
	Telecom cableway, control 0-2 cm	62	1.1	9.80	0.76
	Telecom cableway, control 2-5 cm	63	2.1	9.75	0.52
	SB active layer disturbance site, control 0-2 cm	64	3.0	9.82	1.86
	SB active layer disturbance site, control 2-5 cm	65	6.7	9.98	1.00

Soil pH, soil electrical conductivity, and soil water content of Ross Sea region sites

General Location	Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)
Marble Point, Antarctic Mainland	North of experimental tarmac mound (concrete), disturbed 0-2 cm	66	1.7	9.85	0.19
	North of experimental tarmac mound (concrete), disturbed 2-5 cm	67	1.6	9.94	0.22
	North of experimental tarmac mound (concrete), control 0-2 cm	68	6.9	9.46	0.38
	North of experimental tarmac mound (concrete), control 2-5 cm	69	6.7	9.61	0.09
	Raised beach ridge sequence, control 0-2 cm	70	5.0	9.50	0.73
	Raised beach ridge sequence, control 2-5 cm	71	4.4	9.41	0.35
	Raised beach ridge sequence, control 5-20 cm	72	2.0	9.22	0.17
	Raised beach ridge sequence, control 0-5 cm, moisture sample	73	3.7	9.50	0.71
	Raised beach ridge sequence, compacted 0-2 cm	74	3.1	8.47	3.15
	Raised beach ridge sequence, compacted 2-5 cm	75	6.2	8.90	0.52
	Raised beach ridge sequence, compacted 5-20 cm	76	6.4	8.57	0.31
	Raised beach ridge sequence, bulldozer cut 0-2 cm	77	17.6	8.37	0.54
	Raised beach ridge sequence, bulldozer cut 2-5 cm	78	8.8	9.32	0.10
	Raised beach ridge sequence, bulldozer cut 5-20 cm	79	9.7	9.27	0.11
	Raised beach ridge sequence, side mound winrow 0-2 cm	80	2.0	10.01	0.70
	Raised beach ridge sequence, side mound winrow 2-5 cm	81	3.1	9.41	0.59
	Raised beach ridge sequence, side mound winrow 5-20 cm	82	2.4	9.41	0.09
	1957/58 Camp single pass bulldozer track, control 0-2 cm	83	2.7	10.12	0.66
	1957/58 Camp single pass bulldozer track, control 2-5 cm	84	4.9	10.19	0.32
	1957/58 Camp single pass bulldozer track, control 5-IC	85	7.5	9.68	0.26
	1957/58 Camp single pass bulldozer track, cut site 0-2 cm	86	3.5	9.92	0.27
	1957/58 Camp single pass bulldozer track, cut site 2-5 cm	87	6.5	10.14	0.28
	1957/58 Camp single pass bulldozer track, cut site 5-IC	88	8.0	9.78	0.51
	Marble Point 57/58 explosion pit, control DP-2 cm	89	2.2	10.03	5.57
	Marble Point 57/58 explosion pit, control 2-5 cm	90	3.0	9.97	0.89
	Marble Point 57/58 explosion pit, control 5-35 cm	91	3.4	9.49	0.25
	Marble Point 57/58 explosion pit, control 35-IC cm	92	3.4	9.33	0.29
	Marble Point 57/58 explosion pit, DP-2 cm	93	0.9	8.17	16.31
	Marble Point 57/58 explosion pit, 2-5 cm	94	1.2	8.05	7.62
	Marble Point 57/58 explosion pit, 20-70 cm black	95	2.8	9.73	0.31
	Marble Point 57/58 explosion pit, 20-70 cm brown	96	3.6	9.35	0.44

Soil pH, soil electrical conductivity, and soil water content of Ross Sea region sites

General Location	Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)
Vanda Station, Wright Valley, McMurdo Dry Valleys	Lower Wright Valley, Vanda Fan TT, disturbed DP-2 cm	97	0.2	8.84	0.29
	Lower Wright Valley, Vanda Fan TT, disturbed 2-5 cm, silt cement	98	0.2	8.60	0.60
	Lower Wright Valley, Old Vanda Station court area, disturbed DP-2 cm	99	0.1	8.41	0.25
	Lower Wright Valley, Old Vanda Station court area, disturbed 2-5 cm	100	0.2	8.37	0.58
	Lower Wright Valley, Old Vanda Station court area, control DP-2 cm	101	0.2	8.02	0.18
	Lower Wright Valley, Old Vanda Station court area, control 2-5 cm	102	0.2	8.11	0.35
	Lower Wright Valley, Vanda Fan TT, control DP-2 cm	103	0.2	8.77	0.14
	Lower Wright Valley, Vanda Fan TT, control DP-2 cm, silt cement	104	0.3	8.60	0.39
	Lower Wright Valley, Vanda Fan TT, control 2-5 cm	105	0.3	8.04	0.93
	Lower Wright Valley, Vanda Fan TT, control 5-32 cm	106	0.3	7.92	0.60
	Lower Wright Valley, Vanda Rocky TT, disturbed DP-2 cm	107	0.1	8.71	0.15
	Lower Wright Valley, Vanda Rocky TT, disturbed 2-5 cm	108	0.2	8.64	0.22
	Lower Wright Valley, Vanda Rocky TT, control DP-2 cm	109	0.2	8.52	0.68
	Lower Wright Valley, Vanda Rocky TT, control 2-5 cm	110	0.2	8.31	1.35
Cape Roberts, Antarctic Mainland	Cape Roberts, pre-CRP southern plot, DP-2 cm	111	5.0	9.2	1.00
	Cape Roberts, pre-CRP southern plot, 2-5 cm	112	6.8	9.25	0.28
	Cape Roberts, pre-CRP southern plot, 28-32 cm, organic-rich abv IC	113	8.5	8.19	0.40
	Cape Roberts, pre-CRP southern plot, control DP-2 cm	114	23.0	9.24	1.58
	Cape Roberts, pre-CRP southern plot, control 2-5 cm	115	15.5	9.37	0.44
Cape Roberts, Antarctic Mainland	Cape Roberts, pre-CRP northern plot, DP-2 cm	117	1.0	8.7	0.09
	Cape Roberts, pre-CRP northern plot, 2-5 cm	118	1.4	8.35	0.08
	Cape Roberts, pre-CRP northern plot, 20-IC	119	3.1	7.74	0.10
	Cape Roberts, pre-CRP northern plot, control DP-2 cm	120	0.3	7.07	0.22
	Cape Roberts, pre-CRP northern plot, control 2-5 cm	121	0.5	6.55	0.14
	Cape Roberts, pre-CRP northern plot, control 20-IC	122	0.9	7.11	0.02
Cape Evans, Ross Island	Cape Evans Windvane Hill Track IR 6, track DP-2 cm	116	3.6	9.19	0.11
	Cape Evans Windvane Hill Track IR 6, track 2-5 cm	123	6.0	8.85	0.06
	Cape Evans Windvane Hill Track IR 6, control DP-2 cm	124	4.1	8.92	0.48
	Cape Evans Windvane Hill Track IR 6, control 2-5 cm	125	3.6	8.74	0.25

Soil pH, soil electrical conductivity, and soil water content of Ross Sea region sites

General Location	Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)
Observation Hill, Ross Island	Up Observation Hill Track IR2, track DP-2 cm	126	3.2	8.91	0.13
	Up Observation Hill Track IR2, track 2-5 cm	127	5.1	8.89	0.13
	Up Observation Hill Track IR2, track 5-IC (15 cm)	128	4.9	8.5	0.17
	Up Observation Hill Track IR2, control DP-2 cm	129	4.8	8.31	0.07
	Up Observation Hill Track IR2, control 2-5 cm	130	6.0	8.26	0.06
	Up Observation Hill Track IR2, control 5-IC (12 cm)	131	5.6	7.81	0.06
	Round Observation Hill Track IR3, track DP-2 cm	132	7.8	8.77	0.05
	Round Observation Hill Track IR3, track 2-5 cm	133	10.8	8.79	0.05
	Round Observation Hill Track IR3, track 5-IC (20 cm)	134	12.6	9.04	0.10
	Round Observation Hill Track IR3, control DP-2 cm	135	7.1	9.34	0.12
	Round Observation Hill Track IR3, control 2-5 cm	136	8.2	9	0.09
	Round Observation Hill Track IR3, control 5-IC (24 cm)	137	12.1	8.93	0.06

APPENDIX 4

Soil chemistry data for bacterial community structure experiment, Scott Base (Chapter 6)

Soil chemical data from Scott Base disturbance experiment – Day 0.
Soil data are from three plots analysed for bacterial community composition studies

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)
Day 0 - Plot 1 - Control - DP-2 cm	1a	1.3	9.7	0.35	0.10	0.01	10	1543
Day 0 - Plot 1 - Control - DP-2 cm	1b	1.2	9.7	0.35				1371
Day 0 - Plot 1 - Control - 2-5 cm	2a	2.4	9.7	0.20	0.10	0.02	6	1622
Day 0 - Plot 1 - Control - 2-5 cm	2b	2.3	9.7	0.20				1515
Day 0 - Plot 1 - PRE-Disturbed - DP-2 cm	3a	1.3	9.5	0.50	0.10	0.01	8	1377
Day 0 - Plot 1 - PRE-Disturbed - DP-2 cm	3b	1.4	9.6	0.48				1521
Day 0 - Plot 1 - PRE-Disturbed - 2-5 cm	4a	2.4	9.7	0.26	0.08	0.01	10	1442
Day 0 - Plot 1 - PRE-Disturbed - 2-5 cm	4b	2.4	9.8	0.26				1341
Day 0 - Plot 1 - Disturbed - 0-2 cm	5a	1.7	9.7	0.34	0.12	0.02	7	1482
Day 0 - Plot 1 - Disturbed - 0-2 cm	5b	1.6	9.7	0.32				1458
Day 0 - Plot 1 - Disturbed - 2-5 cm	6a	2.6	9.6	0.13	0.09	0.01	7	1418
Day 0 - Plot 1 - Disturbed - 2-5 cm	6b	2.6	9.6	0.12				1509
Day 0 - Plot 2 - Control - DP-2 cm	7a	1.1	9.2	0.21	0.11	0.02	6	1591
Day 0 - Plot 2 - Control - DP-2 cm	7b	1.2	9.3	0.22				1440
Day 0 - Plot 2 - Control - 2-5 cm	8a	2.5	9.3	0.10	0.11	0.02	7	1566
Day 0 - Plot 2 - Control - 2-5 cm	8b	2.6	9.3	0.11				1628
Day 0 - Plot 2 - PRE-Disturbed - DP-2 cm	9a	1.2	8.8	0.25	0.21	0.03	7	1371
Day 0 - Plot 2 - PRE-Disturbed - DP-2 cm	9b	1.2	8.8	0.22				1514
Day 0 - Plot 2 - PRE-Disturbed - 2-5 cm	10a	2.1	9.2	0.08	0.27	0.04	7	1362
Day 0 - Plot 2 - PRE-Disturbed - 2-5 cm	10b	2.1	9.0	0.06				1449
Day 0 - Plot 2 - Disturbed - 0-2 cm	11a	1.8	9.0	0.08	0.19	0.03	7	1513
Day 0 - Plot 2 - Disturbed - 0-2 cm	11b	1.7	9.0	0.08				1385
Day 0 - Plot 2 - Disturbed - 2-5 cm	12a	2.7	8.8	0.07	0.21	0.03	7	1254
Day 0 - Plot 2 - Disturbed - 2-5 cm	12b	2.7	8.9	0.07				1345
Day 0 - Plot 3 - Control - DP-2 cm	13a	1.2	9.6	1.31	0.15	0.02	8	1461
Day 0 - Plot 3 - Control - DP-2 cm	13b	1.3	9.8	1.15				1384
Day 0 - Plot 3 - Control - 2-5 cm	14a	2.9	9.7	0.57	0.15	0.02	6	1393
Day 0 - Plot 3 - Control - 2-5 cm	14b	2.8	9.6	0.57				1477
Day 0 - Plot 3 - PRE-Disturbed - DP-2 cm	15a	2.3	9.8	2.41	0.16	0.02	10	1444
Day 0 - Plot 3 - PRE-Disturbed - DP-2 cm	15b	2.2	9.8	2.43				1455
Day 0 - Plot 3 - PRE-Disturbed - 2-5 cm	16a	4.7	10.0	0.77	0.11	0.01	9	1563
Day 0 - Plot 3 - PRE-Disturbed - 2-5 cm	16b	4.8	10.0	0.76				1518
Day 0 - Plot 3 - Disturbed - 0-2 cm	17a	2.7	9.9	0.90	0.13	0.01	9	1476
Day 0 - Plot 3 - Disturbed - 0-2 cm	17b	2.5	9.9	0.92				1564
Day 0 - Plot 3 - Disturbed - 2-5 cm	18a	2.7	10.0	0.48	0.09	0.01	7	1521
Day 0 - Plot 3 - Disturbed - 2-5 cm	18b	2.6	10.0	0.45				1320

Soil chemical data from Scott Base disturbance experiment – Day 7.
Soil data are from three plots analysed for bacterial community composition studies

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)
Day 7 - Plot 1 - Control - DP-2 cm	19a	1.5	9.2	0.36	0.10	0.02	5	1277
Day 7 - Plot 1 - Control - DP-2 cm	19b	1.4	9.4	0.34				1397
Day 7 - Plot 1 - Control - 2-5 cm	20a	2.3	9.5	0.41	0.10	0.02	6	1399
Day 7 - Plot 1 - Control - 2-5 cm	20b	2.2	9.5	0.41				1410
Day 7 - Plot 1 - Disturbed - 0-2 cm	21a	1.5	9.7	0.26	0.10	0.02	6	1466
Day 7 - Plot 1 - Disturbed - 0-2 cm	21b	1.5	9.7	0.24				1435
Day 7 - Plot 1 - Disturbed - 2-5 cm	22a	2.6	9.6	0.15	0.09	0.02	6	1501
Day 7 - Plot 1 - Disturbed - 2-5 cm	22b	2.5	9.6	0.15				1510
Day 7 - Plot 2 - Control - DP-2 cm	23a	1.8	9.2	0.25	0.11	0.02	7	1565
Day 7 - Plot 2 - Control - DP-2 cm	23b	1.9	9.2	0.26				1475
Day 7 - Plot 2 - Control - 2-5 cm	24a	2.7	9.4	0.10	0.08	0.01	6	1258
Day 7 - Plot 2 - Control - 2-5 cm	24b	2.6	9.4	0.09				1494
Day 7 - Plot 2 - Disturbed - 0-2 cm	25a	1.4	8.8	0.06	0.16	0.03	6	1424
Day 7 - Plot 2 - Disturbed - 0-2 cm	25b	1.5	8.8	0.05				1411
Day 7 - Plot 2 - Disturbed - 2-5 cm	26a	2.0	9.0	0.05	0.15	0.03	6	1320
Day 7 - Plot 2 - Disturbed - 2-5 cm	26b	2.1	9.0	0.05				1400
Day 7 - Plot 3 - Control - DP-2 cm	27a	1.7	9.6	1.08	0.12	0.02	8	1391
Day 7 - Plot 3 - Control - DP-2 cm	27b	1.6	9.7	0.95				1529
Day 7 - Plot 3 - Control - 2-5 cm	28a	3.7	9.7	0.63	0.11	0.02	7	1361
Day 7 - Plot 3 - Control - 2-5 cm	28b	3.5	9.7	0.62				1422
Day 7 - Plot 3 - Disturbed - 0-2 cm	29a	1.8	9.7	0.79	0.12	0.02	7	1274
Day 7 - Plot 3 - Disturbed - 0-2 cm	29b	1.8	9.7	0.77				1306
Day 7 - Plot 3 - Disturbed - 2-5 cm	30a	2.3	9.8	0.53	0.07	0.01	8	1506
Day 7 - Plot 3 - Disturbed - 2-5 cm	30b	2.3	9.8	0.52				1396

Soil chemical data from Scott Base disturbance experiment – Day 14.
Soil data are from three plots analysed for bacterial community composition studies

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)
Day 14 - Plot 1 - Control - DP-2 cm	31a	4.3	9.8	0.46	0.11	0.01	8	1369
Day 14 - Plot 1 - Control - DP-2 cm	31b	4.8	9.8	0.44				1416
Day 14 - Plot 1 - Control - 2-5 cm	32a	4.5	9.9	0.41	0.14	0.02	9	1326
Day 14 - Plot 1 - Control - 2-5 cm	32b	4.4	9.9	0.39				1350
Day 14 - Plot 1 - Disturbed - 0-2 cm	33a	4.0	9.9	0.18	0.10	0.02	6	1305
Day 14 - Plot 1 - Disturbed - 0-2 cm	33b	4.4	9.9	0.19				1438
Day 14 - Plot 1 - Disturbed - 2-5 cm	34a	4.5	9.9	0.20	0.08	0.01	6	1339
Day 14 - Plot 1 - Disturbed - 2-5 cm	34b	4.5	9.9	0.22				1330
Day 14 - Plot 2 - Control - DP-2 cm	35a	5.2	9.3	0.16	0.15	0.03	6	1429
Day 14 - Plot 2 - Control - DP-2 cm	35b	4.4	9.3	0.11				1121
Day 14 - Plot 2 - Control - 2-5 cm	36a	4.6	9.2	0.13	0.18	0.03	6	1531
Day 14 - Plot 2 - Control - 2-5 cm	36b	4.5	9.3	0.13				1294
Day 14 - Plot 2 - Disturbed - 0-2 cm	37a	4.5	9.0	0.07	0.18	0.03	6	1349
Day 14 - Plot 2 - Disturbed - 0-2 cm	37b	4.6	9.0	0.06				1200
Day 14 - Plot 2 - Disturbed - 2-5 cm	38a	4.2	9.1	0.05	0.24	0.04	6	1086
Day 14 - Plot 2 - Disturbed - 2-5 cm	38b	4.7	9.1	0.06				1411
Day 14 - Plot 3 - Control - DP-2 cm	39a	4.3	9.7	1.15	0.13	0.02	9	1471
Day 14 - Plot 3 - Control - DP-2 cm	39b	4.4	9.7	0.98				1350
Day 14 - Plot 3 - Control - 2-5 cm	40a	4.5	9.9	0.99	0.18	0.02	8	1392
Day 14 - Plot 3 - Control - 2-5 cm	40b	4.8	9.9	0.84				1439
Day 14 - Plot 3 - Disturbed - 0-2 cm	41a	4.3	10.1	0.61	0.14	0.02	6	1483
Day 14 - Plot 3 - Disturbed - 0-2 cm	41b	4.1	10.1	0.59				1363
Day 14 - Plot 3 - Disturbed - 2-5 cm	42a	4.4	10.0	0.38	0.09	0.01	8	1334
Day 14 - Plot 3 - Disturbed - 2-5 cm	42b	4.6	10.0	0.31				1515

Soil chemical data from Scott Base disturbance experiment – Day 21.
Soil data are from three plots analysed for bacterial community composition studies

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)
Day 21 - Plot 1 - Control - DP-2 cm	43a	7.9	9.6	0.19	0.10	0.02	6	1290
Day 21 - Plot 1 - Control - DP-2 cm	43b	7.8	9.6	0.17				1059
Day 21 - Plot 1 - Control - 2-5 cm	44a	6.9	9.8	0.17	0.07	0.01	6	1201
Day 21 - Plot 1 - Control - 2-5 cm	44b	6.7	9.8	0.17				1114
Day 21 - Plot 1 - Disturbed - 0-2 cm	45a	8.3	9.8	0.26	0.10	0.01	8	1091
Day 21 - Plot 1 - Disturbed - 0-2 cm	45b	8.1	9.8	0.24				1195
Day 21 - Plot 1 - Disturbed - 2-5 cm	46a	6.8	9.5	0.19	0.10	0.01	7	1128
Day 21 - Plot 1 - Disturbed - 2-5 cm	46b	7.0	9.5	0.18				1239
Day 21 - Plot 2 - Control - DP-2 cm	47a	6.7	9.3	0.16	0.32	0.05	6	1351
Day 21 - Plot 2 - Control - DP-2 cm	47b	9.3	9.3	0.12				1073
Day 21 - Plot 2 - Control - 2-5 cm	48a	7.4	9.2	0.13	0.13	0.02	6	1157
Day 21 - Plot 2 - Control - 2-5 cm	48b	8.0	9.3	0.08				1120
Day 21 - Plot 2 - Disturbed - 0-2 cm	49a	8.8	9.1	0.08	0.28	0.04	7	1066
Day 21 - Plot 2 - Disturbed - 0-2 cm	49b	8.3	9.1	0.07				1080
Day 21 - Plot 2 - Disturbed - 2-5 cm	50a	7.5	9.1	0.08	0.16	0.03	6	1178
Day 21 - Plot 2 - Disturbed - 2-5 cm	50b	7.1	8.8	0.06				978
Day 21 - Plot 3 - Control - DP-2 cm	51a	8.7	10.1	0.67	0.16	0.02	9	1330
Day 21 - Plot 3 - Control - DP-2 cm	51b	8.6	10.0	0.68				1148
Day 21 - Plot 3 - Control - 2-5 cm	52a	7.2	10.0	0.76	0.14	0.02	9	1116
Day 21 - Plot 3 - Control - 2-5 cm	52b	7.5	10.0	0.78				1340
Day 21 - Plot 3 - Disturbed - 0-2 cm	53a	7.2	10.0	0.36	0.11	0.02	7	1089
Day 21 - Plot 3 - Disturbed - 0-2 cm	53b	7.2	10.0	0.33				1140
Day 21 - Plot 3 - Disturbed - 2-5 cm	54a	7.2	9.9	0.43	0.09	0.01	6	1098
Day 21 - Plot 3 - Disturbed - 2-5 cm	54b	6.6	9.9	0.45				1077

Soil chemical data from Scott Base disturbance experiment – Day 35.
Soil data are from three plots analysed for bacterial community composition studies

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)
Day 35 - Plot 1 - Control - DP-2 cm	55a	2.0	9.6	0.55	0.12	0.02	7	1151
Day 35 - Plot 1 - Control - DP-2 cm	55b	2.0	9.6	0.60				1348
Day 35 - Plot 1 - Control - 2-5 cm	56a	4.0	10.1	0.36	0.12	0.01	9	1187
Day 35 - Plot 1 - Control - 2-5 cm	56b	3.7	10.1	0.38				1276
Day 35 - Plot 1 - Disturbed - 0-2 cm	57a	2.0	9.8	0.18	0.14	0.02	7	1096
Day 35 - Plot 1 - Disturbed - 0-2 cm	57b	2.0	9.9	0.20				1139
Day 35 - Plot 1 - Disturbed - 2-5 cm	58a	5.1	9.8	0.12	0.08	0.01	7	1302
Day 35 - Plot 1 - Disturbed - 2-5 cm	58b	4.8	9.8	0.13				1215
Day 35 - Plot 2 - Control - DP-2 cm	59a	2.9	9.2	0.10	0.22	0.04	6	1292
Day 35 - Plot 2 - Control - DP-2 cm	59b	2.3	9.2	0.11				1131
Day 35 - Plot 2 - Control - 2-5 cm	60a	3.9	9.2	0.07	0.16	0.02	7	1132
Day 35 - Plot 2 - Control - 2-5 cm	60b	4.9	9.2	0.08				1170
Day 35 - Plot 2 - Disturbed - 0-2 cm	61a	1.3	8.9	0.04	0.21	0.03	6	1203
Day 35 - Plot 2 - Disturbed - 0-2 cm	61b	1.4	8.9	0.05				1242
Day 35 - Plot 2 - Disturbed - 2-5 cm	62a	3.0	8.9	0.03	0.12	0.02	8	1128
Day 35 - Plot 2 - Disturbed - 2-5 cm	62b	3.3	8.9	0.04				1222
Day 35 - Plot 3 - Control - DP-2 cm	63a	1.3	9.8	0.59	0.16	0.02	8	1317
Day 35 - Plot 3 - Control - DP-2 cm	63b	1.4	9.8	0.64				1099
Day 35 - Plot 3 - Control - 2-5 cm	64a	4.6	9.8	0.26	0.13	0.02	8	1201
Day 35 - Plot 3 - Control - 2-5 cm	64b	4.1	9.8	0.29				1113
Day 35 - Plot 3 - Disturbed - 0-2 cm	65a	1.6	10.0	0.54	0.14	0.02	8	1287
Day 35 - Plot 3 - Disturbed - 0-2 cm	65b	1.6	10.1	0.56				1295
Day 35 - Plot 3 - Disturbed - 2-5 cm	66a	3.5	10.1	0.27	0.08	0.01	7	1289
Day 35 - Plot 3 - Disturbed - 2-5 cm	66b	3.5	10.1	0.27				1379

APPENDIX 5

Soil physiochemical data for Ross Island walking tracks (Chapter 7)

Soil physiochemical characteristics at track counter sites on the Ross Island walking tracks. *EC = electrical conductivity. Three reps of each depth, track and control are shown (at the track counter, 1 m and 3m down track of the counter). *Dry bulk density is the mean of two reps

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)	Dry Bulk Density* g/cm³
Scott Base to McMurdo Station Track									1.32
Rep 1 - Track - 0-2 cm	T1	4.8	9.7	0.20	0.05	0.01	7	1205	
Rep 1 - Track - 2-5 cm	T2	7.1	9.7	0.12	0.05	0.01	6	1040	
Rep 2 - Track - 0-2 cm	T3	3.6	9.9	0.21	0.06	0.01	8	1253	
Rep 2 - Track - 2-5 cm	T4	5.2	9.6	0.12	0.05	0.01	5	1184	
Rep 3 - Track - 0-2 cm	T5	1.6	9.6	0.14	0.04	0.01	6	1011	
Rep 3 - Track - 2-5 cm	T6	6.0	9.7	0.12	0.04	0.01	6	1127	
Scott Base to McMurdo Station Control									1.01
Rep 1 - Contol - DP-2 cm	T7	2.8	8.9	0.89	0.10	0.02	6	1129	
Rep 1 - Control - 2-5 cm	T8	3.4	9.5	0.41	0.12	0.02	7	1225	
Rep 2 - Control - DP-2 cm	T9	2.4	9.7	0.73	0.10	0.02	6	1276	
Rep 2 - Control - 2-5 cm	T10	4.4	9.6	0.39	0.10	0.01	7	1349	
Rep 3 - Control - DP-2 cm	T11	2.0	9.7	0.67	0.12	0.02	7	988	
Rep 3 - Control - 2-5 cm	T12	3.4	9.7	0.40	0.11	0.02	7	1090	
Cape Evans Wind Vane Hill Track									1.21
Rep 1 - Track - 0-2 cm	T13	2.3	9.3	0.15	0.02	0.01	4	867	
Rep 1 - Track - 2-5 cm	T14	5.4	9.3	0.05	0.02	0.00	4	1101	
Rep 2 - Track - 0-2 cm	T15	3.3	9.1	0.12	0.02	0.00	3	725	
Rep 2 - Track - 2-5 cm	T16	4.9	9.2	0.05	0.02	0.01	3	678	
Rep 3 - Track - 0-2 cm	T17	2.9	9.0	0.21	0.02	0.01	3	697	
Rep 3 - Track - 2-5 cm	T18	5.4	9.3	0.05	0.02	0.00	4	756	
Cape Evans Wind Vane Hill Control									1.11
Rep 1 - Contol - DP-2 cm	T19	1.8	9.3	0.16	0.01	0.00	3	714	
Rep 1 - Control - 2-5 cm	T20	3.5	8.6	0.14	0.04	0.00	8	466	
Rep 2 - Control - DP-2 cm	T21	1.7	9.1	0.15	0.02	0.00	3	745	
Rep 2 - Control - 2-5 cm	T22	4.1	9.1	0.08	0.01	0.00	3	635	
Rep 3 - Control - DP-2 cm	T23	2.2	9.2	0.12	0.01	0.01	2	548	
Rep 3 - Control - 2-5 cm	T24	3.6	9.0	0.07	0.02	0.01	3	793	

Soil physiochemical characteristics at track counter sites on the Ross Island walking tracks. *EC = electrical conductivity. Three reps of each depth, track and control are shown (at the track counter, 1 m and 3m down track of the counter). *Dry bulk density is the mean of two reps

Site Description	Sample No.	Water Content (% dry wt)	pH (water)	EC (1:5) (mS/cm)	Organic C (%)	Total N (%)	C/N ratio	Total Kjeldahl P (mg/kg)	Dry Bulk Density* g/cm^3
Round Observation Hill Track									
Rep 1 - Track - 0-2 cm	T25	8.0	8.9	0.04	0.03	0.00	8	958	1.74
Rep 1 - Track - 2-5 cm	T26	9.8	9.0	0.04	0.04	0.01	6	974	
Rep 2 - Track - 0-2 cm	T27	7.0	9.0	0.04	0.02	0.00	5	722	
Rep 2 - Track - 2-5 cm	T28	10.4	9.0	0.03	0.04	0.01	7	1042	
Rep 3 - Track - 0-2 cm	T29	6.3	9.0	0.04	0.03	0.00	10	1015	
Rep 3 - Track - 2-5 cm	T30	11.0	9.0	0.03	0.04	0.00	10	1188	
Round Observation Hill Control									
Rep 1 - Contol - DP-2 cm	T31	7.8	9.6	0.28	0.05	0.01	9	1077	1.08
Rep 1 - Control - 2-5 cm	T32	12.4	9.3	0.11	0.05	0.01	8	1048	
Rep 2 - Control - DP-2 cm	T33	7.7	9.6	0.28	0.05	0.01	9	936	
Rep 2 - Control - 2-5 cm	T34	10.1	9.3	0.09	0.05	0.01	9	1022	
Rep 3 - Control - DP-2 cm	T35	7.6	9.7	0.29	0.04	0.01	8	1128	
Rep 3 - Control - 2-5 cm	T36	12.4	9.3	0.10	0.05	0.01	9	956	
Up Observation Hill Track									
Rep 1 - Track - 0-2 cm	T37	3.1	9.0	0.18	0.03	0.00	16	548	n/a
Rep 1 - Track - 2-5 cm	T38	4.9	8.9	0.11	0.03	0.00	7	612	
Rep 2 - Track - 0-2 cm	T39	3.5	8.7	0.31	0.03	0.00	12	506	
Rep 2 - Track - 2-5 cm	T40	6.5	8.8	0.13	0.03	0.00	18	594	
Rep 3 - Track - 0-2 cm	T41	4.1	9.0	0.17	0.03	0.00	26	476	
Rep 3 - Track - 2-5 cm	T42	6.6	8.8	0.11	0.03	0.00	31	443	
Up Observation Hill Control									
Rep 1 - Contol - DP-2 cm	T43	5.9	8.7	0.03	0.08	0.01	7	704	n/a
Rep 1 - Control - 2-5 cm	T44	5.8	8.4	0.03	0.05	0.01	8	811	
Rep 2 - Control - DP-2 cm	T45	7.2	8.5	0.03	0.08	0.01	7	799	
Rep 2 - Control - 2-5 cm	T46	6.8	8.4	0.03	0.05	0.01	8	633	
Rep 3 - Control - DP-2 cm	T47	7.0	8.4	0.04	0.08	0.01	7	608	
Rep 3 - Control - 2-5 cm	T48	7.0	8.4	0.03	0.05	0.01	8	597	

APPENDIX 6

TRF data for bacterial community structure experiment, Scott Base (Chapter 6)