Environmental Assessment of the McMurdo Dry Valleys: Witness to the Past and Guide to the Future

Report of an NSF Workshop
Colorado State University
2-3 May 2016

John C. Priscu and Adrian Howkins, Editors

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Front Cover photograph:

Scientist collecting samples from Don Juan Pond, Wright Valley, using clean techniques.

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View of Lake Bonney and the lower Taylor Glacier from the Nussbaum Riegel.

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EXECUTIVE SUMMARY

The Dry Valleys region is magnificent–a terrestrial theater of the prehistoric, the alien, and the dead. Like a beautiful language, this landscape communicates how far into the past and into the future our planet continues without us. At a time when the conversation around the world is centered on how we affect the Earth, and how in turn, it will affect us, seeing the world from a vantage point where humans never lived–where indeed, nothing large enough for us to see ever lived–gives a profound sense of perspective on the human situation and the value of life………

Chris Kannen 2008, NSF Artist and Writers Program

The Antarctic continent is often perceived as a symbol of the last great wilderness, untouched by human presence. Unfortunately, like other regions of the Earth, the Antarctic environment is now being impacted by local and global anthropogenic activities. The McMurdo Dry Valleys (MDV) of southern Victoria Land form the largest ice-free expanse on the continent and represents the coldest and driest desert on our planet. This region consists of a mosaic of glaciers, soils, streams and lakes that are intricately connected to support a fragile ecosystem.

Research in this region began during the British expeditions of the early 1900's and has since yielded much information on specific physical, chemical and biological features. Results from these efforts, particularly since the mid-1990's, have shown that even small changes in climate or local disturbances produce a cascade of tightly coupled events that ultimately lead to large changes in ecosystem structure and function. This research also showed that the organisms within the MDV ecosystem are extraordinarily well adapted to surviving and even thriving in this cold polar desert, properties that may someday prove their demise if scientific activities to study them continue to increase unregulated at their current pace. We have reached a point where, as scientists, we now have to ask ourselves if we are beginning to sample our own disturbance.

Scientists working in the MDV region since the late 1950's quickly recognized that human activity could impact the ecosystem and addressed this issue in scientific colloquia and published manuscripts on the topic in the 1970's. As research ramped up in the region, scientists working in the dry valleys initiated a series of four international workshops that were convened between 1991 and 1999. All of these meetings stressed that the environment is extremely sensitive to human presence and that formal plans should be put in place for the protection of scientific values and the ecological integrity of the region. This emphasis recognizes the significance of the dry valleys as a globally important region of scientific interest, and acknowledges this interest as the primary reason for human presence in the area.

Research and tourism in the McMurdo Valleys has intensified dramatically over the 17 years since the last formal workshop was held. The establishment of a McMurdo Dry Valleys Antarctic Specially Managed Area (ASMA) and several new Antarctic Specially Protected Areas (ASPA's) has occurred over this period, providing tools for international coordination of both science and environmental planning. The 17-year hiatus since the last formal environmental assessment of the dry valleys, in concert with the notable increase in research activity, prompted the scientific community to propose a new workshop to assess the present environmental integrity of the region, to examine the efficacy of present management strategies, and to make recommendations for future environmental management. To this end, an international workshop was convened from 2-4 May 2016 at Colorado State University, CO (USA) with support from the United States National Science Foundation. Invitations were sent to appropriate members of funding agencies, Antarctic support contractors and policy makers, helicopter support personnel, and key scientists who have conducted research on select components of the MDV landscape. This effort resulted in 53 attendees representing six nations. Almost one quarter of the attendees represented members of funding agencies, managers and logistical support contractors, with the remainder representing the science community. The overarching objectives of the workshop were to: (i) outline documented and potential human impacts (including level of severity) from various research activities in the area; (ii) determine the efficacy of the present management strategies in the dry valleys and discuss potential changes with respect to environmental protection and implementation; (iii) develop recommendations for management of future research and tourist activities in the region with an emphasis on the logistical requirements needed to implement these recommendations.

Workshop participants agreed that the specific aims of this workshop could not be met explicitly without a clearer definition of the McMurdo Dry Valleys ASMA's management activities that would cover the state of the current environment, the pressures on the environment from direct human activities and from global change, and more detailed management responses to those pressures. A framework was developed for an expanded ASMA management plan that complements the existing structure and strives to address these pending issues. This plan requires an adaptive management approach based on timely updates to the knowledge of the environment as affected by past, present, and emerging pressures. Workshop participants developed ten focused recommendations to improve the effectiveness of the ASMA and ASPA's for preserving the unique values of this region through specific management responses:

1. National Antarctic Programs (NAPs) operating in the ASMA should move toward a management strategy that recognizes the impact of global change (e.g., climate warming) when developing and implementing environmental protocols. The management strategy should be based on best available scientific evidence.

2. NAPs have been collecting data on human activities for decades, but relatively little is readily available to managers and scientists. It is important that collaboration is enhanced among the programs operating in the ASMA to track sample and instrument sites, camp locations, landing sites, personnel movements, and environmental incidents, and to integrate this information in a publically available GIS-based system. The input data will be primarily from existing collection mechanisms implemented by national programs as well as relevant information provided by tourism operators.

3. Field activity data are not being collected routinely and made accessible to inform management decisions and future science planning by NAPs and funding agencies. Stakeholders should invest in accessible technology to facilitate consistent documentation, streamlined analysis, and easy dissemination of past and present field activities. This technology will enhance end-of-season reporting and allow newly collected data to be directly incorporated into Recommendation 2.

4. NAPs and funding agencies should invest in research that integrates scientific evidence with management strategies. Such an integration can be used to determine and map intrinsically sensitive landscape components as well as collect

baseline information on ecology, climate, geomorphology, and hydrology. Information should include (i) areas of high priority for conservation and restoration as well as those in need of special management, (ii) habitats at elevated risk of biological invasion, (iii) locations suitable for sustainable tourism activities with tolerable environmental impact, and (iv) projected vulnerability to climate change for individual landscape features. Such information must account for seasonal and annual variations where appropriate, and incorporate the experience of public and private conservation organizations.

5. NAPs should synthesize outcomes from Recommendations 2 to 4 to assess the environmental footprint of current scientific, logistic, and tourism activities to guide future development of management policies for the ASMA.

6. All parties operating in the MDV should be consistent in adopting the environmental guidelines provided in the ASMA Management Plan and other recommendations by the Committee for Environmental Protection (CEP) to safeguard against the introduction of non-native species. Practices could include cleaning boots as well as field and scientific equipment between field sites, encouraging field personnel to have equipment dedicated to the MDV, and identifying higher-risk personnel, equipment, and activities.

7. NAPs should facilitate research activities that enhance the management and protection of the ASMA. Examples of this could include designing better tools (including indicators of cumulative impact), and supporting future monitoring programs that evaluate the effectiveness of the ASMA Management Plan (e.g., by creating 'Inviolate Areas', as recommended by the Protocol on Environmental Protection to the Antarctic Treaty).

8. NAPs and stakeholders should hold workshops to assess environmental management of the ASMA at regular intervals (e.g., every five years) on a rotational basis.

9. NAPs should consult available and/or relevant scientific personnel in response to environmental incidents.

10. NAPs should charge education and outreach programs to address issues such as the environmental sensitivity of the ecosystem, the role of the MDV as sentinels of global environmental change, and the importance of environmental stewardship in all aspects of work in the area.

This workshop was made possible by a grant from the National Science Foundation (PLR 1548256). We are especially grateful to Polly Penhale (NSF), Paul Cutler (NSF) and Lisa Clough (NSF) for encouragement, particularly during the proposal stages of the workshop. NSF and U.S. support contractors were present to learn about attendee perspectives and to act as resources-they did not shape the final recommendations. Adrian Howkins and Diana Wall kindly acted as the local organizing committee and hosted the meeting. Amy Chiuchiolo assisted participants with travel and contributed to report preparation. Clive Howard-Williams and Warwick Vincent were instrumental in the development of charts and associated text addressing various management strategies. Colin Harris and Ceisha Poirot provided text and figures on environmental stewardship. Cindy Dean, Peter Doran, Michael Gooseff, Clive Howard-Williams, Adrian Howkins, Charles Lee, Diana Wall, and Warwick Vincent reviewed early drafts of this report. Ronald Sletten reviewed a near final draft of this report. On behalf of the organizing committee, I thank the keynote speakers for providing the backdrop for the meeting, and the workshop break-out chairs and rapporteurs for keeping everyone on track and summarizing ideas within each group.

Finally, the workshop would not have been successful without input from all participants who provided novel and exciting ideas throughout the meeting. Their ideas fill the pages of this report.

John C. Priscu,
Montana State University (Chair)

The Organizing Committee:

Peter Doran (Louisiana State University)
Adrian Howkins (Colorado State University)
Berry Lyons (Ohio State University)
Diana Wall (Colorado State University)

We are drowning in information, while starving for wisdom. The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely.

E.O. Wilson

1. INTRODUCTION AND STATEMENT OF NEED

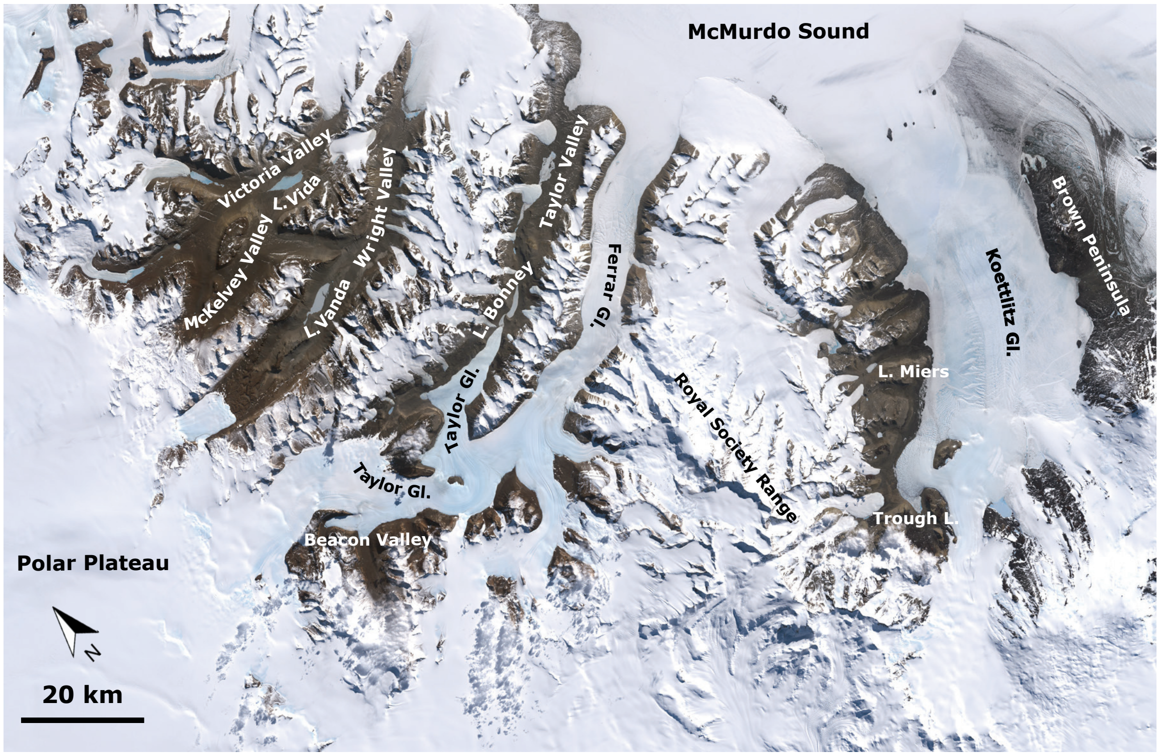

Figure 1. Satellite map of the central McMurdo Dry Valley region of Antarctica.

Through the unique global partnership that is the Antarctic Treaty System, the entire continent is formally designated as a 'natural reserve, devoted to peace and science'. Antarctica is regarded as the last great wilderness on our planet, still pristine with wildlife and landscapes that currently show little evidence of direct human activity. To visit, and operate in, an environment like this comes with a responsibility to do so carefully and with minimal impact. It is thus imperative that scientists, contractors and managers operating in Antarctica convene regularly to assess the state of the environment and delineate requirements for the future that will maintain the pristine nature of the continent.

A region of Antarctica that is particularly vulnerable to human impact is the McMurdo Dry Valleys (MDV). The MDV represent the largest ice-free expanse on the continent (ice free area = 4,500 km^2) and encompasses a total area of 22,700 km^2 (Levy 2012) (Figure 1). The MDV contain cold desert soils millions of years old, special geological features, and novel assemblages of primarily microscopic organisms. The landscape is a mosaic of glaciers, mountain ranges, permanently ice covered lakes, ephemeral streams and hyperarid soil ecosystems. Materials are transported among landscape units by strong winds and seasonal water flow (Šabacká et al. 2012; Michaud et al. 2012). The geomorphology we see today has changed little over the past 3 million years (Sugden et al. 1995a; Bockheim and McLeod 2008) providing us with a unique glimpse into the past that can be used to guide us into the future.

The biological systems in the MDV are relatively simple; there are no vascular plants or vertebrates, and few insects. Trophic interactions and biogeochemical cycles are largely limited to microbiological populations and microinvertebrates. Despite the apparent simplicity, complex interactions among species and between biological and physiochemical components occur within and between glaciers, ancient brines, streams, soils, and lakes. The

MDV pose one of the most extreme ecosystems on Earth in terms of temperature, liquid water availability, and darkness. It is a natural laboratory in which unique adaptations can be elucidated and their origin and evolution understood. Research to date has shown that this environment is poised at a threshold where small changes to the system can produce a cascade of ecological consequences. As we enter an era of rapid global change, awareness of the role played by Antarctica's ecosystems in the Earth system has led to a concern that the global values afforded by these polar systems are being compromised.

The global uniqueness of the MDV has led to increased levels of scientific research and tourism over the past several decades. Given the increase in human presence within the MDV, it is imperative that we assess routinely the impact of human activities on this delicate ecosystem. Such an assessment should focus not only on developing guidelines for responsible stewardship to protect this unique environment; it must also focus on the impact that human presence has on the science itself.

2. FORMER MEETINGS ADDRESSING ENVIRONMENTAL MANAGEMENT OF THE McMURDO DRY VALLEYS

Environmental concerns from human activities on the Antarctic continent were first addressed in the 1960's and 1970's through proceedings of colloquia (Parker 1972) and published manuscripts (e.g., Parker 1978) on the topic. International workshops specifically addressing environmental management of the MDV were convened in 1991, 1995, 1998, and 1999. Titles and key points addressed by these workshops follow:

- ➢ Wharton, R.A. (ed.) McMurdo Dry Valleys: A Cold Desert Ecosystem. Report of a U.S. National Science Foundation workshop held at the Institute of Ecosystem Studies, The New York Botanical Garden, Millbrook, New York, 5-7 October 1991.
    - Direct research funding toward an integrated ecosystem approach
    - Investigate carbon and nutrient flows, and relate to community structure and functioning
    - Characterize biodiversity
    - Characterize survival strategies and adaptations of key organisms to the environment to establish limits to life in the MDV
- ➢ Vincent, W.F. (ed.) Environmental Management of a Cold Desert Ecosystem: The McMurdo Dry Valleys. Report of a U.S. National Science Foundation Workshop held in Santa Fe, New Mexico, 14-17 March 1995.
    - Recommend management plans for regions within the MDV
    - Recommend an environmental monitoring program, including suitable indicators, that can address project-specific impacts and cumulative impacts
    - Develop a code of environmental conduct for working in the MDV
- ➢ Wharton, R.A. and P. T. Doran (eds.) McMurdo Dry Valley Lakes: Impacts of Research Activities.

Report of a U.S. National Science Foundation Workshop held at the University of Illinois at Chicago, 15-17 July 1998.

- Identify areas where additional information is required to assess impacts of research activities on the lakes. These include:

  ➢ Monitor pollutants generated from helicopters, vehicles, and generators

  ➢ Investigate groundwater movement and hydrological connections and circulation in the lakes to trace potential pollutants

  ➢ Develop a soil map noting areas near streams/lakes vulnerable to human impact

  ➢ Evaluate the impacts of ice, water and benthic mat/sediment removal

  ➢ Develop methods for documenting and managing research activities on the lakes

  ➢ Develop a web-based database and geographic information system that incorporates past, present and future scientific and tourist usage of the MDV

➢ Priscu, J.C. (ed.) Year-Round Access to the McMurdo Region: Opportunities for Science and Education. Report of a U.S. National Science Foundation Workshop held at NSF Headquarters, Arlington, Virginia, 8-10 September 1999.

- Identify scientific questions that can be addressed only by winter research
- Identify alternatives to winter deployment
- Define the additional logistic and scientific support that will accompany a winter program
- Describe the educational possibilities that higher-level winter deployment would offer, particularly in relation to the role of the Crary Laboratory
- Describe any environmental impacts that an elevated winter effort may cause
- Define the safety issues surrounding winter research in the McMurdo region as far away as the dry valleys
- Recommend strategies for funding extended season projects

These four workshops all concluded that the MDV environment is extremely sensitive to human presence and special priority should be given to the protection of scientific values and the ecological integrity of the region. This conclusion recognizes the global significance of the MDV as a scientific information resource, and acknowledges this as the principal reason for human activities in the valleys. Protection of the scientific values of this region also serves to protect many other attributes that characterize this environment.

It has been 17 years since environmental stewardship of the MDV has been addressed formally in a workshop format. During these 17 years, research activities in the valleys have increased and major research campaigns have been established in the Taylor, Wright, Miers, Garwood, Beacon, and Victoria Valleys. This 17-year period has seen the implementation of a MDV ASMA and several new Antarctic Specially Protected Areas (ASPA's) in the region (Appendix 12.1). These areas provide tools for international coordination allowing stakeholders to define clear values, set objectives, set priorities, and coordinate and communicate activities. Research has reached the point where scientists are starting to ask, are we beginning to sample our own disturbances? Given the relatively long hiatus since the last environmental assessment of the MDV, in concert with substantial increases in research activity, the present workshop was convened to assess the environmental integrity of the region, discuss the success of present management strategies, present data describing the current state of the environment, and develop an international plan with which to move forward. Discussion during this workshop focused on environmental stewardship and scientific site integrity, and addressed the linkages shown in Figure 2.

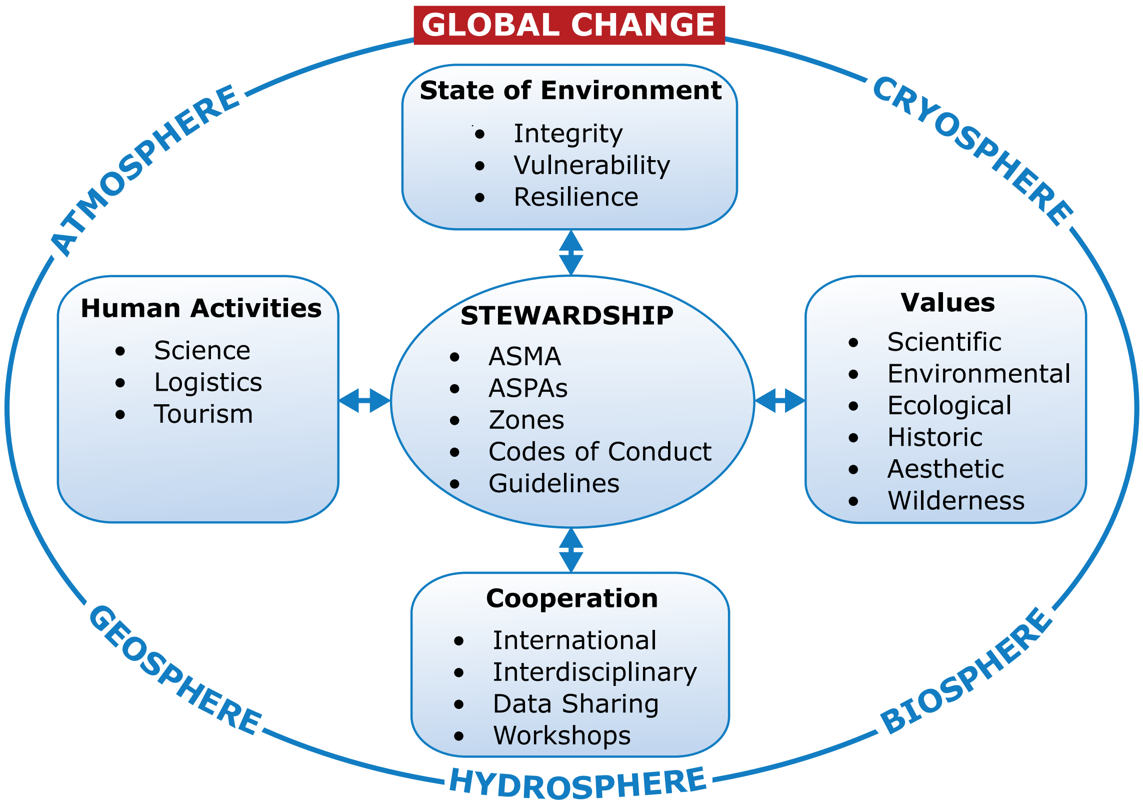

Figure 2. The complex relationships that must be considered in the MDV to successfully address issues related to environmental stewardship. The outer ring denotes the major landscape units in the region and shows the overarching role that global change has on all relationships.

3. WORKSHOP APPROACH

An international workshop was convened from 2-4 May 2016 at Colorado State University, CO (USA) with support from the United States National Science Foundation. Invitations were sent to appropriate members of funding agencies, the Antarctic support contractors and policy makers, helicopter support personnel, and key scientists who have conducted research on select components of the MDV ecosystem. The scientific invitations included early, mid, and late career scientists, emphasizing balanced gender representation. In the end, a total of 53 individuals attended the workshop representing 6 nations. Twenty two percent of the attendees represented members of funding agencies, managers, and logistical support contractors, the remainder were scientists who conduct research on various landscape units in the MDV (Appendix 12.2). The organizing committee for the workshop consisted of John Priscu

(Chair-Montana State University), Berry Lyons (The Ohio State University), Peter Doran (Louisiana State University), Diana Wall (Colorado State University), and Adrian Howkins (Colorado State University).

3.1 Overarching Objectives of the Workshop:

1. Outline documented and potential human impacts (including level of severity) from various research activities in the MDV.

2. Determine the efficacy of the present management strategies in the MDV (e.g., ASMA's, ASPA's, Management Zones) and discuss potential changes with respect to environmental protection and implementation.

3. Develop recommendations for management of future research and tourist activities in the area with an emphasis on the logistical requirements needed to implement these recommendations.

3.2 Specific Questions Considered by the Participants:

1. What is the current research and tourist "footprint" in the area, and is it affecting the integrity of the ecosystem?

2. How is projected climate change in the area going to influence environmental management decisions?

3. How will Unmanned Aerial Vehicles affect the environment and what rules will be placed on their use?

4. We now have the dry valleys ASMA with new ASPA's in place since the last environmental review. How have these managed and protected areas provided environmental protection to the environment?

5. To what level do we need to catalogue sampling sites and sites of instrument deployment?

6. What are the current regulations for handling hazardous materials and are they adequate?

7. Are current guidelines for the response to environmental incidents (e.g., spills and other releases) adequate?

8. What is the effect of increased helicopter use on carbon deposition and landing sites in the MDV?

9. How will extended season research affect the integrity of the environment?

10. Do we need guidelines for ROV and autonomous deployments in the lakes?

11. What is the status of former sites of known pollution (e.g., Vanda Station)?

3.3 Workshop Organization

Day one of the meeting included keynote presentations focusing on the state of selected ecosystem components and the present status of management. These presentations focused on the overarching objectives and specific questions described above and set the tone for ensuing discussion. To encourage input from all participants, the objectives were addressed in a working group format similar to that used in previous NSF-sponsored environmental workshops addressing the MDV ecosystem. Three groups were formed, each comprised of scientists, contractors, and managers with expertise in the various activities associated with research and environmental protection in the MDV. Each group addressed the objectives and specific questions. The groups then met together to discuss the individual outcomes and develop a consensus of ideas. Groups were formed to produce a list of recommendations that reflected previous discussion. Writing assignments were allocated and a draft report was developed during the last day of the workshop. This format allowed all perspective ideas to be aired, discussed, and documented. The Chair of the workshop then worked together with the organizing committee, discussion group leaders, rapporteurs, and attendees to prepare a final document.

This report presents outcomes from workshop discussions addressing the environmental history of the region, the overarching objectives and specific questions posed to the group, and educational and outreach opportunities that can be implemented. The information will inform the next generation of polar scientists of important environmental issues (Sections 4 through 8). Section 9 provides an overview of contemporary knowledge of the atmosphere, biosphere, cryosphere, hydrosphere, and geosphere in the MDV, furnishing the overarching umbrella for environmental awareness and decision making—if we are to design and implement ecosystem management practices, we first must understand the ecosystem. Section 10 includes a list of recommendations formulated for the MDV to improve the effectiveness of the ASMA and ASPA's for preserving the unique values of this region through specific management responses.

4. HISTORY OF HUMAN IMPACT IN THE MCMURDO DRY VALLEYS

The first people to enter the MDV were Captain Scott and two companions in December 1903 on the return journey from the Polar Plateau. "It is certainly a valley of the dead," Scott famously wrote of the region, "even the great glacier which once pushed through it has withered away" (Scott 2001). As part of Ernest Shackleton's Nimrod expedition, Raymond Priestley and two companions spent a day exploring the area around New Harbor. In February 1911, a party led by Griffith Taylor spent a week traveling through what is today known as Taylor Valley along with Charles Wright, Frank Debenham, and Edgar Evans. The Taylor Party produced sketches, took photos, and described the landscape in considerable detail, providing a brief snapshot of environmental conditions 100 years ago (Howkins 2016). In contrast to Scott's description of the region as a "valley of the dead," both Priestley and the members of Taylor's party observed the presence of algal mats in the lakes and ponds. There is some evidence that these early expeditions left behind some equipment in Taylor Valley, but the environmental impact of these "heroic era" explorers was minimal.

Following Taylor's 1911 expedition, there was no human activity in the MDV until the second half of the 1950's, when United States and New Zealand parties explored the region as part of the International Geophysical Year (IGY) (e.g., Bull 2009). The IGY and the subsequent signature of the Antarctic Treaty in 1959 marked the beginning of the modern era of scientific research in the MDV. Scientists have visited the region every summer season since the IGY. There have also been three winter parties in the dry valleys, in 1969, 1970 and 1974. Increased scientific work in the MDV since the IGY has clearly impacted certain landscape units. Examples include: (i) the construction and early occupation of New Zealand's Vanda Station utilized land leaving transport trails still visible today (Harrowfield 1999; Figure 3A); (ii) drilling activities from the Dry Valleys Drilling Program of the 1970's left borehole casings that remain visible today (Figure 3B); (iii) techniques used by early researchers that would not be permitted under current regulations may produce yet unknown impacts. Despite the occurrence of activities that impacted the environment, the number of scientists

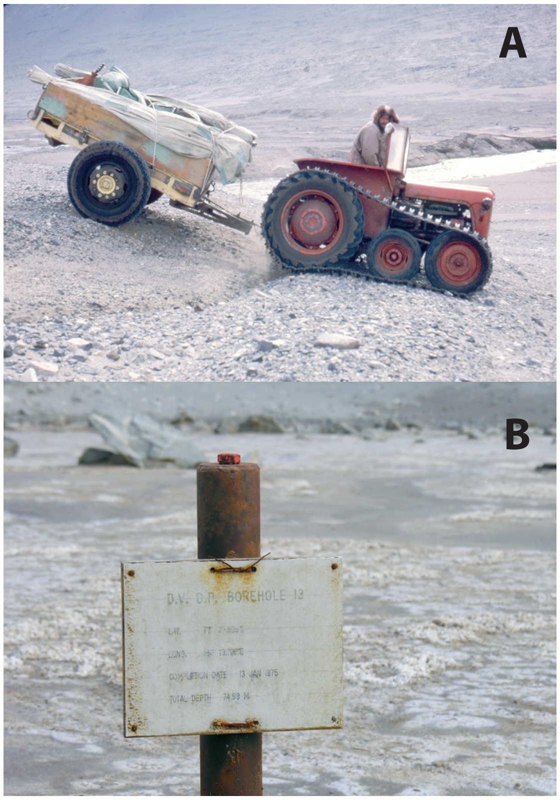

Figure 3. A) Tractor and trailer used to haul materials at Vanda Station; B) Borehole remnants at Don Juan Pond (Borehole 13) from the Dry Valley Drilling Project. The borehole was completed on 13 January 1972 and reached a depth of 74.99 m.

working in the MDV remained relatively small in the immediate years following IGY, and the overall impact across the region as a whole remained low.

The lack of easily accessible historical data on human activities in the MDV means that we do not have an accurate overview of trends in human activity over time. Despite the patchiness of these records, it is clear that human activity in the region has increased over the past ~30 years. Science parties from a number of nations, primarily New Zealand and the United States, have increased their presence in the region since the mid-1980's, conducting research in an expanding array of scientific disciplines. The establishment of the United States Antarctic Program's McMurdo Dry Valleys Long Term Ecological Research (MCM LTER) site in 1993 increased the number of camps in the Taylor Valley and boosted the number of researchers and support contractors working in the MDV during the spring, summer, and autumn seasons. Statistics from the International Association of Antarctic Tour Operators show that ~4,000 tourists have visited the MDV since the early 1990's. This period has also seen a shift in logistical support away from the military towards civilian contractors. Importantly, the increase in human activity in the region over the past 25 years has been accompanied by a significant rise in environmental awareness and management (see below). Unfortunately, the lack of comprehensive data on human activity in the MDV makes it difficult to determine how effective these management efforts have been or whether environmental impact has been increasing over time.

5. EVOLUTION OF ENVIRONMENTAL AWARENESS

Since the resumption of human activity in the MDV during the late 1950's, there has been some awareness of the potential for human activity to impact the region's environment. Following the signature of the Antarctic Treaty in 1959, the "Agreed Measures for the Conservation of Antarctic Fauna and Flora" were adopted in 1964 by the Consultative Parties, which put in place a number of regulations for the protection of the environment. These environmental regulations extended into the dry valleys, and the first specially protected area in the MDV (ASPA No. 123 Barwick and Balham Valleys, Southern Victoria Land) was designated in 1975. The Dry Valleys Drilling Program of the 1970's brought increased attention to the potential for environmental impact. It was in this context that Bruce Parker and Mary Holliman published the 1978 volume titled "Environmental Impact in Antarctica: Select Papers by Scientists

Addressing Impact Assessment, Monitoring, and Potential Impact of Man's Activities in the Antarctic" (Parker 1978). Regardless of these initiatives, in comparison to today's environmental concerns, environmental protection was a relatively low priority behind the need for scientific research and the challenges of working in such an extreme environment during the first ~25 years of modern scientific activity in the MDV.

Since the mid-1980's, there has been a growing awareness that human activities can have a negative impact on the MDV environment. This was in part due to external pressure from environmental organizations in opposition to ongoing negotiations for exploitation of Antarctic minerals. However, much of the impetus for change came internally, as the scientific community working in the region recognized the urgent need to coordinate and document research activities to protect the scientific and environmental values of the MDV. In moving forward with these goals, there was a need for an international and interdisciplinary approach toward addressing environmental issues. During the 1990's, scientists working in the MDV held a series of workshops to discuss environmental protection (see Section 2).

At a continental scale, the Protocol on Environmental Protection to the Antarctic Treaty (hereafter referred to as the Protocol) was adopted in 1991 and entered into force in 1998, bringing about major changes to the environmental management of Antarctica. The Protocol designates Antarctica as "a natural reserve, devoted to peace and science" and calls for the comprehensive protection of the Antarctic environment, and dependent and associated ecosystems, prohibits any activity relating to mineral resources, except for scientific research, and requires all activities to be subject to a prior assessment of the environmental impacts. Further detailed requirements for environmental protection are provided for in 6 Annexes to the Protocol that outline the requirement for an Environmental Impact Assessment (Annex 1), the Conservation of Flora and Fauna (Annex 2), measures for Waste Disposal and Waste Management and the Prevention of Marine Pollution (Annex 3 and 4), measures for Area Protection and Management (Annex 5), and the issue of Liability Arising from Environmental Emergencies (Annex 6 – not yet entered into force). The Protocol also established a new body, the Committee for Environmental Protection (CEP), to advise the Antarctic Treaty Parties on the effectiveness and implementation of the Protocol.

The environmental discussions that took place during the 1990's and early 2000's culminated in the designation of the MDV ASMA (ASMA No. 2) in 2004, following a joint proposal by New Zealand and the United States (Appendix 12.1). The MDV ASMA management plan, found in Annex 5 on Protection and Management, identifies a number of values (scientific, environmental, ecological, historic, aesthetic and wilderness) to be protected, and identifies a number of management aims and objectives to conserve and protect the unique and outstanding environment of the MDV, such as protecting against the unintended introduction of species not native to the area. The ASMA management plan has a Code of Conduct for managing activities in the MDV and outlines requirements for (i) access to and movement within the area, (ii) activities that may be conducted in the area, (iii) installations, modifications or removal of structures, (iv) field camps, (v) disturbance to flora or fauna, (vi) collection or removal of materials (i.e., sampling/site marking), (vii) waste management, and (viii) reporting. Further guidance is provided in the General Environmental Guidelines, Guidelines for Scientific Research, and in the Guidelines for Scientific Zones, Restricted Zones and Visitor Zones. The ASMA management plan establishes four types of zones within the Area: (i) Facilities (e.g., Lake Fryxell Camp); (ii) Scientific (e.g., Explorers Cove, New Harbor); (iii) Restricted (e.g., Prospect Mesa, Wright Valley); (iv)

Visitor (e.g., Taylor Valley). The ASMA currently contains five ASPA's: ASPA 123 Barwick and Balham Valleys (first protected in 1975); ASPA 131 Canada Glacier (1985); ASPA 138 Linnaeus Terrace (1985); ASPA 154 Botany Bay (1987); ASPA 172 Lower Taylor Glacier and Blood Falls (2012). The strengths of the ASMA include: defined values, set objectives, explicitness, clarity, reviews, and stakeholder engagement. The challenges facing the ASMA include: complexity, coordination, communication, priority setting, stakeholder engagement, and implementation uncertainty.

As part of the five-year review process required under Annex 5 of the Protocol, the ASMA management plan underwent a significant review in 2009 resulting in major revisions to the maps, management zoning, and rationalization of the Codes of Conduct. A revised management plan was formally adopted at the Antarctic Treaty Consultative Meeting (ATCM) in 2011 (Measure 10 (2011)), and again in 2015 (Measure 18 (2015)), which consisted of minor updates to the maps and associated text. The objectives of the management plan provide for the formation of a MDV Management Group that includes National Programs operating within the Area. The group currently includes representatives from the United States, New Zealand, Italy, Korea, and China (see www.mcmurdodry-valleys.aq/management). Members from the Management Group meet at least annually during the ATCM/CEP to provide an update on progress against an agreed work plan.

A workshop before the 2012 Scientific Committee on Antarctic Research (SCAR) open science meeting was convened to plan a Terrestrial Observation Network (TON) to coordinate the collection and sharing of long-term terrestrial observations (Levy et al. 2013a). This workshop produced (i) a list of key physical and biological processes that must be measured in order to detect ecosystem level responses to environmental change, (ii) a consensus list of standards and protocols for measuring these processes, (iii) an information management system that can account for the different types of data housed in the TON and the required infrastructure for making them accessible, and (iv) a list of short- and long-term assessment activities to develop questions about the efficacy of the current environmental management policies in the region. Two years later, in 2014, at an informal meeting during the SCAR open science meeting (Auckland, New Zealand), requests for data for ASMA Management Group Support, GIS mapping, historic activities, environmental releases, deployed equipment, facilities, helicopter operations, and the need for proper geo-referencing were discussed.

6. FUTURE ENVIRONMENTAL CHALLENGES

The environmental challenges facing the MDV are constantly developing in response to changes in technology, climate, and the nature of human activity. A significant challenge facing the environmental management of the dry valleys is the issue of how to manage under conditions of uncertainty. Such management involves the constant testing and reassessment of values and objectives with ongoing evaluation and monitoring. Issues that have been identified as future issues of concern include the following:

<u>6.1 Remotely and Autonomously Operated Vehicles.</u> There has been a history of use of both Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) in MDV lakes. NASA funded both a relatively large ROV to operate in Lake Hoare in the early 1990's and an AUV to operate in Lake Bonney in the late 2000's. The

AUV deployed in Lake Bonney, ENDURANCE (Environmentally Non-Disturbing Under-Ice Robotic Antarctic Explorer; Figure 4 A, B), was designed to operate near the ice-water interface to avoid disturbing the chemical stratigraphy deeper in the water column (Stone et al. 2010; Gulati et al. 2010). ENDURANCE deployed a small sonde on a tether to profile the lake on a 100 x 100 m grid. Although the vehicle was autonomous, it remained tethered on a fiber optic line the entire time it was in the lake.

ROVs and AUVs are becoming more affordable, and technically and scientifically more capable. As such, they are becoming integral tools for answering hypothesis-driven science questions and for addressing issues related to environmental management. Vehicles small enough to deploy through a hole in the ice now include navigation and mapping tools (e.g., sonar, Ultra Short Base Line (USBL) positioning systems), manipulators for sampling, high definition imagery, and the ability to carry add-on sensors. These systems can perform science tasks that may otherwise require SCUBA divers, thereby reducing human risk and lowering environmental impact. There is an existing Record of Environmental Review (ROER; MCDV1400.R01.AM1) for ROV use in the lakes of the Taylor Valley that outlines best practices for small ROV deployment.

Unmanned Aerial Vehicles (UAVs) (also referred to as Unmanned Aircraft Systems (UASs), drones, quadcopters, or similar versatile flight and camera systems) are inherently different from manned aircraft and introducing them into controlled airspaces has been challenging for administrators and the aviation community. They can be relatively lightweight, inexpensive and controlled by a smartphone or similar device. The use of UAVs in Antarctica has raised concerns about privacy, interference with scientific work, use in controlled airspace, and potential impacts if lost. The Antarctic Treaty System, various National Antarctic Programs (NAPs), and the International Association of Antarctica Tour Operators (IAATO) are all developing guidelines for the use of UAVs to minimize potential impacts or interference. Before the 2013–14 summer field season, various

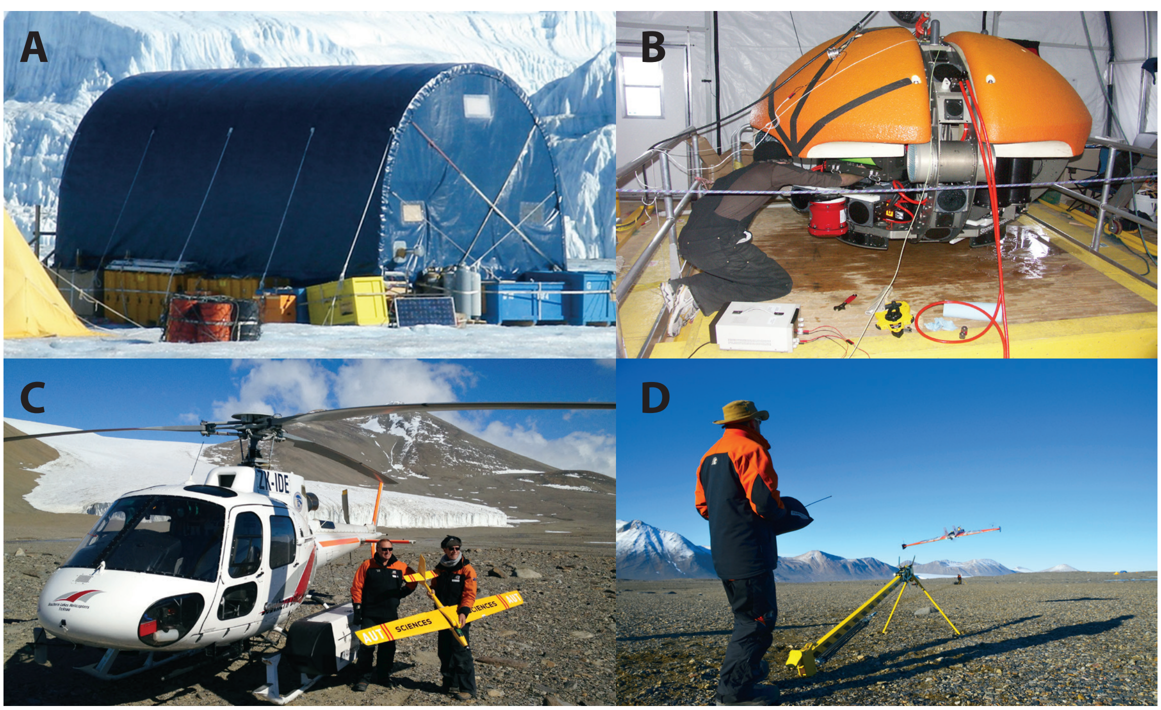

Figure 4. A) Support hut on Lake Bonney for the Endurance AUV; B) Endurance AUV being prepared before deployment through the ice cover of Lake Bonney; C) Helicopter support for UAV deployment in the MDV; D) UAV deployment in the Taylor Valley.

clients, expeditions and government research groups brought UAVs to Union Glacier, and a UAV was flown by an expedition at the South Pole in January 2014. Acknowledging this rapidly evolving technology and its potential for disturbance, IAATO drafted guidelines and submitted an informational paper (IP88) as an agenda item at the Antarctic Treaty Consultative Meeting (ATCM) 10, CEP 8b. This paper outlined discussions and policy evolution by IAATO membership regarding the use of UAVs during IAATO members' activities.

UAVs are now being deployed by MDV research teams to make valuable scientific measurements at their study sites. For example, New Zealand Scientists are using UAVs equipped with cameras and GIS spatial mapping equipment to identify cyanobacterial mats, estimate mat extent, and discriminate between different mat types (Figure 4 C, D). Their mapping has also identified the footprint of campsites and walking trails on soils, highlighting their potential use to examine human impact in the ecosystem. USAP participants, with approval from NSF, operate UAVs in the McMurdo area, including the MDV, in accordance with the guidelines in the Air Operations Manual (a document currently in the final stages of review and made available to approved UAV operators). Given the importance of UAVs to science, education, and environmental monitoring, in concert with the rapid evolvement of this technology, it is imperative that NAPs working in the MDV develop an agreed upon set of guidelines for their use.

6.2 Non-Native Species. Antarctica is now known to have a richer biodiversity that is more ecologically diverse and biogeographically structured than previously thought (Chown et al. 2015). Non-native species have yet to be documented in the MDV partly because present-day biodiversity remains largely unknown (e.g., Beet et al. 2016). Also, the MDV ecosystems are dominated by microorganisms (e.g., viruses, bacteria, fungi, protists, small metazoans), which are much harder to detect than invasions by macroorganisms. Non-native microorganisms have the potential to significantly alter community structure and ecosystem functioning in the diverse terrestrial and aquatic environments of the MDV. Importantly, global change and human disturbance can exacerbate microbial invasions, elevating the chance of an increase in non-native species in the future (Litchman 2010). Current evidence reveals that the distribution patterns of taxa across the aquatic and terrestrial habitats in the MDV are highly variable, with some groups such as aquatic viruses largely unknown. Additionally, while some species of rotifers and nematodes appear to be circum-Antarctic, other groups like Collembola have extremely restricted distributions with genetically distinct local populations (Bennett et al. 2016; Collins and Hogg 2016, see also soil section in this report). Such species could be used as indicators of change for biodiversity in aquatic or soil habitats that might occur with increasing numbers and movements of camps or people in the dry valleys.

Although many Antarctic taxa have mechanisms to allow natural transport by air (e.g., bacteria, cyanobacteria, archaea, some eukaryotes such as nematodes, mosses) (Bottos et al. 2014; Pearce et al. 2016; Marshall 1996; Nkem et al. 2006; Michaud et al. 2012), climate change combined with increased human movement can result in increased dispersal of non-indigenous propagules between ecoregions of Antarctica and from beyond the continent awith a high chance of establishment (Litchman 2010; Huiskes et al. 2014). Species introductions to the continent from regions such as the Arctic and sub-Antarctic continue to increase, with many carried by scientists and tourists (Huiskes et al. 2014). The implementation of prevention and management strategies is considered the most promising strategy to mitigate the effects of non-native species in the MDV and Antarctica as a whole (Chown et al. 2015).

The Committee for Environmental Protection's Revised Non-Native Species Manual was adopted by the Antarctic Treaty in 2016 (http://ats.aq/documents/recatt/att608_e.pdf). This document provides guidance to Antarctic Treaty Parties to meet the objective of minimizing the risk of accidental or unintentional introduction of non-native species and to provide effective responses should an introduction occur.

6.3 Extended Season Research. Three major scientific field campaigns have extended the length of human presence in the MDV since the early 1990's. These include two early season (August 1991, August 1995) and one late season (April 2008) deployment. The focus of these research events has been on the aquatic systems, which provide the only year-round functioning ecosystem in the area. These extended season efforts deployed more than 30 scientists to various field camps utilizing helicopter support (Figure 5). More than 5,000 gallons of diesel fuel was used to heat the Lake Bonney camp alone during the 1991 early season deployment (Priscu, unpublished data). Total diesel and propane use at the Lake Hoare camp during the 2008 late season effort increased by 400% and 800%, respectively, relative to the average usage of these fuels at Lake Hoare since 2002.

Clearly, the expansion of the science effort in the MDV beyond the typical "summer" season (October through February) has an impact on the environment that may cause a cascade of environmental consequences resulting from increased routine emissions, waste, and physical disturbance. Despite these concerns, the MDV ecosystem provides a sentinel for environmentally driven change on our planet. Research beyond the "typical" summer logistical season will provide important information on environmental processes, enabling scientists to better understand how to manage the region over an annual cycle (Priscu 2001). A more complete understanding of the range of natural variability within the system on annual time scales is crucial for unambiguous recognition of human-induced perturbations and to ensure that impacts on this relatively pristine environment are minimized.

6.4 Fossil Fuels. Fuel use associated with scientific activities has an impact on the environmental quality of the MDV. For example, Lyons et al. (2000) calculated the annual non-gaseous carbon and nitrogen fluxes from scientific activities of the US program (i.e., primarily from fossil fuel burning) for Taylor Valley and found that, while these anthropogenic non-gaseous carbon fluxes were minor, the NOx flux could be significant over long-term time scales. A more recent update of these fluxes from scientific activities suggests that they have remained relatively constant from the late 1990s to the present (Lyons et al. unpublished data).

6.5 Tourism. Data from IAATO revealed that total visitor landings in the Taylor Valley Visitor Zone between the 1992-1993 and 2014-2015 seasons were 3,619 (average = 157 per year), with an average time on the ground of 2 hours (Figure 6). The product of these values represents 7,238 visitor hours on the ground in the Taylor Valley over the entire period. It should be noted that there is only one small site in the Taylor Valley where tourists land. This site is subject to a set of treaty-approved guidelines (http://ats.aq/siteguidelines/documents/Taylor_e.pdf); hence the overall footprint of tourists in the MDV is spatially constrained. Similar figures for the number of person days that scientists and support staff have spent in the valleys are not easily available in part because of the large geographical deployment area of these groups.

6.6 Cumulative Impacts. International concern has been expressed about the long-term cumulative effects of science and tourist activities in the MDV. There is evidence that a single environmental perturbation can produce a cascade of unanticipated, negative environmental consequences (e.g., Vincent 1996; Wharton and Doran 1999; Priscu 2001). For example, extended season research in this region will directly increase

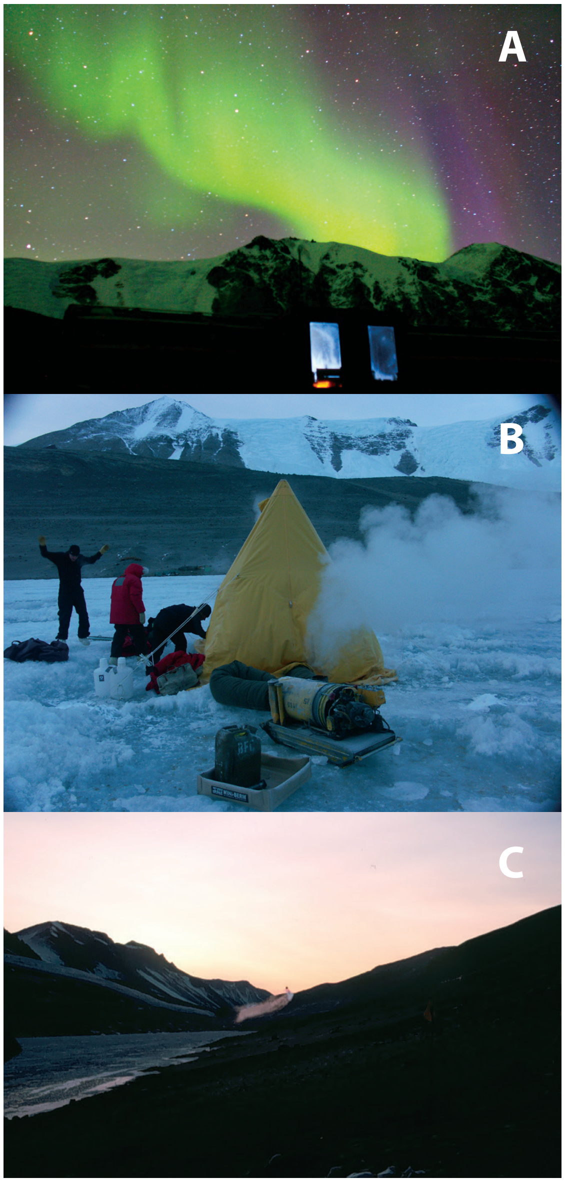

Figure 5. Images from extended season research in the Taylor Valley. A) Aurora over Lake Bonney camp (April 2008); B) Sampling Lake Bonney (April 2008, note Bonney camp in background); C) Helicopter leaving a contrail as it approaches Bonney camp (August 1995).

the number of person-days in the dry valleys, which, over time, will elevate the use of fossil fuels increasing the risk of spills and anthropogenic carbon input to the ecosystem. Increase human presence beyond the typical summer research season will also increase the potential for the introduction of non-native species that can accumulate over time.

<u>6.7 Stakeholder Engagement.</u> Another future challenge in the MDV is the level of ongoing stakeholder engagement in the region. To facilitate a strategy of adaptive environmental management there is a need for active participation from stakeholders to: (i) define common interests and goals; (ii) sustain scientific and environmental values; (iii) avoid duplication, conflicts, and mutual interference; (iv) minimize footprint and impacts; (v) derive long-term plans; (vi) coordinate activities; (vii) share information and data. The ASMA management group offers one body for encouraging and coordinating stakeholder engagement, but there may be other ways to do this.

<u>6.8 Education and Outreach Challenges.</u> Antarctica inspires a sense of adventure and wonder for children and adults around the world. Children especially are as eager to learn about Antarctica as they are about dinosaurs and the exploration of the planets. This high level of worldwide interest was enhanced by scientists and educators a decade ago during the International Polar Year (IPY, 2007-2008) (Zicus et al. 2011). Two of the many activities were an "ice stories" website presenting stories about polar scientists in the field (http://icestories.exploratorium.edu/dispatches/) and a Polar

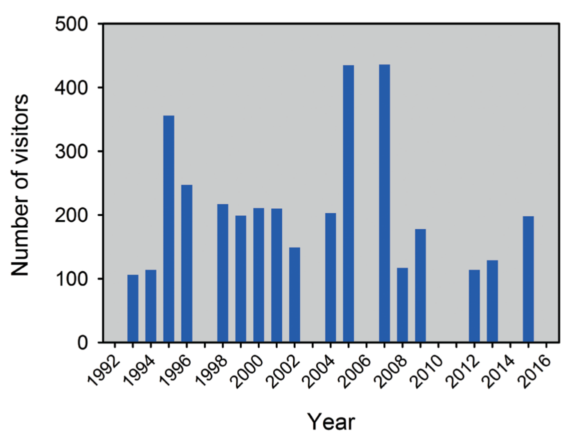

Figure. 6. Number of visitors landed per season within the McMurdo Dry Valleys Tourism Zone from 1992 through 2015. Data source: IAATO. Compiled by the U.S. NSF from data provided by U.S. tour companies in response to treaty reporting requirements. Tick marks on x-axis represents the end of each respective season, i.e., 1993 represents the 1992-1993 summer season.

Book Collection (http://www.ipy.org/images/uploads/Polar_Books_web_summary.pdf) identifying books that correctly conveyed science and values.

Although the MDV does not provide a habitat for charismatic animals such as penguins and seals, researchers and environmental managers have successfully leveraged the unique physical and biological properties of the MDV into engaging educational and other outreach activities (see: http://www.mcmlter.org/education-and-outreach). These outreach and education efforts illustrate the potential for other MDV research and stewardship themes to reach broad audiences. Workshop participants recommended that the goals of these efforts should be to (i) educate the public about the MDV ecosystems, (ii) use the MDV ecosystems as context for greater competency in science literacy, including the interpretation and analysis of scientific data, and (iii) build upon the broad interest in Antarctica to foster a general appreciation for effective environmental protection of natural environments. Wherever possible, efforts to achieve these goals should incorporate approaches that promote environmental empathy and avoid a discouraging sense of ecophobia (the general sense of feeling powerless to address impending environmental change) (Sobel 1996; McKnight 2010). By starting first with a focus on the fascinating aspects of the MDV environment, the concerns that adults and children may have for the future can be re-directed towards more positive outcomes through a concerted effort to present (in education and outreach activities) the drivers and impacts of climate-driven environmental changes in terms of positive, solution-based narratives. In this context, the McMurdo Dry Valleys ASMA represents a success story for environmental stewardship that can inspire others. Careful management of resources and effort can lead to significantly improved educational outcomes without impacting scientific research objectives.

7. SOURCES AND AVAILABILITY OF ENVIRONMENTAL DATA

Although human activity in the MDV has been relatively well documented, these records are scattered across various archives, government departments, private companies, personal collections, published books and articles, and grey literature. In addition, data collection has been patchy and some records of human activity in the region have been lost. As a consequence, it is difficult to put together a comprehensive overview of human presence in the region. This in turn makes it hard to quantify changing patterns of human impact in the MDV over time. It is difficult to quantify, for example, whether human activities in the region have increased steadily over time, or if there have been fluctuations in levels of human activity. Sources of environmental data are summarized below:

<u>7.1 Antarctica New Zealand.</u> The New Zealand program maintains an extensive collection of data relating to human activities in the MDV (Appendix 12.3). These records have been kept since 1956, and are in the process of being digitized and made available online. The environmental data are being used by several NZ based programs to understand human impact in the region. The Ross Sea Region Terrestrial Data Analysis program is leveraging existing environmental data (climate, water, soil, bioregionalization, human movement/impacts) to provide policy-relevant insights into environmental pressures. The Dry Valleys Ecosystem Resilience program (DryVER) aims to produce the first regional scale environmental impact assessment by examining the physical, chemical, and biological impacts from human activities.

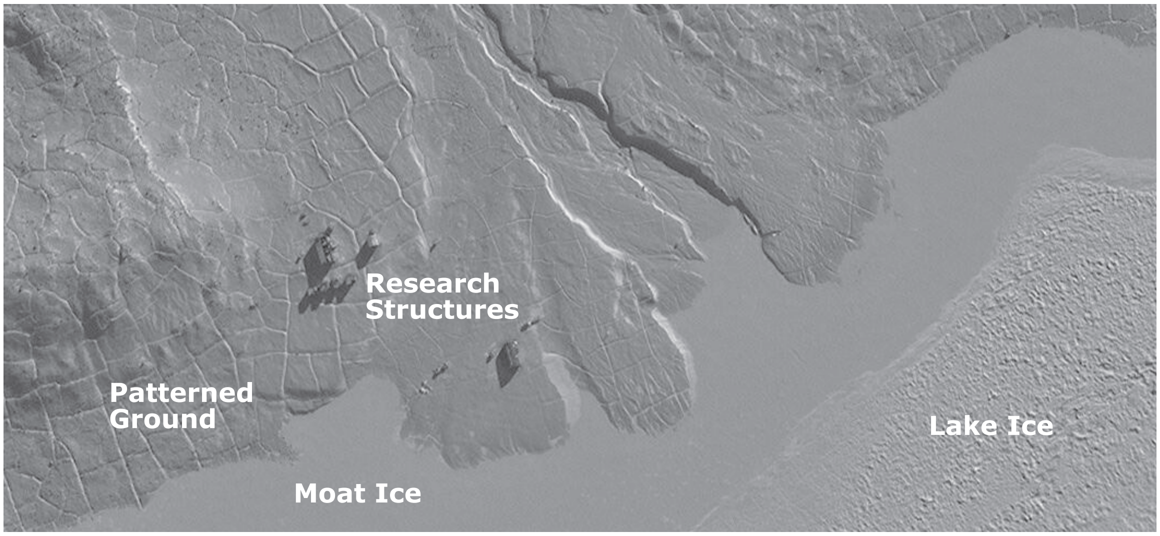

Figure 7. Worldview-1 image of Lake Fryxell. Imagery ©2015 DigitalGlobe, Inc.

7.2 United States Antarctic Program (USAP). USAP activities have been conducted in the MDV for over 50 years with initial program support provided by the U.S. Navy. In March 1993, an interagency working group developed a plan for Navy withdrawal from all USAP support missions except the LC-130 air logistic support, which it eventually relinquished to the Air National Guard in 1995. A series of civilian contractors have provided support for McMurdo-based operations since this transition. Many of the records of human activities in the MDV were paper-based or in old-format discs. The amount and quality of data collected over this period is not well known and it would take a concerted effort to find, consolidate and analyze data that might or might not have been transferred between contractors over the years.

Field reports in publications such as the Antarctic Report (1964-1965), the Antarctic Status Report (1962-1963), the Bulletin of the U.S. Antarctic Projects Officer (1959-1965), the Antarctic Status Report USNC-IGY (1956-1958), and the Antarctic Journal of the United States (1966 to 1996) could provide insight into past activities (see http://www.coldregions.org/vufind/ajus/home). Systematic data collection of USAP science activities began around 2003 via mandatory End of Season reports and would be a good source of data. However, to date, resources for data analysis of human activities in the MDV have not been available. In addition to these reports, USAP has contributed to the development of the Polar Geospatial Center, VALMAP, and maintenance of the McMurdo LTER program database (see below) as venues to summarize human activities in the MDV.

7.3 Polar Geospatial Center (PGC). PGC (http://www.pgc.umn.edu/) provides geospatial support, mapping, and GIS/remote sensing solutions to researchers and logistic providers in the polar science community. They collaborate with scientists to complete their research goals in a safe, timely, and efficient manner by providing a service that most groups do not have the resources or expertise to complete. Their goal is to introduce new, state-of-the-art techniques from the geospatial field to effectively solve problems in the least-mapped places on Earth. The PGC holds an extensive collection of satellite imagery and aerial photography at varying resolutions. PGC can process and deliver imagery to federally-funded researchers, but most datasets are directly available for download from their satellite imagery page or aerial photography page. An example of an image produced by PGC showing human activities in the Lake Fryxell basin in the MDV is shown in Figure 7.

7.4 VALMAP. In the 1990's, a University

of New Hampshire team headed by Mike Prentice produced the first major GIS of the major physical features of the MDV with funding from the NSF and collaboration with the US Geological Survey and the New Zealand Institute for Geological and Nuclear Sciences (NZ IGNS). Known as VALMAP (Valleys in Antarctica: Layered Mapping, Analysis, and Planning), the project captured the metadata for geographic control points (GCPs) collected previously in the MDV by USGS and Land Information New Zealand. Three SPOT satellite images were rectified using these GCPs and served as the satellite image basemap for VALMAP. Using aerial photographic coverage of the MDV from the late 1940's, VALMAP produced an ArcMap theme that inventories all 250 flight lines and provides metadata. Thematic layers on major physical features were provided by specialists in their respective fields. VALMAP is no longer maintained, but many of the thematic layers are archived at the PGC.

7.5. MCM LTER Database. The MCM digital assets (http://www.mcmlter.org/power-search/data-set), include tabular and spatial data from 1993 to present, in addition to some pre-LTER data since 1967. These data are from glaciers, streams, lakes, soils, and meteorological stations, and represent metadata, real-time data, background project information, outreach activities, personnel information, and an up-to-date list of publications supported by the MCM LTER. Core (long term) and ancillary (short term and opportunistic) data are stored in relational databases. LTER research projects are linked to other external datasets and collections, such as the Freshwater Diatom Collection at INSTAAR, the LTER Network Information System PASTA, Genbank, MG-RAST, DataOne and other national metadata clearinghouses. The MCM LTER aims to make all data publicly available within two years of collection. Exceptions are made for ongoing unpublished experiments or data with extensive QA/QC needs.

7.6. Science Teams. In addition to centralized information from NAPs, individual science teams working in the MDV have often kept a record of their activities. For example, reports from Griffith Taylor's 1911 exploration of the dry valleys can be found in the National Library of Australia, the University of New England Archives in New South Wales, Australia, and the Scott Polar Research Institute in Cambridge, England (Howkins 2016). In addition to national program reports, information about New Zealand research in the MDV has been published in grey literature journals such as The Waikato University Antarctic Research Unit Reports and the Bibliography of International Dry Valley Publications volumes 1 (1907-1977), 2 (1978-1984) and 3 (1985-1994) compiled by the Antarctic Division of the Department of Scientific and Industrial Research (DSIR) and the New Zealand Antarctic Program. Similar information on United States research can be found in The Antarctic Journal of the United States, which is searchable on line at http://www.coldregions.org/vufind/ajus/ajus. Alongside these archival and grey literature sources, peer reviewed publications offer a valuable source of information about the work of individual science teams in the region.

7.7. International Association of Antarctica Tour Operators (IAATO). IAATO maintains a detailed database summarizing statistics for tourist visits to Antarctica (http://iaato.org/tourism-statistics). Information in this database is broken down by location (e.g., peninsula, continental), year, nationality and total numbers of visitors. A compilation of the seasonal visitor numbers to the MDV from 1992 to 2015 was presented previously in this report (see Figure 6).

8. ENVIRONMENTAL MANAGEMENT

The designation of the MDV as an ASMA (Appendix 12.1) recognizes the unique scientific values of this region and its potential sensitivity to human impacts. The ASMA management plan (reproduced as a field manual by Antarctica New Zealand, and the United States and Italian Antarctic Programs, 2015 (4th Ed)) outlines the values to be protected, aims and objectives of the management plan, and management activities to be undertaken to ensure the long term protection of this environment. An example is the management activity requirement that "National Programs operating within the Area and tour operators visiting should ensure that their personnel (including staff, crew, passengers, scientists and any other visitors) are briefed on, and are aware of, the requirements of the Management Plan, and in particular the General Environmental Guidelines that apply within the Area." Both the U.S. and New Zealand programs conduct environmental training for personnel working in the MDV; this training includes environmental guidelines found in the ASMA Management Plan.

Other aims and objectives of the management plan, however, have not as yet been adequately met, and require urgent attention in ways described in the recommendations presented in Section 10. For example, the ASMA aim and objective to "prevent the unintended introduction of species not native to the Area, and minimize as far as practicable the unintended transfer of native species within the Area" needs the development and subsequent implementation of specific protocols. Similarly, the ASMA management activity to "maintain a record of activities, and where practical, impacts in the Area, and to develop strategies to assess cumulative impacts" requires a concerted effort by all NAPs operating in the region to compile, synthesize and make available such data to all stakeholders.

The McMurdo Dry Valleys ASMA management plan follows guidance in Annex V

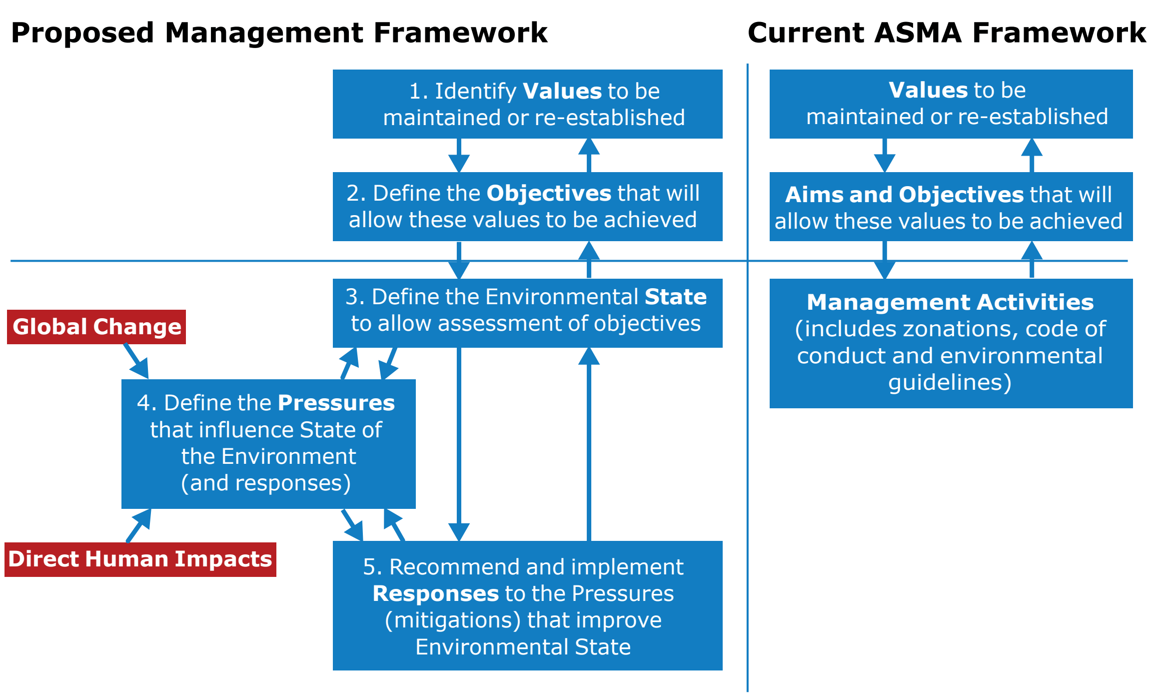

Figure 8. Proposed expansion of the MDV ASMA Management Plan to reflect the scientific and value-based relationships presented in Figure 2 and discussed in this section. The current ASMA framework is presented on the right side of the diagram.

of the Protocol in that it addresses: Values to be protected; Aims and Objectives; and Management Activities. The last has a list of activities that need to be coordinated between the NAPs, and sections on zonations and structures, Code of Conduct, provisions for information exchange, and General Environmental Guidelines. However, many of the guidelines for the management activities are defined at a high general level and their implementation requires more specific measures. Effectual implementation requires personnel visiting the dry valleys to evaluate, understand, and modify their behaviors to ensure that they are following the minimum requirement guidelines. Workshop participants noted emphatically that science should inform policy! Policy makers do not visit the MDV to the extent that scientists do and they must hear from the users of the dry valleys (i.e., the scientists) and modify policy accordingly.

All workshop participants agreed that the specific aims of this workshop could not be met explicitly without a clearer definition of the ASMA's management activities that would explicitly cover the state of the current environment, the pressures (threats) on that state (i.e., from direct human activities and from global change), and more detailed management responses to those pressures (see Figure 2). We have therefore provided a suggested management structure to support the ASMA Management Plan framework, and assist with the Aims and Objectives of the Management Plan to include these specific components using a recognized framework for environmental management plans. This plan involves five sequential and iterative steps from definition of values to specific management responses (Figure 8). The plan further requires an adaptive management approach based on continuous updates to knowledge of the state of the environment (Figure 8, step 3) made by monitoring and data collation that is affected by the current and emerging pressures (Figure 8, step 4). In turn, the state of the environment and the pressures direct what responses (Figure 8, step 5) are needed and vice versa.

There is an urgent need to address concerns over the accelerating environmental pressures on these unique landscapes and ecosystems. These multiple stressors range from increasing local perturbation associated with science and tourism activities, to the threat of non-native species, and the effects of global change. Distinguishing natural, inter-annual variability from longer term, directional shifts also requires an improved assessment and management of local human impacts, including appropriate long term monitoring. Additionally, the recovery rate of disturbed sites needs full attention to assess resilience and variation among landscape types. Finally, given the decreasing availability of near pristine environments, there is an urgent concern for further spatial protection in the area. This is particularly relevant to Annex V, Article 3, 2a of the Protocol, which states that Parties shall seek to identify Antarctic Specially Protected Areas (ASPA's), including "areas kept inviolate from human interference so that future comparisons may be possible with localities that have been affected by human activities." A small number of candidate areas for such demarcation are apparent at present, but need urgent evaluation before their imminent loss as potential reference sites.

9. STATE OF THE ENVIRONMENT

An overarching idea behind this workshop was that effective environmental management of the MDV cannot be achieved without a thorough knowledge of the environment. There has been a rapid increase in new knowledge about the intricacies of the MDV landscape over the 17 years since the last environmental workshop report. Knowledge of the atmosphere, biosphere, cryosphere, hydrosphere, and geosphere provides the overarching umbrella for environmental awareness and decision making, all of which is driven by global change (Figure 2). This section was written with the input of experts in each of these fields, and represents the current understanding of each field as they relate to environmental integrity now and for the future.

<u>9.1 Climate: Present and Future.</u> The MDV mean annual valley bottom air temperatures range from -17 to -30 °C (Doran et al. 2002a), and precipitation is low (~50 mm annual water equivalent as snow; Fountain et al. 2010). Summer air temperatures typically hover around freezing and winter air temperatures are commonly < -40 °C. Evidence that lake levels have risen significantly overall since the first visit to the valleys by Robert Falcon Scott in 1903 (Chinn 1993) indicates that climate over the last century has likely been dominated by relatively warm summers. There was a general cooling trend between 1987 and 2001 (Doran et al. 2002a), which ended abruptly with an anomalously warm summer (Doran et al. 2008). In the 15 years since the end of that cooling trend, summers have been generally warmer, which is partly responsible for lake levels rising over time (Figure 9). The MDV climate and surface energy balance is tightly coupled to regional atmospheric dynamics, specifically the Antarctic Oscillation, which appears to be at least partly correlated to the ozone hole (Priscu 2016; Fountain et al. 2016). Although the dry valleys are currently in a period of quasi-stable climate, with temperature trends being near zero since the start of the longest record at Lake Hoare, climate models predict warming in the short and long term across Antarctica as the ozone hole "heals" (Schindell and Schmidt 2004; IPCC 2013). Modelling future trends specifically for the MDV region has not been done, but in general the Ross Sea coast, as much of Antarctica, will experience rates of warming below the global average (IPCC 2013). Nevertheless, projected warming has implications for the future cryosphere and water balance in the valleys. Lake levels should continue to rise, and ice covers will continue to thin (Obryk 2014, Obryk et al. 2016a) setting the stage for a future of larger seasonally ice-free lakes, and perhaps even events of liquid precipitation (rain).

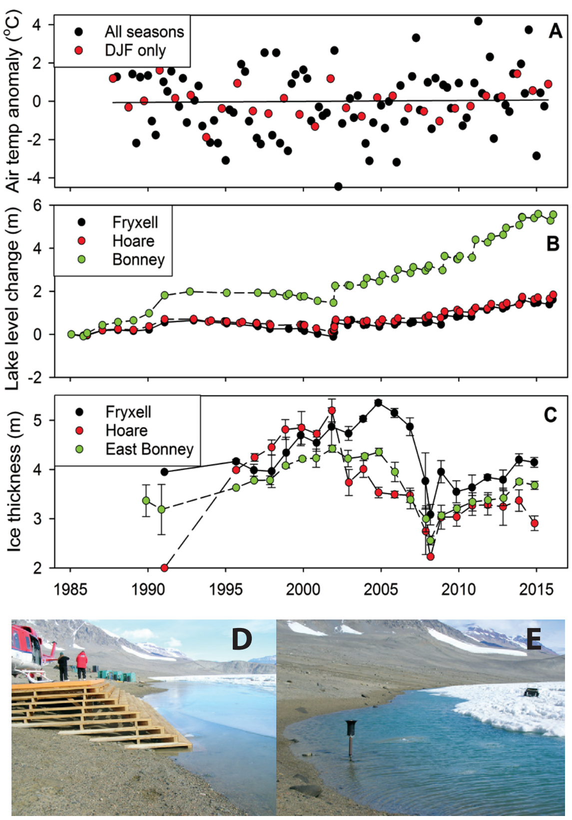

Figure 9: A) Trends in air temperature at Lake Hoare meteorological station (as deviations from the seasonal mean). Red circles represent summer (December, January, February) values; black circles represent values from all seasons (January through December); black line represents a least squares fit through the data from all seasons; B) Lake level change, and C) ice thickness, for the main Taylor Valley lakes; D, E) Images taken at Lake Bonney camp in January 2006 showing the impact of rising lake levels on camp infrastructure.

<u>9.2 Geology.</u> The MDV are home to a breadth of geomorphic surfaces with varying sensitivity to human disturbance. A description of the main geomorphic features and their sensitivity, as well as highlights of potentially finite climate archives, are presented below.

<u>9.2.1 Bedrock Geology.</u> Bedrock surfaces in the high-elevation valleys and plateaus,

such at Mt. Fleming and Shapeless Mountain, exhibit some of the lowest erosion rates on Earth, 5–10 cm Myr^{-1} (Summerfield et al. 1999). Slow erosion in these sites is a consequence of intrinsic bedrock properties (e.g., composition, strength) and environmental factors, such as a near-lack of biological weathering, limited chemical weathering, and little physical erosion from hydrological activity.

9.2.2 Landforms and Surficial Geology. The MDV are a complex patchwork of landscapes and landforms that range from modern to mid-Miocene in age. Common landforms in the MDV highlighted in this section are: (i) talus slopes, (ii) gullies and streams, (iii) viscous flow features, (iv) patterned ground, (v) desert pavement, and (vi) paleo-lake deposits.

9.2.3 Talus slopes. In general talus slopes are unstable and relatively young. However, in high-elevation regions, such as the Quartermain Range, some talus appears to be stable over 10^5 to 10^6 years and therefore might be sensitive to human disturbance (Putkonen et al. 2008).

9.2.4 Gullies and streams. Gullies and streams occur most commonly along the slopes of the main valleys. Where gullies are incised into unconsolidated sediments, they exhibit variable erosive activity, closely tied to inter-annual variability in summer meltwater and the presence of snowbanks (Levy 2015). As such, they are relatively dynamic, however given their direct response to summer conditions they are also an important landform for monitoring climatic and geomorphic change in the dry valleys.

9.2.5 Viscous flow features. Viscous flow features and/or debris-covered glaciers are common throughout the central MDV at low elevations. Rock glaciers affect ~10% of the land surfaces in the valleys (Hassinger and Mayewski 1983).

9.2.6 Patterned ground. Patterned ground is the surface expression of vertical contraction cracks that form in ice-rich soils and buried ice during the winter (see the patterned ground near the camp in Figure 7). Patterned ground in the MDV falls into three broad classifications: ice-wedge polygons in wet permafrost, sand-wedge polygons in non-thawing permafrost, and sublimation polygons in regions with buried glacial ice (Marchant et al. 2002). Because patterned ground varies with climate and hydrology, changes in patterned ground with time might provide information on landform response to climate change in the dry valleys.

9.2.7 Desert pavement. Desert pavements occur throughout the MDV, varying significantly in development, age, and sorting (Figure 10). Well-developed desert pavements occur on the oldest surfaces at higher elevations. These well-developed desert pavements are fragile, may take 10^4 to 10^6 years to fully develop (Matmon et al. 2009), and recover slowly after disturbance (O'Neill et al. 2012).

9.2.8 Paleo-lake deposits. Paleo-lake deposits from Pleistocene lake high stands are common in the MDV and consist largely of deltaic and lake-bottom deposits (Hall et al. 2010). Dating of these deposits sheds light on ice sheet position, MDV climate, and regional circulation patterns.

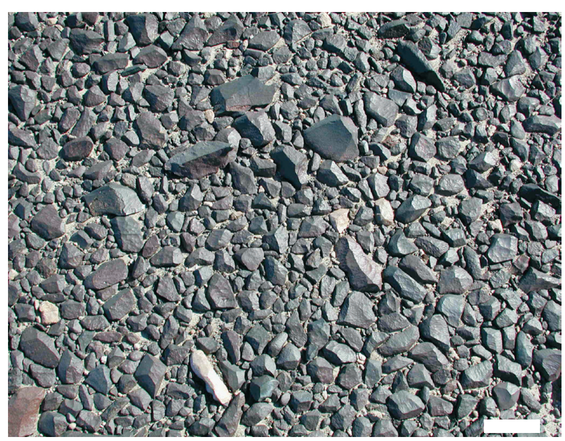

Figure 10. Ancient surface in Arena Valley, a higher elevation part of MDV, showing well-developed ventifacts that have formed an interlocking desert pavement. This pavement protects the surface from wind erosion. Scale bar = 10 cm.

9.2.9 Geologically Sensitive and Finite Climate Archives. In addition to bedrock and surficial landforms that are sensitive to human impacts, some MDV geological deposits are sensitive due to their paucity. The Hart Ash in Wright Valley is one example of a finite climate archive and novel geomorphic deposit. Similar deposits are located throughout the dry valleys and are often the only climate archives available for a given region and/or time period. These distinct, and often limited, climate archives include Pleistocene drop moraines in the Olympus Range, preserved organic material in the Friis Hills from the mid-Miocene, and ash deposits that range from Pleistocene to Miocene in age (Marchant et al.1996; Lewis and Ashworth 2015). These deposits are highly sensitive to over-sampling and human disturbance.

9.3 Cryosphere

9.3.1 Glaciers. The MDV host two types of glaciers. Alpine Glaciers flow from the local mountain ranges (e.g., the Kukri Hills and Asgard Range), while trunk glaciers flow into the valley bottoms as outlet glaciers of the East Antarctic Ice Sheet. The smaller alpine glaciers have a faster dynamic response time, which makes them more susceptible to changes in ambient air temperature (Fountain et al. 2004) or snowfall in the mountains. The glaciers are assumed to be cold-based because the average annual air temperature is typically -17 to -30 ºC, and therefore without a subglacial hydrological system (Cuffey et al. 2000), although small melt streams flow on the surface and along the terminus during the summertime. Some, such as the Canada Glacier, terminate in lakes and may be susceptible to lake level changes.

Trunk glaciers, such as Taylor Glacier, however, are much larger and therefore would normally not be considered susceptible to change in the environment at their terminus (Jóhannesson et al. 1989). Due to their thickness, they are warmer at their base, especially where they sit in an over-deepened valley floor, as Taylor Glacier does (Hubbard et al. 2004). Recent work has shown that liquid-brine saturated sediment underlies Taylor Valley (Mikucki et al. 2015), and likely feeds a brine subglacial hydrological system that both causes accelerated flow in the terminus region (Pettit et al. 2014) and feeds an englacial hydrological system at Blood Falls. Taylor Glacier, therefore, is likely susceptible to retreat due to rising lake levels in Lake Bonney. Based on recent work by Pettit et al. (2016) and Badgeley et al. (2015), substantial lake level rise (more than 5 m above present) could lead to degradation of the ice-cored moraines, significant retreat of the glacier terminus, and de-pressurization of the Blood Falls feature.

The glaciers of the MDV provide habitat for microbial activity both within surface melt channels and in cryoconite holes (Porazinska et al. 2004; Foreman et al. 2007). Due to the impermeable nature of glacier ice, there is unlikely to be any connection between the surface environment and the subglacial environment. While crevasses are rare (except in the ice falls) and moulins are non-existent, the subglacial environment is generally protected from contamination. For the alpine glaciers, however, any dust, windblown organisms or organisms associated with human presence that fall on the snow in the accumulation areas will be integrated into the glacier ice as the snow is compressed. In the ablation areas, however, which is where the majority of human visits occur, there is a net outward flux of ice; any potential source of contamination stays near the surface or is flushed off the glacier with summer melt water.

9.3.2 Snow. Annual snowfall in the MDV ranges from 3 to 50 mm water equivalent (Fountain et al. 2010). Strong spatial gradients exist with highest snowfall near the coast, and katabatic winds transporting a significant amount of up-valley snowfall down-valley. Much of the snowfall sublimates rather than melts; therefore, it contributes little to the hydrological cycle

(Fountain et al. 2010). Snow can act as an important insulator for both lake ice and frozen ground. Because snowfall occurs on a short (hours to days) timescale compared to other processes within the valleys, its role in the ecosystem is unlikely to be affected by direct human activity. Longer term changes in climate, however, may lead to changes in the timing and frequency of snowfall events, the spatial pattern and seasonality of precipitation, and the redistribution due to winds.

9.3.3 Ground ice. Ground ice is common in the MDV and is dominated by ice-cemented sediments (pore ice) (Bockheim et al. 2007), as well as massive ice deposits from buried glaciers (Marchant et al. 2002; Sugden et al.1995b) and till-covered ice sheet remnants (Pewe 1960; Stuiver et al. 1981; Arcone et al. 2002). Ice lenses or wedges from refreezing of active layer meltwater are rare, but not wholly absent, and at high elevations, ground ice may form directly from vapor deposition (Hagedorn et al. 2007; Lacelle et al. 2013). A hallmark of the ice-rich permafrost is polygonal patterned ground (see Figure 7) that occurs extensively throughout the MDV (Pewe 1959; Black and Berg 1963; Sletten et al. 2003; Levy et al. 2009). Possibly in reflection to a recently warming climate, ground ice in the coastal thaw zone (Marchant and Head 2007) is undergoing rapid melting, resulting in the formation of large thermokarst slumps, cliffs, and ponds (Levy et al. 2013b), while ground ice at higher elevations is sublimating at slower rates, allowing ice to persist for long periods of time (Liu et al. 2015). Ground ice itself is an important paleoclimate indicator (Kowalewski et al. 2011), and is also the substrate underlying landforms such as paleolake deltas and moraines, which provide geological evidence of past ice sheet and regional climate conditions (Denton and Marchant 2000; Levy et al. 2013c; Hall et al. 2015). A deepening active layer, the depth to which permafrost thaws seasonally, may be changing the thermal state of MDV soils by increasing soil moisture content. The deeper active layer creates a positive melting feedback resulting in deeper thaw and further soil wetting from ground ice melt. This process implies that rapid loss of ground ice may be possible under only modest warming scenarios (Levy and Schmidt 2016). A suite of stations monitors the active layer depth in the MDV and other regions in Antarctica (Paetzold et al. 2003; Vieira et al. 2010).

9.4 Permafrost. Permafrost in the MDV was shown to exceed 970 m depth in Dry Valley Drilling Project (DVDP) boreholes (Decker and Bucher 1977). Two more recently monitored boreholes within the SCAR-ANTPAS (Antarctic Permafrost And Soils) network show a permafrost depth of 680 m at the inland site of Wright Valley, becoming shallower (490 m) at the coastal site of Marble Point (Guglielmin et al. 2011). Permafrost temperatures at the depth of zero annual amplitude range between -17 and -24 °C (Vieira et al. 2010). Since 2008, both Marble Point and Wright Valley have shown increasing permafrost temperatures, especially at deeper depths (M. Guglielmin, Insubria University, Italy, personal communication), despite negligible changes in air temperature.

The active layer depth has a large spatial and temporal variability related primarily to local conditions (e.g., Adlam et al. 2010; Guglielmin et al. 2011). The active layer may exceed 80 cm at lower elevations and can be almost negligible at higher elevations (e.g., 3 cm at Mount Fleming; Vieira et al. 2010). The active layer depth has recently become deeper in Wright Valley, a situation that is also occurring in some areas of the Arctic that are undergoing warming (M. Guglielmin, Insubria University, Italy, personal communication). This deepening of the active layer may lead to the large landscape changes (Fountain et al. 2014) that are likely to induce severe changes in the soil ecosystems.

9.5 Streams. The streams of the MDV connect glacier sources to lakes on the valley floors or ocean outlets. They generally flow for 4-8 weeks per year (Wlostowski et al. 2016) beginning as early as November and lasting as late as February. Where the beds are composed of stable substrate (e.g., large clasts, desert pavement), extensive microbial mats exist, which harbor communities of cyanobacteria, diatoms, and nematodes. Streambeds also contain extensive thawed hyporheic zones through which stream water exchanges, enhancing nutrient cycling and driving high chemical weathering rates (Gooseff et al. 2002; Lyons et al. 1997). The microbial mats persist through the winter in a freeze-dried state awaiting the onset of stream flow each summer; when they become re-wetted metabolism is initiated almost immediately (Vincent and Howard-Williams 1986). These mats also control the flux of nutrients to lakes through direct assimilation and regeneration (Howard-Williams et al. 1989; Gooseff et al. 2004; McKnight et al. 2004). The microbial mats are subject to two types of disturbance: (i) natural disturbance (i.e., scour) and (ii) human trampling. Recent studies suggest that the mats take more than one entire flow season to re-grow after significant removal from streambeds (Kohler et al. 2015a). In addition, algal mat biomass is strongly controlled by hydrologic variability in these streams (Kohler et al. 2015b). It has been documented recently that stream banks are deteriorating owing to permafrost degradation (Figure 11) (Gooseff et al. 2016; Levy et al. 2013b). The resulting thermokarst formation provides new sediment and nutrient (i.e., dissolved salts from bank sediments) inputs to streams, which may result in greater mechanical abrasion of streambeds and microbial mats, or burial of microbial mats.

<u>9.6 Lakes.</u> The permanently ice-covered lakes are prominent features of the MDV and provide the only year-round bulk water environment in the region. As such, they serve as extended oases for life in this polar desert ecosystem. The lake basins were inundated with seawater in the late Neogene (23 million to 2.6 million years ago) when sea level was higher, and have been modified to their present state by active hydrology, geochemical weathering, and biogeochemical processes. The combination of year-round liquid water and a source of energy (i.e. transmitted sunlight; redox gradients) is rare in the Antarctic interior, and supports truncated, microbially-dominated food webs within the lakes of the MDV (Priscu et al. 1999).

<u>9.6.1 Lake Ice Covers.</u> Perennial lake ice covers, typical of MDV lakes, largely decouple underlying aquatic ecosystems from atmospheric interactions, permitting the development of unique quasi-stable biogeophysical systems. The perennial ice covers inhibit wind-driven mixing of the water column and gas exchange with the atmosphere, leading to super-saturation of many gases in the water column (Wharton et al. 1986; Priscu et al. 1996; Priscu 1997) and the presence of strong chemical gradients in certain lakes (Spigel and Priscu 1996; Spigel and Priscu 1998). These gradients, in turn, regulate vertical diffusion of nutrients, which controls the nutritional status of phytoplankton (Priscu et al. 1989; Priscu 1995). Solar radiation that penetrates the

Figure 11. Thermokarst resulting from permafrost degradation and erosion along Crescent Stream (Fryxell basin), in January 2012.

Figure 12. Image of the microbial habitat located 2 m beneath the ice surface in Lake Bonney. The organisms are transported into the system on wind-blown sediments and grow in melt water inclusions associated with the sediments. The bubble patterns follow the freezing front in the ice and show that the inclusions do indeed contain liquid water.

ice cover, in concert with non-turbulent mixing, results in unique thermal profiles of the water column (Hoare et al. 1964; Spigel and Priscu 1998), which can take many hundreds of years to develop (Vincent et al. 2008). The ice cover also greatly alters the attenuation of photosynthetically active radiation reaching the underlying water column, resulting in extremely shade-adapted phytoplankton that form vertically distinct chlorophyll maxima (Priscu et al. 1988; Lizotte and Priscu 1992; Morgan-Kiss et al. 2016). It is clear that within this polar desert system, small climatic changes alter the surface energy balance leading to changes in ice dynamics that alter hydrologic response (Doran et al. 2002b) and associated ecosystem response.

The permanent ice covers mediate responses of the aquatic ecosystems to seasonal and long-term changes as they mitigate heat fluxes between the atmosphere and the underlying water column. One of the longest ice thickness records comes from Lake Hoare, which thinned from 1977 to 1986 at a rate of >0.28 m yr^{-1} (Wharton et al. 1989) and thickened between 1986 and 1999 at a rate of 0.11 m yr^{-1} in association with an annual air temperature decrease of 0.7 °C $decade^{-1}$ (Doran et al. 2002b; Obryk et al. 2016b). All ice covers in Taylor Valley lakes began to thin in the early to mid-2000's (see Figure 9). However their response to climate is modulated by the heat fluxes from the water columns, which are influenced by penetrating solar radiation (Obryk et al. 2016a).

The permanent lake ice also harbors an environmentally sensitive microbial community immured about 2 m beneath the surface of the ice (Figure 12) (Priscu et al. 1998). This ice-bound habitat forms when wind-blown sediments land on the surface of the lake ice and melt into the ice during the summer (Fritsen et al. 1998), reaching a depth of thermal equilibrium where microorganisms thrive on melt water inclusions that form during periods of adequate solar radiation. This microbial ecosystem is diverse (Gordon et al. 2000) and most new carbon is formed via cyanobacterial photosynthesis (Fritsen and Priscu 1998). The system modifies inorganic and organic nutrients that enter the water column and influences the transparency of the ice (Adams et al. 1998; Fritsen and Priscu 1999), which in turn can influence water column photosynthesis (Fritsen and Priscu 1999).

9.6.2 Lake Water columns. A number of perennially ice-covered lakes in the MDV have been investigated since the early 1960's. These lakes can be considered sentinels of climate change because they integrate climate over spatial and temporal scales. Three lakes located in the Taylor Valley (Fryxell, Bonney, and Hoare) have been the focus of intensive study since the establishment of the McMurdo LTER in 1993. Owing to the permanent lake ice cover, the lakes exhibit modest connections to the surrounding environment and each other, allowing the water columns to maintain strong, permanent chemoclines along which the microbial communities are vertically stratified along permanent chemoclines (Lizotte and Priscu 1994; Morgan-Kiss et al. 2016). The nature of the ice cover changes in response to air temperature, and ephemeral streams provide climate-dependent pulses of glacial meltwater to the lakes, affecting lake levels as well as nutrient and organic matter availability. By virtue of the perennial ice-cover, low advective stream flow, and saline bottom waters, the lakes are permanently stratified and exhibit thermodynamic and geochemical conditions reflecting the climate evolution and watershed characteristics of each lake (Lee et al. 2004; Spigel and Priscu 1998). Prokaryotes (Bacteria and Archaea) and eukaryotic photoautotrophic plankton dominate the biomass of the open water ecosystems of MDV lakes; crustacean zooplankton are rare and no fish exist (Priscu et al. 1999; Bielewicz et al. 2011). Where adequate light exists, mats form on the bottom dominated by cyanobacteria and pennate diatoms, which in the absence of disturbance form thick, annually laminated microbial mats, often assuming elaborate emergent morphologies (Hawes et al. 2001; Hawes et al. 2016). Mat communities contain a common assemblage of organisms across all lakes so far investigated, though relative abundance can vary (Zhang et al. 2015). Within lakes, composition is structured by depth, transitioning from oxygenic to anoxygenic phototrophy at the oxycline (Jungblut et al. 2016). The mats support a diverse array of prokaryotic and eukaryotic microorganisms, as well as nematodes, tardigrades, and rotifers, and are providing insights into the biogeochemistry of microbial ecosystems on early Earth (Sumner et al. 2015).

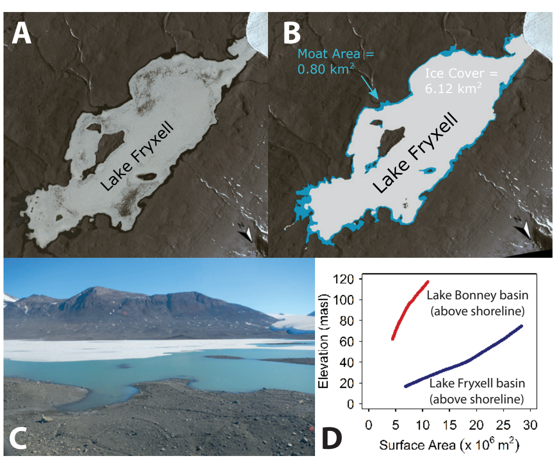

Figure 13. Images of Lake Fryxell showing A) the permanent ice cover, B) the moat area, C) a view of an open moat, and D) the relationship between lake elevation and surface area in Lakes Bonney and Fryxell (Hillary Dugan personal communication).

<u>*9.6.3 Lake Moats.*</u> Moats form around the MDV lakes during the austral summer in response to increased solar radiation and associated stream input. The moats are dynamic, varying from meters to tens of meters wide, and can occupy over 10% of the lake surface area (Figure 13). The open moat water represents the only part of the lakes that (i) interacts directly with the atmosphere where gases can diffuse across the air-water interface (Priscu et al. 1996), (ii) interfaces directly with inundated soils along the shoreline (Gooseff et al. 2011), and (iii) forms a mixing zone with inflowing stream water (Moore 2007). It is anticipated that increases in glacial meltwater will lead to continued lake level rise, expanded moat area, and a conversion of dry soils to benthic sediment. This increased flow will also seed the moat with inorganic nutrients and biota. The most conspicuous biota of moats are microbial mats (Figure 14). The

Figure 14. Photosynthetic microbial mat collected from Lake Brownworth moat. Scale bar = 1 cm.

architecture of these is dominated by filamentous cyanobacteria, mostly genera of the Oscillatoriales, though several taxa of atmospheric nitrogen-fixing Nostocales are also present (Hawes and Schwarz 2001; Taton et al. 2003).

<u>*9.6.4 Lake Food Webs.*</u> The year-round liquid water columns of the MDV lakes provide an oasis for viruses, archaea, bacteria, and microbial eukaryotes (protists), which interact within simplified, microorganism-dominated food webs (Priscu et al. 1999; Bowman et al. 2016). Each lake harbors distinct communities that are vertically stratified within the water column based on light and nutrient availability (Priscu et al. 1999; Bielewicz et al. 2011; Kong et al. 2012a). Photosynthetic protists (phytoplankton) provide the majority of organic carbon through light-dependent primary production (Bielewicz et al. 2011). Evidence for phototrophic and chemoautotrophic bacteria has also been reported (Voytek et al. 1998; Karr et al. 2003; Dolhi et al. 2015; Kong et al. 2012b). Heterotrophic nanoflagellates and ciliates represent the dominant predators, grazing on bacteria and smaller protists. Despite the energetic cost of maintaining and regulating both photosynthetic and heterotrophic cellular apparatus, mixotrophy appears to be very prevalent in MDV aquatic food webs.

<u>**9.7 Ponds.**</u> The MDV region contains more than 500 recognizable water bodies, most of which are small. The median size is less than $5x10^3$ m^2 and 70% are less than $50x10^3$ m^2 (e.g., Archer et al. 2015). These small water bodies are found from sea level to 2,000 m elevation and represent a significant habitat that is spread throughout the region, albeit one still poorly documented. Antarctic ponds tend to freeze solid, or nearly so, during winter, while they may lose ice cover completely during some or all summers (Quesada et al. 2008). Winter freezing partitions salts into hypersaline basal brines, which can persist as stratified layers throughout summer (Wait et al. 2006). Water sources may be direct in-

Figure 15. Scientist collecting samples from Don Juan Pond, Wright Valley. Note the protective clothing worn as a safeguard against contamination of this site and to protect the integrity of the sample.

flow of glacier melt streams or indirect via groundwater flow (Lyons et al. 2012; Jungblut et al. 2012). Relatively few ponds have overland outflow streams and many show extensive inter- and intra-annual variation in level (Moorhead 2007; Lyons et al. 2012). The chemistry of ponds is determined by their water history and location, and a wide range of dominant cations and anions. Inland, high elevation ponds often containing nitrate as a major ion.

Freshwater pond biota tends to be dominated by organisms with wide environmental tolerances (Jungblut et al. 2012) and most are shared between ponds in different regions of the MDV (Archer et al. 2015). Filamentous, mat-forming cyanobacteria are the most conspicuous biological community in ponds, mostly dominated by Oscillatoriales and Nostocales. Flagellates, ciliates and rotifers dominate planktonic communities.

Where evaporation and/or freeze-concentration has been extensive, high pond salinities can be reached (Torii et al. 1989; Matsumoto et al. 1992; Jungblut et al. 2012). Don Juan Pond (Figure 15) is an extreme example of a saline pond, having an ionic strength about 20 times seawater. $CaCl_2$-$6H_2O$ is the dominant salt in this pond and incorporates much of the free water into its hydration shell providing an inhospitable environment for life. Work on the accumulation of salts has provided a new model of salt accumulation as well as updating thermodynamic models of salt chemistry, and may explain the mechanism for the formation of the $CaCl_2$ in Don Juan Pond (Toner and Sletten 2013). The Toner and Sletten work highlights the extended presence of liquid water at subzero temperatures and provides estimates of water activity, one of the key determinants of habitable zones in the MDV.

9.8 Soils.

9.8.1 Physical and chemical attributes of soils. MDV soils are among the harshest habitat type in the region with three edaphic parameters imposing primary constraints on life: soil moisture, salinity, and organic carbon availability. Soil moisture in exposed dry valley mineral soils ranges from 0.25 to 3.0% by weight (Barrett et al. 2006; Barrett et al. 2004). The primary sources of soil moisture are transient snowfall events, melt from seasonal snow packs deposited by winter precipitation, and snow movement from the polar plateau (Gooseff et al. 2003). MDV soil salinity ranges widely (19 to >7,000 μS cm^{-1}) with a threshold of ~ 1,000 μS cm^{-1} found to limit the distribution of higher organisms (Bockheim 1997; Barrett et al. 2004; Poage et al. 2008).

Soil organic carbon is low in the MDV averaging ~0.03% by weight (Burkins et al. 2001, Barrett et al. 2004). Soil organic carbon originates largely from primary production in areas surrounding water sources (Moorhead et al. 2003), but also from organic carbon fixed by the autotrophic members of endolithic communities (Friedmann et al. 1993). Aeolian dispersal of contemporarily produced organic matter from lake and stream microbial mats, and sediment (Moorhead et al. 1999; Šabacká et al. 2012; Michaud et al. 2012) is important in the distribution of organic carbon across the dry valley landscape to less productive areas. At larger time scales, climatic variation resulted in significant lake level fluctuations that exposed lacustrine cyanobacterial mats and sediments to the atmosphere where they could be moved throughout the valleys via aeolian transport. Stable isotope analysis of soil organic carbon showed that this legacy carbon continues to be an important source of organic matter for MDV mineral soils (Burkins et al. 2000; Burkins et al. 2001).

9.8.2 Soil Microbiology. Interest in the microbiology of the MDV soils began in the 1960s and was motivated by a desire to understand the controls on life in an extreme environment (Cameron et al. 1968a; Cameron et al. 1968b; Horowitz et al. 1969). Initial results using culturing techniques were equivocal with some researchers claiming MDV soils were essentially sterile (Horowitz et al. 1969; Horowitz et al. 1972) while others successfully cultured ~150 genera, including representatives of the Streptomyces, Corynebacterium, and members of the Firmicutes, among others (Cameron et al. 1972). These seminal studies found that, although bacterial abundance was low (70 to 29,500 cells g^{-1} of soil), diversity of cultivated bacteria increased with abundance, though it was noted that some soils contained no viable or culturable microorganisms (Cameron et al. 1968a; Cameron et al. 1970). We now know that, globally, not all microorganisms are amenable to culturing and it is not an effective method for assessing microbial diversity. Amann et al. (1995) estimated that less than 1% of organisms in the environment are culturable using traditional techniques, and within this 1%, few play significant roles in ecosystem functioning (Ward et al. 1998). The application of culture independent molecular biology methods to investigate the prokaryotic microbial diversity of the MDV has revealed that these low biomass arid soils contain a surprising bacterial richness (Cary et al. 2010). Studies of 16S rRNA gene sequences have inferred relatively diverse communities with representatives from numerous phyla including Acidobacteria, Actinobacteria, Bacteroidetes, Chloroflexi, Cyanobacteria, Deinococcus-Thermus, Gemmatimonadetes, Firmicutes, Beta, Delta, and Gamma-Proteobacteria, and Verrucomicrobia (Aislabie et al. 2006, Smith et al. 2006; Aislabie et al. 2008; Niederberger et al. 2008; Wood et al. 2008; Babalola et al. 2009; Pointing et al. 2009).

Understanding controls over the distribution of soil bacteria is a fundamental step toward describing soil ecosystems, understanding their functional capabilities, and predicting their responses to environmental change. Abiotic factors such as moisture, pH, temperature, organic matter, conductivity, landscape position and historical context as well as biotic factors including competition, predation, and UV induced mutation are key drivers of diversity and community structure (Cary et al. 2010; Takacs-Vesbach et al. 2010; Van Horn et al. 2013; Okie et al. 2015). Geographic variation in the distribution of bacterial communities has been detected. For example, a bacterial survey of six areas distributed across the lower, middle and upper Taylor and Wright Valleys indicated that microbial communities throughout Taylor Valley are remarkably similar and not significantly different than communities from the lower Wright Valley. However, the middle and upper Wright Valleys host a unique bacterial flora (Van Horn et al. 2013). Thus, the existence of potential biogeographic zones that necessitate protection from cross contamination are apparent among prokaryotic soil communities.

9.8.3 Soil Fungi. The study of fungal communities in the MDV has lagged behind other microbial work yet has gained renewed interest in recent years. The earliest research occurred during the first International Geophysical Year (IGY) 1957–1958 and found an abundance of yeasts as well as several species of *Penicillium* (di Menna 1960; Soneda 1961; Meyer et al. 1962; Sinclair and Stokes 1965; Tubaki and Asano 1965; di Menna 1966; Goto et al. 1969). There were few fungal research endeavors into the MDV in the following decades (Vishniac 2006) with renewed interest after 2000 for using Antarctica as an analog for Exobiology (Onofri et al. 2008; Onofri et al. 2009 and see Figure 16). As has been found for both bacteria and invertebrates, fungal distribution is heterogeneous across the landscape.

Recent culture and molecular studies of the MDV soil fungal communities have shown that they are dominated by Ascomycota and Basidiomycota with some Chytridiomycota associated with wetted areas (Fell et al. 2006; Connell et al. 2008; Dree-

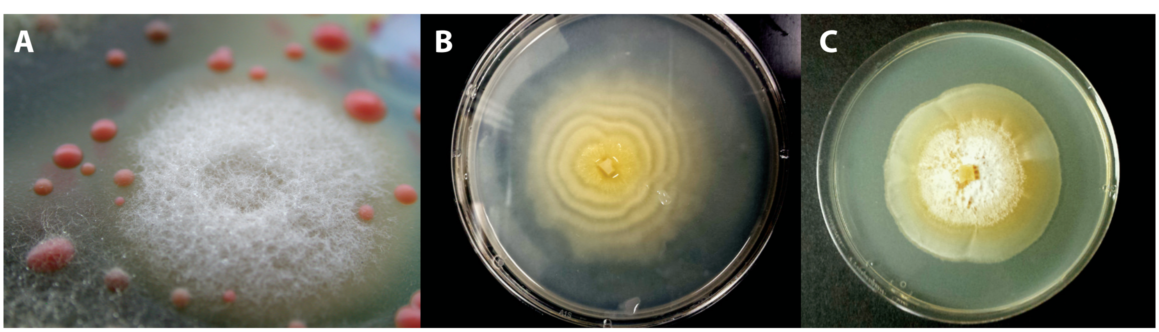

Figure 16. Fungal cultures isolated from various locations in Taylor Valley. A) Unknown soil fungi; B) Tetracladium ellipsoideum isolated from the ice cover of Lake Chad; C) An unidentified Ascomycota isolated from the ice cover of Lake Bonney. The fungi pictured in (B) and (C) were shown to be psychrotolerant and possess volatile substances that were active against known plant pathogens (Kudalkar 2016).

sens et al. 2014). The soil habitats with <5% soil moisture, especially those with higher salt concentrations, are dominated by Basidiomycota yeasts, with filamentous forms found in greater abundance near coastal regions (Fell et al. 2006; Connell et al. 2014). The effects of pH, moisture, and UV appear to be significant abiotic driving forces in community structure. Some of the most dominant genera, such as *Cryptococcus* and *Rhodotorula*, are known to have resistance to high UV input as well as freeze-thaw cycles. Further, there is little overlap in edaphic fungal communities, either among the habitat types within valleys (Connell et al. 2008) or between valleys (Dreesens et al. 2014). However, fungi are highly adaptable to extreme conditions (Onofri et al. 2007). This suggests that the local conditions have selected for specific communities demonstrating both biogeographic zonation, as with bacteria, as well as community interaction.

For vascular plants to invade the MDV, ectomycorrhizal fungi must also be present. Therefore, invasion of vascular plant species, either through expansion due to climate change or through unintentional spread by humans, will substantially alter the edaphic fungal community. In addition to ectomycorrhizal fungi, several species of fungi that have a strict requirement for vertebrate-based oils for growth have been found in areas along the valley floor. These fungi, from the *Malassezia* genus, are most likely relying on seals, birds, and humans as their nutrient source. A clear understanding of the current status and breadth of that community is still ongoing and is required for a full understanding of the health and function of MDV soils.

9.8.4 Soil invertebrates. The low abundance and patchy distribution of bacteria that was reported by early studies was consistent with the distribution of MDV invertebrate communities. For example, four hundred soil samples collected throughout the valleys yielded an average of ~700 nematodes kg^{-1} of dry soil, which is low compared to temperate soils, though the highest densities of ~4,000 kg^{-1} of dry soil are similar to those found in other desert ecosystems (Freckman and Virginia 1998). Eukaryotic communities in the MDV are home to few invertebrate species, most of which are small, microscopic species and endemic. These include the microinvertebrates such as nematodes, rotifers, and tardigrades, as well as the microarthropod springtails (Collembola) and mites (Acari). Within the ASMA there are 21 species of rotifers, four species of tardigrades, four species of nematode, three species of mite, and three species of springtail (Collembola), all endemic.

Of the springtails, only one species is found throughout the MDV ASMA. Two other range-restricted species are found within the ASMA but only in the area to the immediate north of the MDV in the vicinity of the Mackay Glacier. A further four species are found north of the Drygalski Ice Tongue (~75 °S) in Northern Victoria Land and another three species are found only in the deep south (<82 °S). Accordingly, springtails currently have extremely restricted distributions and only a small portion of the landscape provides suitable habitat owing to unfavorable soil chemistries, lack of liquid water or inappropriate substrates. Microarthropods currently have limited dispersal opportunities and gene flow among habitats. This has led to genetically distinct springtail populations that in some cases have been isolated for millions of years (Stevens and Hogg 2003). In Taylor Valley, individuals of the widespread organ-

Figure 17. Image of the Collembola Gomphiocephalus hodgsoni, a common and widely distributed arthropod in the MDV. Environmental changes are expected to have a detectable effect on their dispersal and reproductive success.

ism Gomphiocephalus hodgsoni (Figure 17) are genetically distinct between upper and lower valley sites (Nolan et al. 2006). Within the wider ASMA, the two range-restricted species north of the MDV show strong genetic divergences (mtDNA COI barcodes) on scales often < 10 km (Bennett et al. 2016; Beet et al. 2016). The potential for human-mediated transfer of these taxa therefore has the potential to disrupt co-adapted gene complexes that may have been isolated since the Pliocene. Monitoring the DNA barcodes of species among sites could be used as a sensitive indicator of human disturbance.

Sixty five percent of dry valley soils contain nematodes. Despite their relatively widespread occurrence, these organisms are highly sensitive to human activities. For example, Ayres et al. (2008) found that heavily used pathways (>80 individual person movements over a single season) resulted in decreased densities of living nematodes found in soils. Even short-term foot traffic disturbances (<2 years) were associated with decreases of 52% - 76% for two common nematode species.

9.8.5 Soil Lichens and Moss. Approximately 35 species of lichen and 10 species of bryophyte have been observed during sampling in Taylor Valley and Botany Bay (Colesie et al. 2014). Both groups have restricted distributions. For example, lichens are absent from much of the valley floors and largely restricted to elevations >1,000 m, which corresponds to the prevailing cloud layers found in the dry valleys. In contrast, moss beds are often found at lower elevations in the flush areas of glaciers and streams. As a consequence, they are very prone to human disturbance from trampling or from disruption of soil surfaces and subsequent erosion due to blowing sediment. The ASPA located at the Canada Glacier was designated to protect the extensive moss growths found at this location. Importantly, some lichen species are often very slow growing and potentially long-lived (>1,000 y), making them both susceptible to environmental disturbance as well as being sensitive indicators of past and future climate changes (Sancho et al. 2007).

Figure 18. Upper McKelvey Valley with Prentice Plateau in the background

10. RECOMMENDATIONS

The following recommendations have been formulated for the MDV to improve the effectiveness of the ASMA and ASPAs for preserving the unique values of this region through specific management responses.

1. NAPs operating in the ASMA should move toward a management strategy that recognizes the impact of global change (e.g., climate warming) when developing and implementing environmental protocols. The management strategy should be based on best available scientific evidence.

Rationale:

- the MDV contain a high level of abiotic and biotic diversity, and sensitivity varies across landscape elements
- climate change will have pervasive yet variable effects and feedbacks across these elements
- the best management strategy is landscape element-dependent and can potentially mitigate adverse effects of environmental change
- new evidence-based and dynamic (i.e., capable of anticipating change) tools need to be developed to facilitate an assessment of the effectiveness of the current ASMA management plan
- global change (increased people/grantees, climate warming) is (or it may) influencing the way we do business

2. NAPs have been collecting data on human activities for decades, but relatively little is readily available to managers and scientists. It is important that collaboration is enhanced among the programs operating in the ASMA to track sample and instrument sites, camp locations, landing sites, personnel movements, and environmental incidents, and to integrate this information in a publicly available GIS-based system. The input data will be primarily from existing collection mechanisms implemented by national programs as well as relevant information provided by tourism operators.

Rationale:

- these data will allow scientists to make informed decisions while designing experiments and planning fieldwork
- these data will facilitate the synthesis of activity intensity maps allowing rapid assessment of scientific and logistical plans
- the implementation of such a system in the MDV will provide guidelines for the establishment of international guidelines and enhance cooperation among NAPs to document human activities throughout the continent

3. Field activity data are not being collected routinely and made accessible to inform management decisions and future science planning by NAPs and funding agencies. Stakeholders should invest in accessible technology to facilitate consistent documentation, streamlined analysis, and easy dissemination of past and present field activities. This technology will enhance end-of-season reporting and allow newly collected data to be directly incorporated into Recommendation 2.

Rationale:

- immediate recording of field activities will ensure accuracy of information
- a standardized data structure will enhance data sharing among NAPs and ensure information compatibility
- greater data accessibility across multiple organizations will enable better logistics planning, resource sharing, and impact assessment

4. NAPs and funding agencies should invest in research that integrates scientific evidence with management strategies. Such an integration can be used to determine and map the intrinsically sensitive landscape components as well as collect baseline information on ecology, climate, geomorphology, and hydrology. Information should include (i) areas of high priority for conservation and restoration as well as those in need of special management, (ii) habitats at elevated risk of biological invasion, (iii) locations suitable for sustainable tourism activities with tolerable environmental impact, and (iv) projected vulnerability to climate change for individual landscape elements. Such information must account for seasonal and annual variations where appropriate, and incorporate the experience of public and private conservation organizations.

Rationale:

- there is a need to create spatially explicit descriptions of the abiotic and biotic diversities and variable sensitivity across landscape elements
- development of risk-based assessment of sensitive vs. resilient landforms and habitats will better enable conservation and management efforts
- such research will enable the development of strategies to identify and preserve biogeographical zones and monitor their integrity

5. NAPs should synthesize outcomes from Recommendations 2 to 4 to assess the environmental footprint of current scientific, logistic, and tourism activities to guide future development of management policies for the ASMA (see Figure 8).

Rationale:

- landscape elements exhibit differential sensitivity to impact
- different field activities vary in their environmental impact
- there is elevated interest from NAPs operating in the ASMA
- the MDV are an increasingly attractive tourist destination
- the MDV are a small area with unique scientific values that are vulnerable to human disturbance
- there may be a future need to set limits to achieve preservation of the environment and to sustain long-term scientific research in the context of climate change and increased visitor pressure

6. All parties operating in the MDV should adopt consistent environmental guidelines for following the ASMA Management Plan and other recommendations by the Committee for Environmental Protection (CEP) to safeguard against the introduction of non-native species. Practices could include cleaning boots and scientific equipment between field sites, encouraging field personnel to have equipment dedicated to the MDV, and identifying higher-risk personnel,

equipment, and activities.

Rationale:

- minimize introduction of non-native species, recognizing that prevention is the most effective measure
- minimize human-facilitated transfer of MDV taxa across habitats
- ensure uniformity of environmental practices across NAPs

7. NAPs should facilitate research activities that enhance the management and protection of the ASMA. Examples of this could include designing better tools (including indicators of cumulative impact), and supporting future monitoring programs that evaluate the effectiveness of the ASMA Management Plan (e.g., by creating 'Inviolate Areas', as recommended by the Protocol).

Rationale:

- an enhanced management framework based on information included in previous environmental workshops can inform decisions to move and/or designate new Facility Zones
- there is a need to routinely assess the existing ASPA and ASMA management framework to determine whether it appropriately captures and represents the landscape diversity
- there is a strong need to monitor accidental introduction of non-native species, particularly given the increase in scientific and tourist activities, and global change

8. NAPs and stakeholders should hold workshops to assess environmental management of the ASMA at regular intervals (e.g., every five years) on a rotational basis.

Rationale:

- climate change necessitates more frequent reviews of the status quo and projections
- increases in tourism and research activities over time can be expected
- technological and scientific advances (e.g. Autonomous Vehicle Technologies, in situ sensors, remote sensing, etc.) may change how field activities are carried out

9. NAPs should consult available and/or relevant scientific personnel in response to environmental incidents.

Rationale:

- scientists studying the system likely possess the most relevant knowledge and expertise
- event personnel on site can provide an accurate chronology of the incident
- such incidents may compromise the science being conducted

10. NAPs should charge education and outreach programs to address issues such as the environmental sensitivity of the ecosystem, the role of the MDV as sentinels of global environmental change, and the importance of environmental stewardship in all aspects of work in the area.

Rationale:

- contemporary global change has led to a worldwide increase in the awareness of the role that polar regions play in the Earth system, which has led to the growing recognition of this role by the general public

- the general public must be informed that scientists actively participate in activities related to environmental stewardship in this region for both ethical and scientific purposes
- the acclaim received by children's books on scientific activities in the MDV has clearly piqued the minds of these children and engrained in them the importance of environmental stewardship
- such education and outreach activities will produce a new generation that will be acutely aware of the sensitive nature of the MDV and its role in global change

Figure 19. Sand dunes in Victoria Valley

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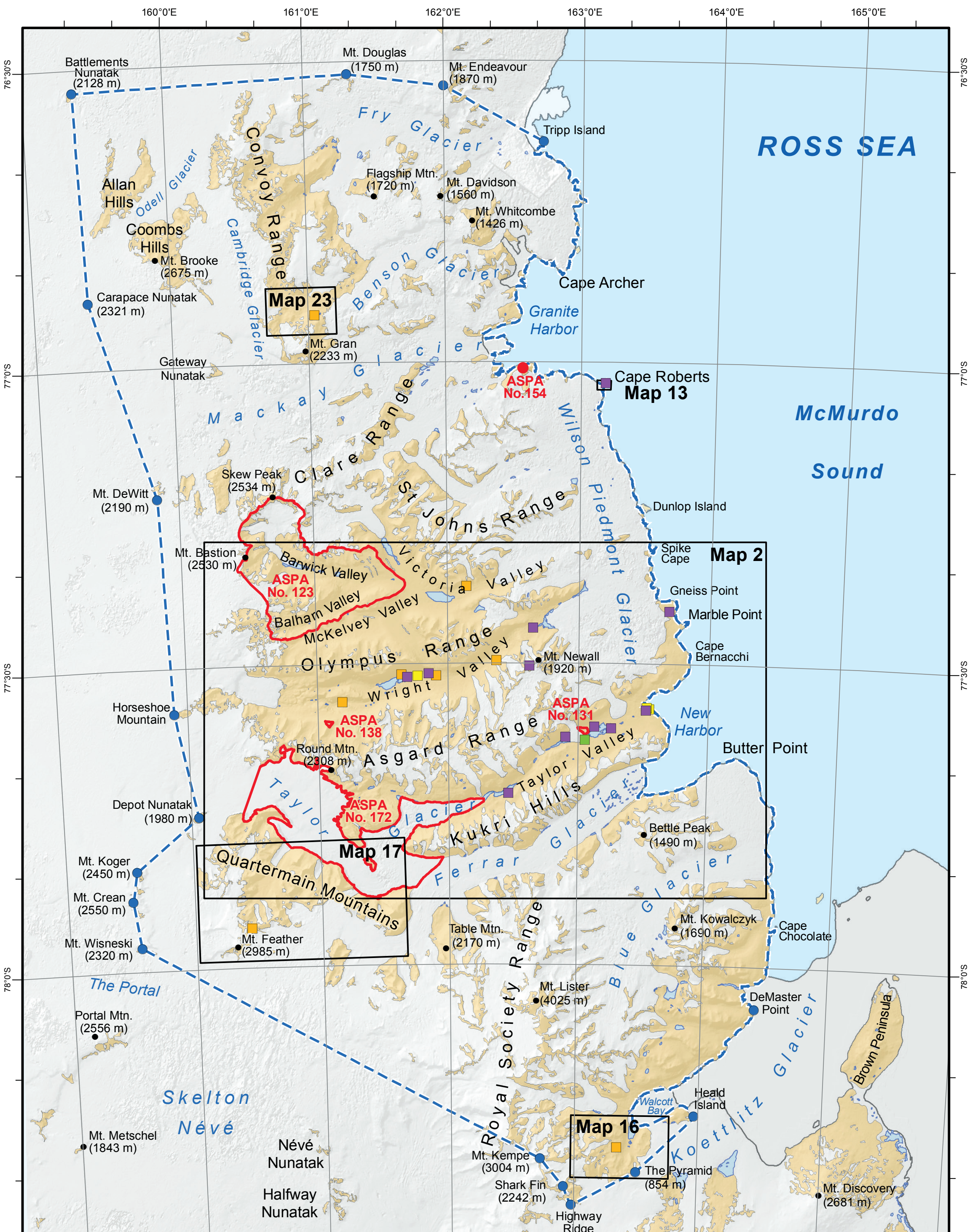
12. APPENDICES

Appendix 12.1. Locator map depicting the boundaries for the MDV ASMA, the locations of ASPA's and zones of interest.



Map 1: Overview
ASMA No. 2 McMurdo Dry Valleys: boundary & zones

Issued 28 Apr 2015 (Map ID: 10068.011.11)
Environmental Research & Assessment

0 10 20
Kilometers

N

- Coastline
- Lake / Ocean
- Permanent ice
- Ice free ground
- Mountain peak
- ASMA boundary point
- ASMA boundary
- ASPA boundary
- Facilities Zone
- Restricted Zone
- Scientific Zone
- Visitor Zone

Antarctica New Zealand

Projection: Lambert Conformal Conic
Spheroid & Datum: WGS84
Contours: derived from SCAR ADD v5 ST 57-60 (2007)
Land features: SCAR ADD v5 ST 57-60 (2007)
Hillshade: derived from ASTER GDEM provided by METI and NASA;
Boundaries & zones: USAP / Antarctica NZ

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Back row left to right: Joe Levy, Poppie Gullet, Ian Hawes, Ceisha Poirot, Warwick Vincent, Keith Cox, Nathan Williams, Peter Doran, Mahlon "Chuck" Kennicutt II, Andrew Klein, Ian Hogg, Ron Sletten, Erin Pettit, Mauro Guglielmin, Paul Cutler, Rachael Morgan-Kiss, Jenny Cunningham, Polly Penhale, Charles Lee, Oscar Schofield, Maciej Obryk, Chris Fritsen. **Middle Row:** Adrian Howkins, Steve Chignell, Chris Jaros, Clive Howard-Williams, John Hobbie, Diane McKnight, Thomas Wilch, Liz Kauffman, Diana Wall, Kaneen Christensen, Meghan Walker, Nature McGinn, Laurie Connell, Matilde Guglielmin, Nicoletta Cannone, Neil Gilbert, Kevin Hughes. **Front Row:** Walter Andriuzzi, Hong Kum Lee, Kate Swanger, Ashley Shaw, Paul Morin, Amy Chiuchiolo, Michael Gooseff, Mary Voytek, Cristina Takacs-Vesbach, Melissa Brett, Colin Harris, John Priscu, Berry Lyons. Missing: Jeb Barrett, Ted Doerr, Byron Adams

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Appendix 12.3. Data from the New Zealand Antarctic program showing person days in specific field locations within the MDV. Data source: C. Poirot