McMURDO DRY VALLEYS: A COLD DESERT ECOSYSTEM

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Report of a
National Science Foundation Workshop
held at the
Institute of Ecosystem Studies
The New York Botanical Garden
Millbrook, New York
5–7 October 1991

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Miers Valley, Antarctica.

Executive Summary

The largest relatively ice–free region on the Antarctic continent is the McMurdo Dry Valleys, located along the western coast of the Ross Sea. The term dry valleys refers to the deeply incised, ice–free valleys that run perpendicular to the coast. The dry valleys were formed by the advances and retreats of glaciers through the coastal ranges of the Transantarctic Mountains, which rise to several thousand meters above sea level and act as barriers to the flow of ice from the Polar Plateau. Glacial and periglacial features are a major component of the landscape, and the valleys contain numerous closed basins in which perennially ice–covered lakes are found. The dry valleys have been predominantly ice free for the past 4 million years although the present ice–covered lakes on the valley floors are much younger. The McMurdo Dry Valleys region is one of the most extreme deserts in the world. The minimal precipitation (< 10 cm yr^{-1}) and low surface albedo of the valley floors, coupled with dry foehn winds descending from the Polar Plateau, result in extremely arid conditions.

The landscapes of the McMurdo Dry Valleys are a mosaic of ice–covered lakes, ephemeral streams, arid soils, permafrost, and surrounding glaciers. Materials are transported among sites by wind and water. Water flows primarily from glaciers to streams to lakes, while wind disperses particulate matter throughout the valleys. The biological systems in the dry valleys are relatively simple. There are no vascular plants or vertebrates and very few insects. Trophic interactions and biogeochemical nutrient cycles are largely limited to microbial populations and microinvertebrates. Species diversity and abundance are low, as would be predicted for such extreme environments. Despite this simplicity, complex interactions among species and between the biological and physicochemical components occur in the lakes, streams, and soils.

In October 1991, a workshop sponsored by the National Science Foundation was held at the Institute of Ecosystem Studies in Millbrook, New York, to discuss the state of scientific knowledge about the terrestrial and aquatic ecosystems of the McMurdo Dry Valleys. Scientists participating in the workshop represented a diversity of disciplines and experiences, from those who had worked in the Antarctic to those who worked in ecosystems that share some similar characteristics (e.g., warm deserts, the Arctic). The scientists were placed into three working groups: terrestrial (soil), streams, and lakes. As part of their charge, the groups were to identify gaps in research, at the landscape through organismic levels, whose investigation would contribute to the understanding of how, though an environment unique on Earth, the McMurdo Dry Valleys are yet intimately tied to the global life–support system. Among the important attributes discussed by the groups were the benefits of extending knowledge from the simple biotic systems of the dry valleys to more complex (and more difficult to study) temperate ecosystems. For example, small increases of air temperature in the dry valleys might be magnified in the structure and functioning of the cold desert ecosystem. Scientists using the dry valleys as a model of simplified biodiversity and ecosystem functioning under a variety of environmental change scenarios could provide workable hypotheses applicable to more complex ecosystems under similar stresses.

The following research priorities were identified by the workshop participants and are relevant to all ecosystems (terrestrial, streams, and lakes) in the McMurdo Dry Valleys.

- Direct a significant percentage of research funding for the dry valleys toward an integrated ecosystem approach in addition to supporting individual "isolated" studies that cannot be linked.
- Investigate carbon and nutrient flows within and among ecosystems as they are the basis of the simple food webs and the community structure and functioning of the dry valleys.
- Characterize the biodiversity within the dry valley ecosystems.
- Characterize the survival strategies and adaptations of key organisms to extreme physical and chemical conditions, thereby establishing limits for life.
- Determine the magnitude to which environmental changes (such as increasing temperature, UV–B, and chemical pollution) affect biodiversity and the structure, functioning, and linkages of the dry valley ecosystems.

Workshop participants suggested that the field season in the dry valleys be extended to include early spring and late fall. The use of instrumentation to acquire year–round environmental information was strongly encouraged. Also considered important for ecosystem–level studies of the dry valleys were the use of remotely sensed data and imagery, a geographical information system, and special labs at field sites to minimize the potential for contamination of field samples during shipment to McMurdo and/or the U.S.A.

Major accidents, such as spills of chemicals or radioisotopes, as well as impacts due to research camp construction and subsequent occupation, represent a significant environmental concern for the McMurdo Dry Valleys. Workshop participants specified that all research projects be evaluated for potential environmental impact and that precautions be taken to minimize these risks.

PREFACE

This report is derived from a workshop sponsored by the National Science Foundation and held at the Institute of Ecosystem Studies in Millbrook, New York in October 1991. The purpose of the workshop was to discuss the state of scientific knowledge of the terrestrial and aquatic ecosystems of the McMurdo Dry Valleys of Antarctica. Workshop participants represented a diversity of disciplines and experiences, from those who had worked in the Antarctic to those who worked in ecosystems that share some similar characteristics, such as warm deserts and the Arctic.

The organizing committee for the workshop consisted of Diana W. Freckman, John E. Hobbie, W. Berry Lyons, Diane M. McKnight, and Robert A. Wharton, Jr. (chair). The workshop was divided into three discussion groups organized around the terrestrial (soil), stream, and lake ecosystems in the McMurdo Dry Valleys. Each group had a discussion leader, who was assisted by a rapporteur in preparing the group's report; leaders and rapporteurs are identified in the list of workshop participants included at the end of this report. This document, which is a synthesis of the group reports, is intended to serve as a planning tool for scientists, program managers, and administrators interested in research activities in the McMurdo Dry Valleys.

The workshop was made possible by a grant from the NSF Office of Polar Programs (DPP–9116419), whose Polly Penhale and Roger Hanson provided much encouragement and support. The beautiful grounds and facilities at the Institute of Ecosystem Studies enhanced the productivity of the workshop. The workshop was a major success, in large part, because of the excellent support provided by the Institute's director, Gene E. Likens, and his staff. In particular, Jan Mittan did a superb job of coordinating travel and local activities. In preparing this report, editorial assistance was provided by Gayle Dana, Peter Doran, Julie Muhilly and Juliet Pierson.

The McMurdo Dry Valleys have recently been selected as a site in the NSF Long–Term Ecological Research (LTER) program. This exciting development will provide an important framework in which to accomplish many of the research priorities discussed at the workshop and presented in this report.

Robert A. Wharton, Jr.
Reno, Nevada
20 January 1993

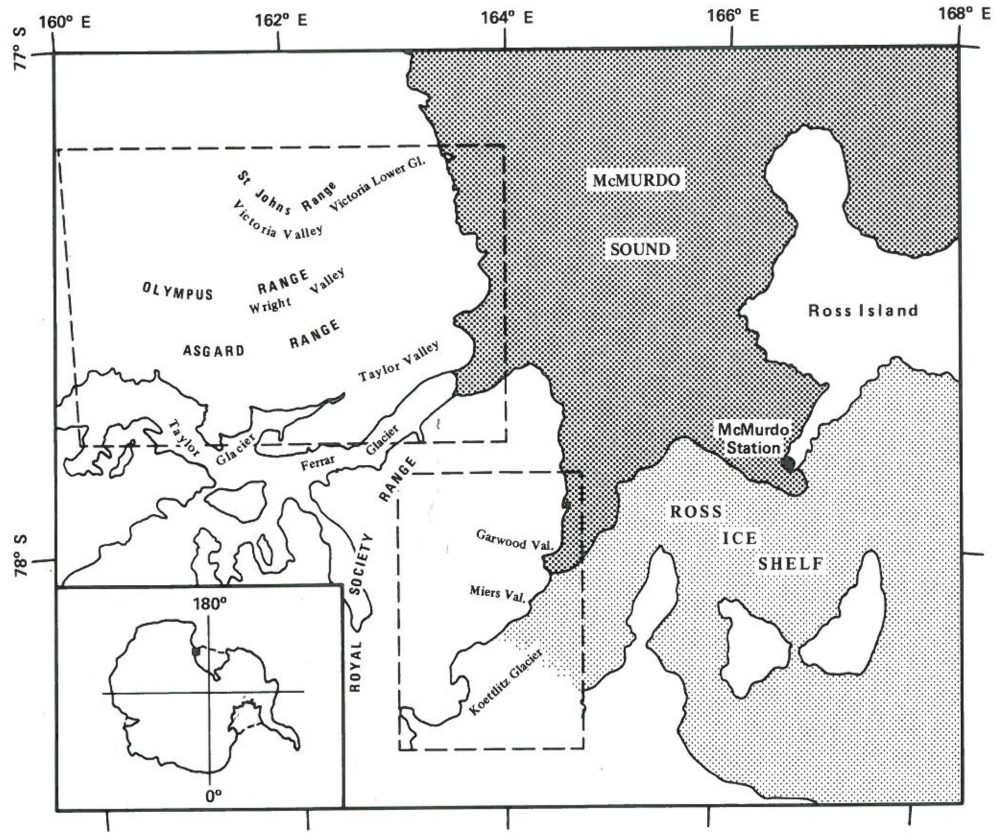
Introduction

The largest relatively ice–free region (~4800 km^2) on the Antarctic continent is the McMurdo Dry Valleys (77 °00 ′ S, 162°52′ E), located along the western coast of the Ross Sea. This region of Antarctica is also referred to as the McMurdo Oasis, Ross Desert, and the southern Victoria Land dry valleys. The McMurdo Dry Valleys region is one of the most extreme deserts in the world. The minimal precipitation (< 10 cm yr^{-1}) and low surface albedo of the valley floors, coupled with dry foehn winds descending from the Polar Plateau, result in extremely arid conditions. The term dry valleys refers to the deeply incised, ice–free valleys that run generally perpendicular to the coast.

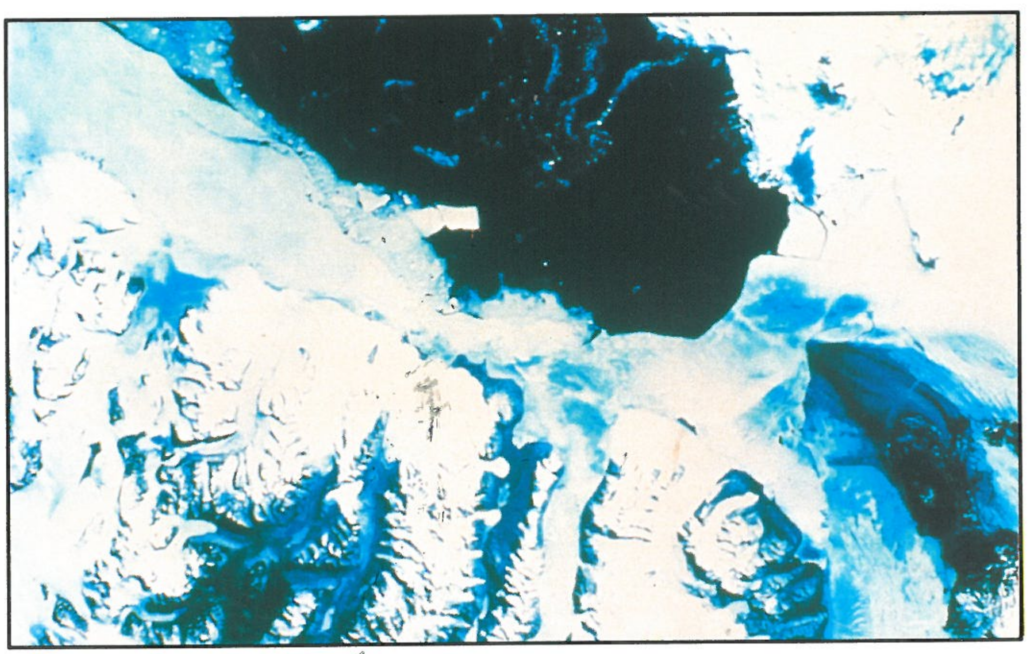
The McMurdo Dry Valleys were formed by the advances and retreats of glaciers through the coastal ranges of the Transantarctic Mountains, which rise to several thousand meters above sea level and act as barriers to the flow of ice from the Polar Plateau. Glacial and periglacial features are a major component of the landscape, and the valleys contain numerous closed basins in which perennially ice–covered lakes are found. The valley bottoms are predominantly glacial till, and the higher slopes consist of granites, dolerites, sandstones, and occasional volcanics. Rock outcrops are typically highly weathered by foehn winds. Piedmont and alpine glaciers drain from cirques onto the valley floors. The dry valleys have been predominantly ice free for the past 4 million years although the present ice–covered lakes on the valley floors are much younger (Denton *et al.* 1989).

This region of Antarctica was originally explored by members of Robert F. Scott's expeditions during the early 1900s (Scott 1905; Huxley 1913). For half a century after their discovery, the climate, geology, and biology of the dry valleys remained unknown. It was not until the International Geophysical Year (1957–58) and the establishment by the United States and New Zealand of scientific stations on Ross Island that studies of the dry valleys resumed.

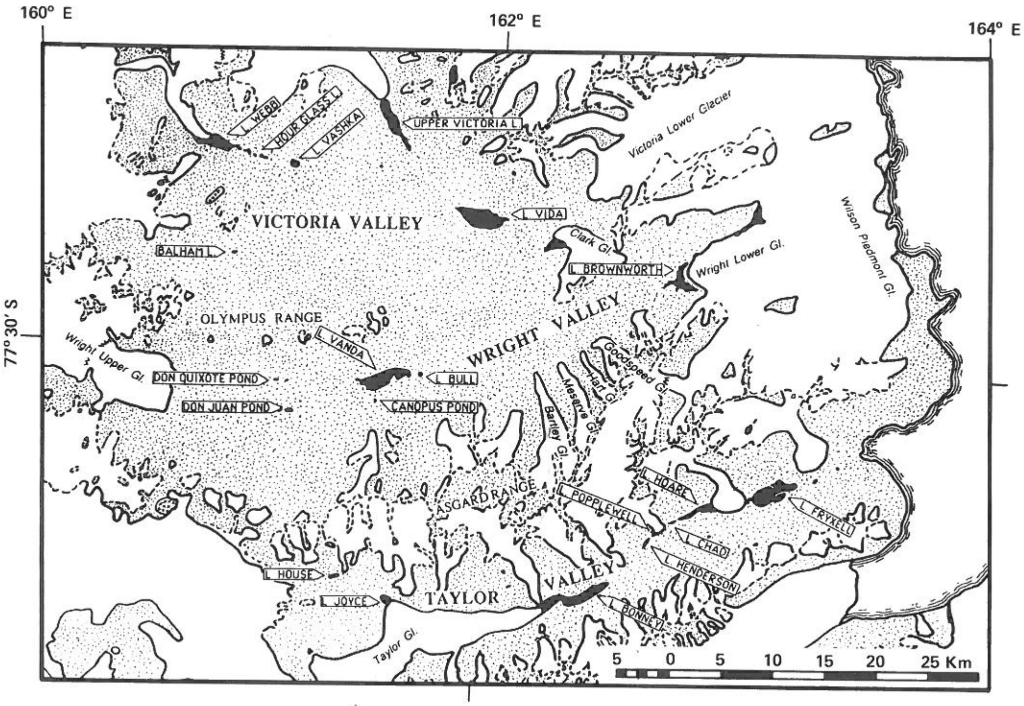
Numerous short–term research projects (< 5 yr) since the late 1950s have contributed important information concerning the dry valley ecosystems. However, as is often the case in individual research projects, much of the information derived from these studies was not integrated into an overall landscape– or ecosystem–level synthesis. To address the issue of ecosystem–level studies in the dry valleys, NSF sponsored a Workshop on the Terrestrial and Aquatic Ecosystems of the McMurdo Dry Valleys, which convened in October 1991. This report presents background information on what is currently known about the terrestrial, stream, and lake ecosystems of the dry valleys; discusses the specific research priorities for these cold desert ecosystems as identified by the workshop participants; and presents approaches recommended for addressing these research priorities. The report also discusses logistical considerations and environmental impact issues related to field research in the dry valleys.



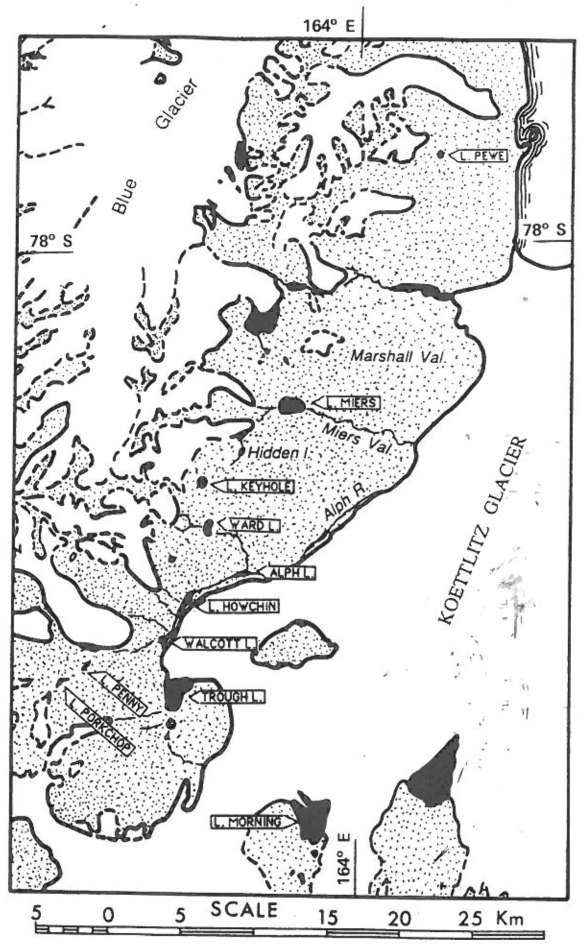
Map of McMurdo Dry Valleys Region.



Landsat Image of McMurdo Dry Valleys.



Map of Victoria, Wright, and Taylor Valleys.



Map of Marshall and Miers Valleys.

BACKGROUND

The landscapes of the McMurdo Dry Valleys are mosaics of ice–covered lakes, ephemeral streams, arid soils, permafrost, and surrounding glaciers. Materials are transported among sites by wind and water—defining functional relationships among these landscape units. Water flows primarily from glaciers to streams to lakes (except in cases where glaciers are in direct contact with the lakes, e.g., Taylor Glacier/Lake Bonney and Canada Glacier/Lake Hoare and Lake Fryxell), while wind disperses particulate matter throughout the valleys. The transport of these materials appears to enhance the overall biological productivity of the dry valleys. Were it not for the melting of surrounding glaciers, there would be no streams or lakes in these valleys, and the lakes would eventually freeze and sublimate. Furthermore, glacial meltwater and leaching from soils adjacent to streams provide nutrients to both streams and lakes, enhancing production. Wind deposits sediment on the lakes and removes microbial mats that have risen through the ice to the lake surface. The productivity of soils appears to exceed the site–specific photosynthetic capacity and may be due to allochthonous organic carbon inputs of wind–borne mat material.

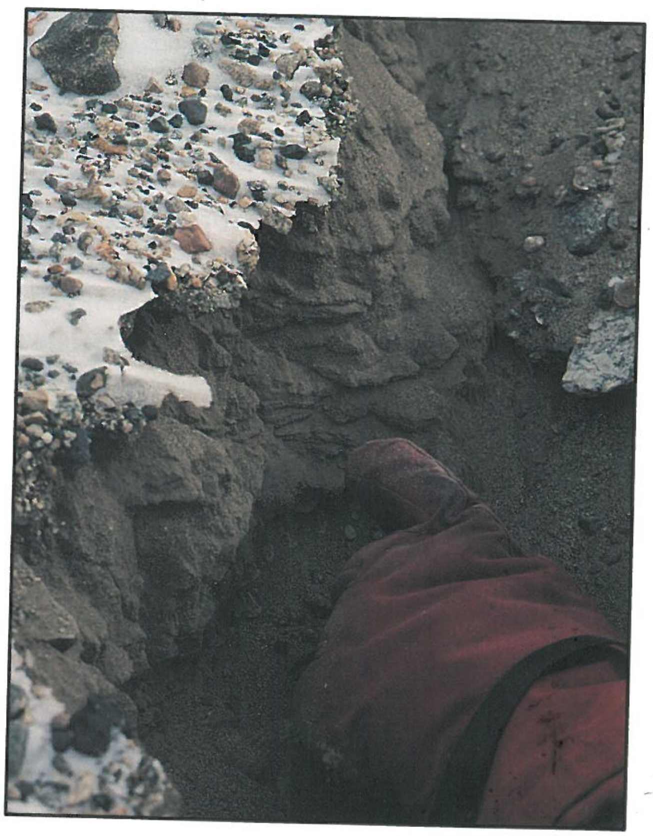
Soils

The key features of the terrestrial (soil) ecosystems in the McMurdo Dry Valleys of Antarctica are presented in Table 1. The soils are largely saline, periglacially active, and coarse textured; they have low biological activity, very low organic carbon contents, and with low moisture are classified as aerosols (Ugolini 1970; Campbell and Claridge 1987). Although the soils are up to 5 million years old, profile structure is generally poorly developed. The soils are underlain by deep permafrost and there are substantial areas of sand and unconsolidated morainal material. Despite a general appearance of apparent uniformity, the dry valleys have a high degree of spatial and temporal heterogeneity in soil properties, hydrologic regimes, biological com-

Table 1. Key features of McMurdo Dry Valleys terrestrial ecosystems.

- High spatial and temporal heterogeneity in soil properties
- Highly saline soils with low organic carbon content
- Arid soils (limited water availability)
- Low biodiversity, productivity, and decomposition rates
- Simple food webs with limited trophic competition
- Biotic adaptations to freezing and salinity
- Poorly developed soil profiles

ties, and the movement of material among sites. Of considerable significance for life in the McMurdo Dry Valleys is the variability, both temporally and spatially, of unfrozen water. Precipitation is very low (< 10 cm yr^{-1} water equivalent); therefore, the soils are not leached and weathering products accumulate in the soil profile (Pastor and Bockheim 1980; Bockheim *et al.* 1990). Antarctic soils are similar to those of other desert regions (Campbell and Claridge 1968) and are primarily oxidized desertic saline or alkaline sands and loams with pH values > 7 (Cameron *et al.* 1970; Campbell and Claridge 1987).



Taylor Valley Soil.

The dry valley soils also have unique chemical attributes related to the absence of higher plants (Wrenn and Beckman 1981; Campbell and Claridge 1987; Vincent 1988). Organic carbon and nitrogen levels are lower than in other desert soils because of the lack of vegetation (Cameron *et al.* 1970). For example, organic carbon and nitrogen contents in the "richest" soils of Victoria Valley are in the ranges 0.02%–0.04% and 0.002%–0.004%, respectively (Cameron and Conrow 1969). Even in moss communities, there appears to be little or no accumulation of humus (Campbell and Claridge 1987). In contrast to temperate soils, NO_3^- exceeds organic nitrogen concentrations by as much as two orders of magnitude (Vincent 1988), although data indicate an atmospheric rather than marine source of nitrate (Wada *et al.* 1981). Age is another important factor in determining chemical properties of dry valley soils. Older soils with the best developed profiles have excessive salt accumulations (Ugolini 1970; Bockheim 1990). Furthermore, the steep physical and chemical gradients and local heterogeneity of dry valley soils at the nano–, micro–, and macroscale are distinctly different from more temperate soils where free flow of water blends such gradients (Wynn–Williams 1990).

Soil temperatures (depth 0–20 cm) in the McMurdo Dry Valleys are consistently above freezing during December and January. Because of high surface roughness there is a layer of relatively calm air immediately above the ground so that surface temperatures are often considerably higher than ambient. Thus, soil temperatures may be favorable for chemical and biological reactions, even in areas where standard meteorological data indicate extremely severe conditions (Vincent 1988). However, these reactions are limited by the lack of liquid water in the soil. The desiccation gradient can be so steep that even the reservoir of ice in the permafrost cannot furnish adequate liquid water for the microbial growth necessary to stabilize the soil surface (Cameron and Devaney 1970; Wynn–Williams 1989).

Studies of biota in the McMurdo Dry Valleys have generally been limited to geographic distribution, or to noting the relationship of the taxa to soil physical or chemical factors. The number of microorganisms in dry valley soils varies widely from below detectable limits to 10^7 g^{-1} soil. It is not uncommon to find soils even in relatively sheltered areas without traces of life (Cameron and Conrow 1969; Cameron *et al.* 1970; Cameron 1972, 1974; Friedmann 1978, 1982). This has contributed to the incorrect dogma of the "sterile" dry valleys (Campbell and Claridge 1987). In fact, species abundance and diversity are constrained by availability of water and soil salinity. Although isolated patches of "complex" ecosystems exist, with food chains including mosses, algae, protozoa, rotifers, nematodes, tardigrades, yeasts, filamentous fungi, bacteria, and an occasional mite or collembolan, these are a very small fraction of the dry valley soils and are generally limited to moist areas near glaciers (Vincent 1988).

The abundance and diversity of organisms from dry valley soils are related to "environmental favorability" (Cameron *et al.* 1970). For example, nonpigmented aerobic heterotrophs dominate the most stressful habitats. As soil conditions become more moderate (increased soil moisture, lower salinity), other groups including actinomycetes, algae, and sulfate–reducing and nitrogen–fixing bacteria are present (Cameron and Conrow 1969; Cameron *et al.* 1970; Vincent 1988). In drier soils, algae and cyanobacteria are restricted to areas that are moistened during at least part of the year (Wynn–Williams 1990). Soil nematodes occur in more than 65% of dry valley soils sampled and are more abundant in dry soils than rotifers and tardigrades (Freckman and Virginia 1991). Rotifers and tardigrades are restricted to moist soils near meltstreams. The spatial distribution of nematodes in the dry valleys is more patchy than in hot desert soils; but, where nematodes occur, the densities (up to 4000 kg^{-1} dry soil) are comparable to those of warm deserts. The relationship between nematodes and soil properties in the valleys is complex. Soil moisture, total nitrogen, organic carbon, PO_4^{-3}, and salinity do not significantly correlate with nematode abundance, although soils without nematodes do have high salinities. The diversity (three genera) and trophic structure of the nematode community in dry valley soils are less complex than in warm deserts (Freckman *et al.* 1987). In the dry valleys, nematodes occupy only two or three functional levels, for example, microbial–feeding (*Scottnema lindsayae*, *Plectus* sp.) and omnivore/predator (*Eudorylaimus* sp.).

Although not strictly soil habitats, certain rocks in the dry valleys contain cryptoendolithic communities (Friedmann 1982). Cryptoendolithic rocks also occur in warm deserts. The distribution of these communities has not been mapped, but is generally limited to sandstone rocks in the mountains above the valley floors. The organisms (lichens, bacteria) establish themselves a few millimeters below an apparently sterile rock surface. Melting snow is the source of moisture, and increased temperatures within the rock during the summer allow the community to grow. The internal rock temperature and moisture were monitored via satellite, demonstrating the level of field monitoring that may be used in dry valley studies (McKay and Friedmann 1985). Friedmann *et al.* (1980) have shown that the soils near these rocks contain high levels of organic nitrogen (1.97–6.06 g m^{-2}), no chlorophyll *a* (chl *a*), and higher levels of adenosine triphosphate (ATP) than in the rocks (19.4–46.3 mg ATP m^{-2} vs. 0.76–18.4 mg m^{-2}).

Wind is an important feature of the dry valley ecosystems, and particles as large as small pebbles may be transported (Campbell and Claridge 1987). The organic content of the soil is probably replenished by propagules of bacteria, fungi (Wynn–Williams 1990), yeasts (Vishniac and Hempfling 1979), cryptobiotic nematodes (Orr and Newton 1971; Freckman 1978; Freckman and Womersley 1983), and pieces of algal mats (Parker *et al.* 1982b; Wharton *et al.* 1985). Fungal spore deposition rate (11 h^{-1} m^{-2}) is estimated to provide sufficient energy to support the observed maximum doubling rate for yeast cells at 10°C in dry valley soils (Vishniac and Hempfling 1979). The wind deposition of such carbon sources could be sufficient for soil community development at microscales. This suggests that the soil communities are mainly dependent on primary production of aquatic habitats.

Streams

Glacial meltwater streams flow intermittently during the austral summer when the area experiences continuous daylight. Streamflow often increases rapidly (within hours) during warm periods and may decrease as rapidly during temperature drops (Vincent 1987). The hydrograph is relatively predictable as to the period of flow (i.e., late November to early February) but highly variable in annual discharge and in daily minimum and maximum streamflow. The streambeds are composed of various size materials from cobbles to fine sediments. Microbial mats and mosses are present in streams that do not have a high sediment load (Howard–Williams and Vincent 1985). In these streams, the sources of solutes and suspended material are input from the glaciers, dissolution of salts, ion exchange and weathering from the streambed materials, and leaching of microbial mats and mosses (Green and Canfield 1984; Green *et al.* 1988).

Nutrient concentrations in stream water vary both temporally and spatially (Vincent 1987). They vary seasonally (e.g., the highest NO_3^- and PO_4^{-3} concentrations occur when glacial melt begins, followed by decrease during the summer) and daily (e.g., NO_3^- concentrations vary inversely with discharge). In Canada Stream, concentrations of NO_3^- and urea decrease and dissolved organic nitrogen and carbon increase downstream of the Canada Glacier

(Downes *et al.* 1986; Howard–Williams *et al.* 1989).

Meltstream Entering Lake Fryxell.

Microbial mats typically occur in areas that are water saturated for some period during the austral summer. In certain streams biomass can be abundant, reaching values of >15 mg chl *a* cm^{-2} (Howard–Williams and Vincent 1989). The mats are composed primarily of filamentous cyanobacteria with species of *Phormidium* and *Nostoc* being common. Bacteria, yeasts, protozoa, rotifers, and nematodes are also found within the microbial mats (Vincent 1987). The estimated age range of the mats is 50–100 years. Biomass accumulation occurs from November to January. Howard–Williams *et al.* (1989) have shown that photosynthesis occurs within hours after the mats first become wetted by the initial streamflow, and that the overall photosynthetic rates are low. However, the low assimilation numbers may be a result of the persistence of photosynthetically inactive chl *a* associated with chl *a* decomposition products (phaeophytins) of senescing cells (Vincent and Howard–Williams 1989). In the Canada Stream communities, the amounts of both measured chl *a* and standing stock carbon are extremely high relative to the amount of carbon fixed (> 1 mg chl *a* (mg C fixed $h^{-1})^{-1}$, > 500 mg biomass–C (mg C fixed $h^{-1})^{-1}$), suggesting the persistence of large quantities of biologically derived material that is not associated with metabolically active cells. It is possible that undecomposed inactive cells or detritus have produced overestimates of chl *a*, and therefore underestimates of assimilation and the strong light limitation of much of the community biomass (Vincent and Howard–Williams 1989; Hawes 1993).

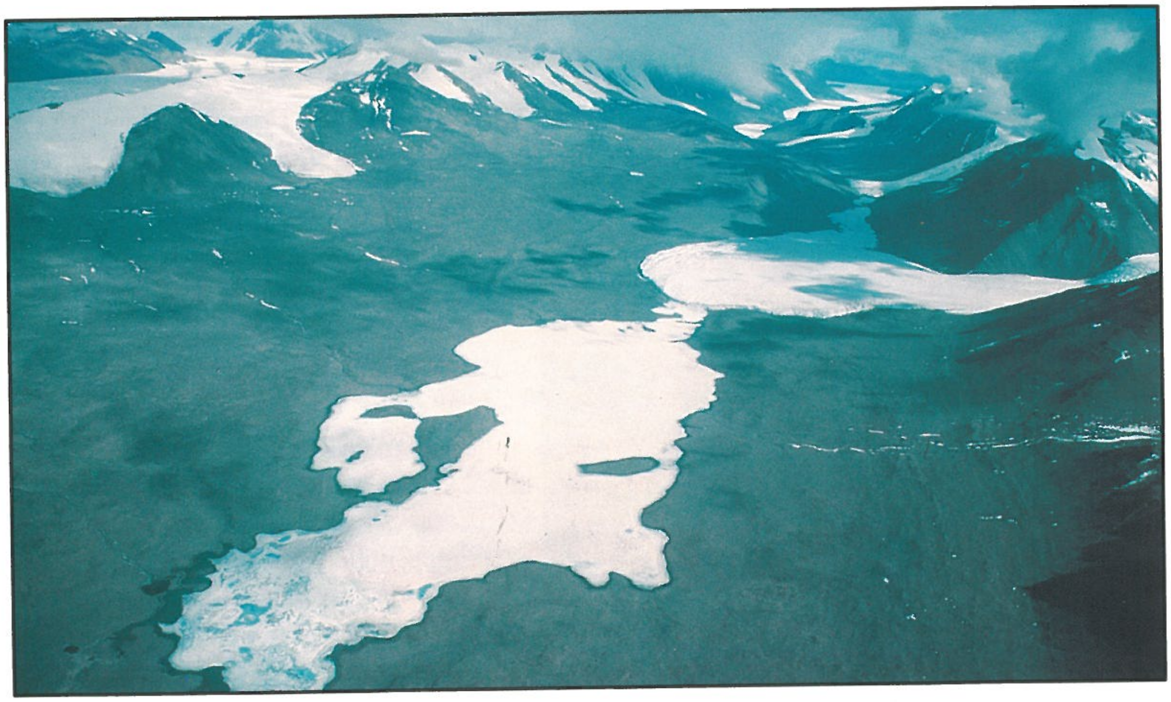
The main linkage between the terrestrial and aquatic systems in the McMurdo Dry Valleys is the hydrologic transport of solutes and suspended material by streams. High concentrations of nitrate and phosphate in the Oynx River during initial flows have been noted by Canfield and Green (1985) and Vincent and Howard–Williams (1989). The sources of the high levels of nutrients are still subject to speculation. Howard–Williams *et al.* (1986) showed that the upper surfaces of melting glaciers have much higher nitrate levels than the ice below. The nitrate concentration in the dry valley glacier ice is, with the exception of some surfaces, low (Lyons *et al.* 1990), thereby suggesting some yet unknown preconcentration mechanism of nitrogen in the glacier–stream systems. One such mechanism may be transport processes occurring in the hyporheic zone of these streams. The extent of the hyporheic zone in the streambed and banks is constrained by the depth of the permafrost. Canfield and Green (1985) further showed that PO_4^{-3} levels are very low in the glacial ice, and that soils are likely the primary source of PO_4^{-3}. Readily soluble NO_3^- and carbonate salts from the ephemeral streambeds and banks may be generally depleted in the hyporheic zone, with significantly increased input of solutes from the terrestrial to the aquatic systems occurring only by incursions of streams into new areas.

Microbial mat abundance in dry valley streams is subject to removal processes different from those in temperate streams because of both the nature of the microbial community (i.e., no macroinvertebrate species present) and the physical environment. Biotic removal processes in dry valley streams include grazing by protozoa and micrometazoans, autotrophic respiration, and possible drift from mats. Physical removal processes include wind ablation when streams are dry, and flood scouring, both representing loss from the stream and input to other ecosystems.

Lakes

Lake environments in the McMurdo Dry Valleys represent the most extreme conditions of saline lakes in cold deserts. These polar extremes provide a unique opportunity to examine lacustrine processes that operate at all latitudes, but under an expanded range of environmental conditions. The sediments in dry valley lakes may in addition offer a valuable record of catchment, regional, and even global changes. These waters are modern–day equivalents of the periglacial lakes that are likely to have been common during periods of glacial maxima at temperate latitudes. Dry valley lakes may therefore assist in the interpretation of temperate lake history, and conversely the paleolimnological records from lower latitudes may further our understanding of Antarctic lacustrine ecosystems.

Compared to the terrestrial and stream ecosystems, the lakes in Taylor Valley have been well studied (e.g., Vincent 1988). Their continuous existence as liquid water–ice equilibria is the result of two climatic conditions: (1) mean summer temperatures are low enough that the winter accumulation of ice does not melt completely in the summer, and (2) meltwater from local glaciers resupplies ablation losses from the lake surface (Wilson 1981; Clow *et al.* 1988). Water level is established by the balance between summer melting and annual ablation (Chinn 1985; Clow *et al.* 1988). The thickness of the ice cover is determined by the energy balance of the lake (Ragotskie and Likens 1964; McKay *et al.* 1985). The turnover times for solutes, dissolved atmospheric gases, water volume, and ice in these lakes are < 3000, 45, 50, and 10 years, respectively (Green *et al.* 1988; Wharton *et al.* 1989). Thus, the lake environment responds to changes on a time scale of 10^1–10^3 years.



Lake Fryxell, Taylor Valley.

Table 2 presents several physicochemical features of Lakes Fryxell, Hoare, Bonney, and Vanda observed primarily during the austral summer. Marked differences occur in the temperature–depth profiles of the dry valley lakes. Lake Hoare's water–column temperature is near 0°C, while Lake Fryxell ranges from 0°C to +4.0°C, and the east lobe of Lake Bonney goes from 0°C immediately below the ice cover to +7.0°C at 15 m, then drops to about –2.0°C at 40 m.

Ice cover affects the quantity and spectral distribution of radiation reaching the underlying water (Ragotzkie and Likens 1964; Lizotte and Priscu 1992; Wharton *et al.* 1993). From an ecological perspective, the penetration of photosynthetically active radiation (PAR) (400–700 nm wavelengths) depends on the general albedo and sediment cover, attenuation coefficient, thickness, and scattering properties of the ice. In Lake Hoare, spectral downwelling measurements showed that the full wavelength PAR beneath the ice was < 3% of maximum incident surface PAR (Palmisano and Simmons 1987). Also, there are significant seasonal variations in the optical properties of ice (Goldman *et al.* 1967; Wharton *et al.* 1989, 1993; Lizotte and Priscu 1992).

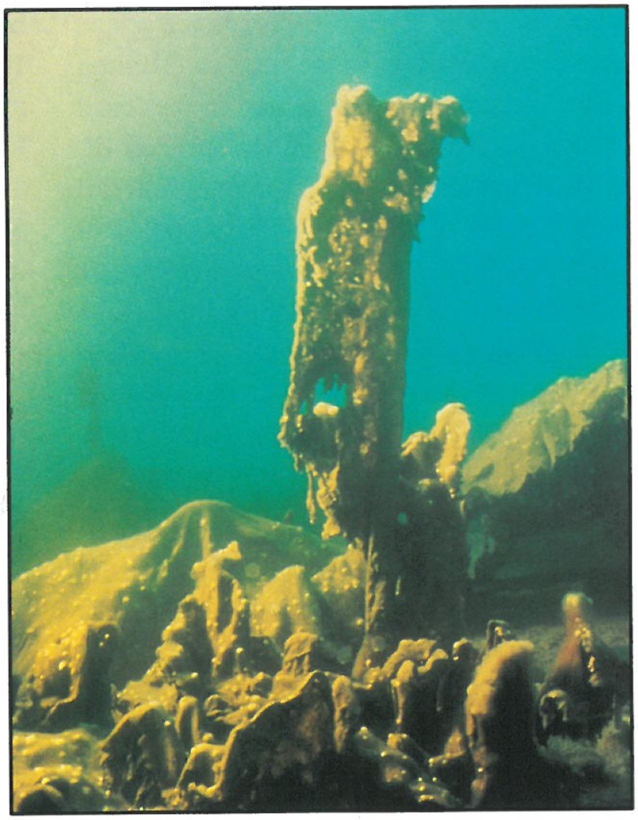
A unique feature of these lakes is the occurrence of supersaturated N_2 and O_2 in the upper portions of the water column; the saturations range upwards from 160% (N_2) and slightly over 400% (O_2). There are two primary sources of O_2: (1) gases carried into the lake by the meltstreams that are forced into the water column when the water freezes onto the bottom of the ice cover, and (2) photosynthesis and loss of reduced carbon in the sediments (Wharton *et al.* 1986, 1987; Craig *et al.* 1992).

Table 2. Physicochemical features of Lakes Fryxell, Hoare, Bonney, and Vanda. Ranges indicate values observed during the austral summer from the ice–water interface to the sediment–water interface.

	Fryxell	Hoare	Bonney[1]	Vanda
Surface area (m^2)	7.0 x 10^6	2.9 x 10^6	3.2 x 10^6	5.2 x 10^6
Volume (L)	4.3 x 10^{10}	2.6 x 10^{10}	6.0 x 10^{11}	1.9 x 10^{11}
Ice thickness (m)	4.5	3.5	4.0	3.5
Maximum depth (m)	18.5	34	40	70
Depth of oxycline (m)	9.5	28	20	60
PAR[2] ($\mu E\ m^{-2}\ sec^{-1}$)	19.5 – 0	10.4 – 0	91.0 – 2.6	190 – 0
% PAR	1.5 – 0	0.8 – 0	7.0 – 0	14.7 – 0
Water temperature (°C)	0 – +4.0	0 – +1.0	–2.0 – +7.0	0 – +24
Conductivity ($\mu mhos\ cm^{-1}$)	500 – 8,600	400 – 800	500 – 156,000	400 – 123,000
pH	8.4 – 7.0	8.9 – 7.3	8.4 – 5.3	7.9 – 5.4
Dissolved O_2 ($mg\ L^{-1}$)	41.9 – 0	52.1 – 0	45.8 – 0	24.1 – 0
AIC[3] ($mM\ L^{-1}$)	6.67 – 60.17	0.67 – 6.50	0.8 – 61.2	0.9 – 46
NH_4^+ ($\mu mol\ L^{-1}$)	0.1 – >7.1	0 – >7.1	0 – 300	0 – 507
$NO_3^- + NO_2^-$ ($\mu mol\ L^{-1}$)	0 – 0.3	0 – 3.5	4.5 – 178.2	0 – 143
PO_4^{-3} ($\mu mol\ L^{-1}$)	0.04 – 11.24	0.02 – 0.12	0.04 – 0.37	0.02 – 6.9

Sources:
Vincent *et al.* 1981; Parker *et al.* 1982a; Green and Canfield 1984; Canfield and Green 1985; Green *et al.* 1988.
[1] East lobe of Lake Bonney
[2] PAR = photosynthetically active radiation (400–700 nm wavelengths)
[3] AIC = available inorganic carbon

Table 2 also illustrates the variation in water chemistry and trophic status among lakes. A continuum exists from ultraoligotrophic (Lake Hoare) to relatively eutrophic (Lake Fryxell). Lake Bonney, which is situated between Hoare and Fryxell in trophic status, has hypersaline bottom waters (i.e., salinity ~ 35%). Lake Fryxell has an intermediate salinity level and Lake Hoare is relatively fresh. Major ions (e.g., Cl^-, Na^+, Mg^{+2}) show clearly different vertical patterns (Parker *et al.* 1982a; Green *et al.* 1988), and macronutrient chemistry varies among lakes (Gardner *et al.* 1984; Green *et al.* 1988). These differences are thought to be due to variations in both stream chemical input and *in–situ* lake processes (Green *et al.* 1988). In Lake Fryxell, an N/P < 10 at all depths suggests that nitrogen is the limiting factor for microbial activity. Experiments utilizing ^{15}N verified that microbial populations immediately beneath the ice were nitrogen–deficient (Priscu *et al.* 1989). In Lake Hoare, nitrogen is apparently deficient to 9 m (N/P < 4.0); however, N/P increased to 51 at 27 m (anoxic boundary) and then dropped to about 2 (Green *et al.* 1988). In Lake Bonney, shallow–water microbial populations were also nitrogen–limited, whereas those near the bottom of the trophogenic zone were not (Priscu, unpublished data). A variety of observations point to phosphorus rather than nitrogen as the biomass–limiting element in Lake Vanda: dissolved phosphorus values lower than 1 µg L^{-1} in the surface waters, dissolved inorganic N:P ratios in excess of 10:1 (up to 5000:1 in the region of the deep chl *a* maximum), and high particulate N:P ratios up to 40:1 (Vincent *et al.* 1981; Vincent and Vincent 1982).



Microbial Mat, Lake Hoare.

The lakes have abundant planktonic and benthic microbial populations (Vincent 1987, 1988). The main phototrophs are cyanobacteria, phytoflagellates, nonflagellated chlorophytes, and, in Lake Fryxell, purple sulfur bacteria. The phytoplankton and other microbial populations are typically stratified with depth, reflecting the hydrologic stability of the water columns (Parker *et al.* 1981, 1982a; Vincent 1981; Priscu *et al.* 1987, 1989). Flagellates such as *Cryptomonas* and *Chroomonas* (Cryptophyceae), *Ochcromonas* (Chrysophyceae), *Chlamydomonas*, and *Pyramimonas* (Chlorophyceae) frequently form unialgal layers (Vincent 1988). The lakes also contain heterotrophic bacteria, fungi, protozoa, rotifers, tardigrades, and nematodes (Vincent 1988).

Microbial mats are abundant throughout much of the benthic regions of these lakes and are composed primarily of cyanobacteria (e.g., *Phormidium*, *Oscillatoria*, and *Lyngbya*), pennate diatoms, and eubacteria (Wharton *et al.* 1983). Many of these mats precipitate calcite, iron, and sulfur, and trap and bind sediments, forming alternating laminae of organic and inorganic material (modern stromatolites) (see, e.g., Parker *et al.* 1981; Wharton *et al.* 1982; Love *et al.* 1983). While there are differences in the relative abundances of the species that make up microbial mats, the most interesting features are the differences in mat morphologies within — and between — lakes. Species distribution and microbial mat morphologies may be dependent upon particular environmental conditions as affected by the nature of perennial ice cover (Likens 1964; Wharton *et al.* 1983, 1993; Simmons *et al.* 1993). Studying the formation of microbial mats within Antarctic dry valley lakes has yielded insight into the physical and chemical conditions of past environments of early Earth. Similar prokaryote ecosystems dominated the earth for 3 billion years and are well represented in the fossil record as stromatolites (Awramik *et al.* 1976). Understanding the formation and preservation of microbial communities in the dry valleys will help us interpret the early stromatolitic record. Dry valley lakes contain prokaryote–dominated communities that have potential to serve as models of Earth's earliest living systems.

The dominant processes involved in carbon cycling in the lakes are growth of phytoplankton and microbial mats, degradation of particulate organic carbon in the water column, degradation and burial of organic matter in the sediments, and diffusive transport of organic carbon and nutrients from the sediments. Biological properties, such as phytoplankton abundance and depth distribution, chl *a* concentration, and primary production differ greatly among the lakes (Simmons *et al.* 1993). For example, maximum chl *a* levels exceed 20 μg L^{-1} near the bottom of the trophogenic zone (~ 9.5 m) in Lake Fryxell, whereas the primary chlorophyll maximum (~ 2 μg L^{-1}) occurs just beneath the ice of Lake Bonney, with secondary maxima in the middle and near the bottom of the trophogenic zone (Priscu *et al.* 1987; Priscu, unpublished data). Maxima in primary productivity generally coincide with these biomass peaks. Such differences presumably reflect the physicochemical properties of each lake since light penetration of the surface ice in all the lakes is similar (Vincent 1981; Priscu *et al.* 1987; Priscu 1989).

Gases, solutes, and solids move through the ice cover in both directions. Microbial mats break free from the lake bottom, rise to the surface, are frozen into the bottom of the ice, and eventually reach the ice surface by sublimation (Parker *et al.* 1982a). Gas and solutes are trapped as the ice forms at the ice–water interface and move upward in the same fashion (Craig *et al.* 1992). Cracks in the ice allow both downward transport of wind–blown sediment and gas exchange between water and atmosphere (Nedell *et al.* 1987; Wharton *et al.* 1989). At Lake Hoare, discrete piles of sediment occur on the lake bottom beneath cracks in the ice (Squyres *et al.* 1991). Surface ice melts around the periphery of the lake forming moats that allow deposition of wind–blown material and gas exchange.

Microbial Mat, Lake Joyce.

General Research Strategies

The workshop reached consensus on three general strategies for studying dry valley ecosystems: (1) establishment of reference sites with ongoing monitoring of key environmental parameters, (2) application of models and geographic information approaches for studying material flux and other linkages among landscape units, and (3) application of modern molecular biological techniques to study adaptation of biota to the Antarctic environment.

Reference Sites

Previous research on the ecosystems in the McMurdo Dry Valleys has been undertaken without an interdisciplinary, organized framework. If synthesis of data from a range of individual studies is to be a primary aim of future investigations, a more formally organized approach will be required. The establishment of instrumented reference sites is an approach that would be effective in addressing the heterogeneity inherent in these ecosystems. As the focal point for most investigations, the reference sites, around which separate investigations of secondary sites would be conducted, could provide both flexibility and interconnection within and among areas of differing soil types and hydrological statuses.

For example, characterization of the physicochemical factors limiting distribution and activity of biota is a general research priority. These studies should be conducted within a defined hydrological unit, that is, a watershed representative of the dry valley landscape. In this watershed, selected landscape units (ecosystems) should be characterized and intensively studied. Research at the reference site will require a two–pronged approach in which long–term data collection is coupled with shorter–term experimental or measurement programs to address specific questions. The long–term data collection will be for parameters that provide insight into critical ecosystem processes.

Modeling of Dry Valley Landscapes

It is possible to define hierarchical levels within a landscape in a number of ways but, for field studies by ecologists, the landscape units must be easily recognizable and duplicated for sampling purposes. A pragmatic definition could utilize a geomorphic classification: lakes – streams – ponds – cryoconite pools – transitional wetlands – patterned soils – unpatterned soils – dunes – endolithic communities. To date, there has been little attempt to link landscape units of the McMurdo Dry Valleys in terms of material flows or environmental adaptations.

Previous research in the dry valleys has focused largely on endolithic communities and lake ecosystems, with much less attention on the lotic and soil systems. The linkages between the fungal and algal constituents of the endolithic communities are reasonably well established, and primary production estimates for examples of this community type already exist. Primary production measurements have been made for several dry valley lakes, although most were made in mid–summer (December). There are estimates of primary production for specific microbial mats in lotic habitats, but none at the ecosystem level. In the soil ecosystems, the extremely xeric conditions limit the potential of organisms for carbon fixation.

Field studies in dry valleys are very expensive, logistics are demanding, and time is at a premium. Under these circumstances, modeling provides an extremely cost–effective means for examining sets of hypotheses prior to conducting specific experiments and for organizing interdisciplinary research. Models can be very useful in helping identify areas of greatest uncertainty and suggesting field experiments that provide maximum information.

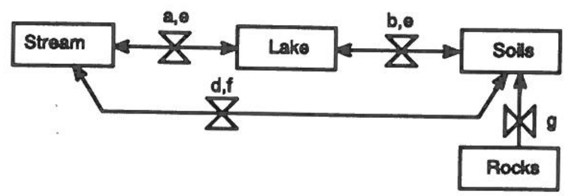
For example, modeling can help in the understanding of carbon flux among landscape elements. It is hypothesized that organic carbon exchange occurs among the various ecosystems that make up the dry valley landscape and that these fluxes may be significant for the functioning and the stability of the ecosystems. A first step could be the development of a simple flow model with an interaction matrix identifying all potential flows of carbon between each pair of landscape units (Table 3).

Table 3. Carbon–flow interaction matrix.

	Lakes	Streams	Soils	Rocks
Lakes		+	+	0
Streams	+		+	0
Soils	+	+		+
Rocks	0	0	0	

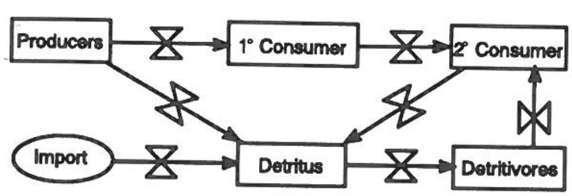
In the table, a positive flow of material (from columns to rows) is specified with +, while 0 denotes no carbon flow. Because it seems likely that such linkages exist in the dry valleys, it is necessary to quantify flow of organic carbon.

When values of these individual flows are determined, they could then be used to describe the flux of carbon through the landscape. This would identify those linkages among landscape units that are not currently understood.



Conceptual model of organic carbon flow.

It is apparent that considerable differences exist in the trophic structures of dry valley ecosystems. A generalized ecosystem structure provides the basis for gross structural differences among ecosystems.



Generalized ecosystem model of carbon flow.

It is likely that information already exists to support this level of model development. Furthermore, the development of interaction and flow matrices for each ecosystem model would then provide a means of examining carbon flow both within and among systems.

Molecular Biology Techniques

Through the use of molecular methods, relatedness among species can be established, and questions on evolution and ecological processes can be addressed. Comparisons of organisms using molecular biology techniques (e.g., polymerase chain reaction (PCR) and 16S rRNA sequencing) can answer questions on evolutionary relationships of species among different habitats and geographical areas. Questions on the origins and dispersal of various taxa among lotic, lentic, and terrestrial environments and determination of the indigenous vs. transient natures of taxa in an ecosystem can be studied. In the longer term, it will be possible to establish the adaptive mechanisms of some key organisms to the environmental extremes of Antarctica and the relationship of these organisms to taxa inhabiting less extreme environments. The evolutionary origins of these adaptations provide insights into how survival mechanisms for extreme habitats evolve.

Research Priorities and Approaches for Terrestrial Ecosystems

1. Establish community structure and trophic relationships

The short food chains and limited number of trophic levels in the dry valleys have produced relatively simple terrestrial ecosystems. The most complex soil communities contain a limited range of heterotrophic microbiota including bacteria, eukaryotic algae, yeasts, fungi, protozoa, rotifers, tardigrades, nematodes, and microarthropods. Population dynamics and distributions have yet to be established for most species, and the food–web structures of these remarkably simple soil systems are not yet known. It is clear that the supply of organic carbon is a principal limitation on community growth.

Wind–driven movement of organic carbon from lakes and streams to soil communities appears to be the key linkage between terrestrial and aquatic ecosystems, in direct contrast to the direction of most organic carbon flow found in other terrestrial ecosystems. Microflora and fauna appear to be dispersed by wind to other soil sites in a cryobiotic state and thus serve as a source of innoculum, carbon, and nutrients.

The communities forming the bases of dry valley terrestrial ecosystems contain numerous interacting populations, each with particular phenological and physiological traits. Although the survival strategies, population dynamics, and/or energy budgets of these species are poorly understood at present, knowledge of their dynamics in other ecosystems can be adapted to design experiments on dry valley survival strategies. For example, models developed for soil nematode populations in other environmental extremes, such as warm desert ecosystems, can be used to model critical interactions and to test where the dry valleys fall in the continuum of arid, water–limited ecosystems.

Models from other terrestrial ecosystems can also provide a basis for identifying the linkages among biotic communities that can be used to develop experimental designs for field studies. For example, the quantitative assessment of productivity during a summer season could be used to determine energy flow and nutrient cycling through the terrestrial ecosystem, as well as the controls or limits to the number of trophic levels that structure the biotic community.

2. Determine the feedbacks between abiotic and biotic portions of terrestrial ecosystems and landscapes

The effects of physical and chemical factors on biological processes, already delineated for the endolithic communities, are not understood for terrestrial communities. Moreover, the lack of quantitative data on the physical and chemical characteristics of the soils precludes application of analytical and numerical models for the prediction of the salinity, moisture availability, and temperature regime in the microenvironment where biotic activity takes place. Long–term data are needed for such factors as microclimate, salt content, water content, water tension, and the extent and distribution of ephemeral streams and ponds. These data are essential for developing a detailed understanding of the physical (i.e., abiotic) factors controlling biological processes in the dry valleys.

There appears to be little resilience in the terrestrial ecosystem because of the low biodiversity and simple soil food webs. It is therefore possible that any change, including those in the physical and chemical environments, affecting the terrestrial food web would have a large impact on the stability of the ecosystem. In addition, extinction of species caused by extreme environmental stress is not expected to result in the niche being filled by trophic competitors, as in more benign ecosystems. Environmental changes affecting the dry valleys could indicate not only effects at the community level, but responses at the ecosystem and landscape levels that occur at a slower rate in more complex and buffered ecosystems.

Important factors affecting dry valley terrestrial ecosystems are rock type, soil type, water availability, soil temperature, salt content, depth of the permafrost, and surface energy balance. Determining the degree of influence of each factor may permit extrapolation to other environments, including communities in other physical locations or the same community under different climatic conditions. Of special importance for terrestrial ecology are: (1) characterization of soils for spatial extrapolation of research results to other sites of similar antarctic soils or lithic habitats; (2) determination of the limits of physiological adaptation to extremes of the physicochemical environment; and (3) determination of the stability of the terrestrial ecosystem. In the reference watersheds, selected landscape units (ecosystems) should be characterized and intensively studied for soil moisture, salinity, and temperature regimes, and community process activity. Maps relating soil characteristics to land forms should be prepared.

3. Characterize survival strategies and adaptations of key organisms under severe environmental conditions and determine their responses to environmental change

The value of extreme environments in the selection of survival traits is well known from other parts of the world (deserts, mountains, deep ocean), and the antarctic environment offers a particular combination of environmental stresses. The limited range of organisms inhabiting dry valley soils exhibits attributes required to survive desiccation, freezing, high salinity, increasing UV–B, and short growing seasons. In contrast to responses in relatively more complex terrestrial ecosystems, the adaptations dry valley organisms use (physiological, biochemical, behavioral) do not include those required to provide competitive advantages. Resource allocation at the individual and community levels appears to be invested entirely for surviving the environment. Thus, the soil food web, limited in biodiversity and trophic competition, may be one of the more responsive indicators of environmental change.

There are major gaps in our knowledge of survival strategies of soil organisms at all hierarchical levels and as defined by their habitats. The survival strategies of the organisms are directly related to ecosystem functioning in the dry valleys and are also applicable to other cold and more complex ecosystems such as temperate alpine and desert ecosystems. Establishing responses of the soil community to environmental change can provide data for modeling the effects of climate change on productivity of temperate ecosystems.

Both experimental field manipulations and laboratory experiments will be necessary to study the terrestrial ecosystems of the dry valleys. Table 4 lists the critical research approaches for investigating the ecology of the soil biota. The use of microcosms can establish the interactions between increasingly complex assemblages under varying environmental stresses. Molecular techniques offer an important means of investigating evolution and dispersal.

Table 4. Research approaches for investigating soil biota of the Antarctic dry valleys.

<u>Species Level</u>

- Determine the specific mechanism for cellular survival during frequent wetting and drying cycles
- Determine the specific physiological mechanisms for organism survival during repeated freezing and thawing
- Characterize the effects of high salinities in a dry and cold environment
- Determine the proportion of true psychrophiles in the microbiota
- Determine how significant metabolic activity is at subzero temperatures
- Measure the life expectancy of individual organisms
- Determine how frequently and under which environmental conditions successful reproduction is possible

<u>Community Level</u>

- Determine the limitation to the number of trophic levels at particular sites
- Determine what constitutes adequate community stability, enabling a population to persist
- Determine the responsiveness of soil communities to changes in the environment

<u>Ecosystem Level</u>

- Determine if biodiversity is maintained by on–site environmental factors or by limitations to dispersal
- Determine if biodiversity affects ecosystem functioning
- Determine the seasonal patterns of activity in the various soil ecosystems

RESEARCH PRIORITIES AND APPROACHES FOR STREAM ECOSYSTEMS

1. Investigate interaction of streamflow and subsurface flow (hyporheos) on stream hydrology and chemistry

An integral part of a stream ecosystem is the hyporheos, or substream, where water moves through the alluvium below and adjacent to the streambed and above the permafrost. The interchange between hyporheic water and surface water along the flow path to the lakes can markedly change the solute and nutrient compositions of these waters before they enter the lakes. Weathering in the hyporheos may control solute flux in the ecosystem. Downward and lateral movement of water from the channel during the diel rise in flow may greatly extend the area and volume of sediment in contact with stream water. With decreases in flow each day, the water in the hyporheos may drain back to the channel, enriching the stream water and adding to the solute flux into the lakes.

Little is known about the development of the hyporheos and the extent of the interactions between the stream and the hyporheos. Longitudinal increases in concentrations of dissolved solids in streamflow in the Taylor Valley have been measured (McKnight *et al.* 1991). However, little is known about how channel morphology and geology interact to modify the concentrations of solutes and nutrients in these fluvial ecosystems. Understanding the effects of this interaction would help in the determination of what portion of the solutes discharged into receiving lakes results from streamflow–hyporheos interactions. This information would also facilitate identification of what filtering effect, if any, these interactions have on solute and nutrient concentrations.

The approach includes the determination of the rate of thaw and extent of the development of the hyporheos, as well as the effect of seasonality and diel variations on streamflow–hyporheos interaction and solute flux in the system. Portable devices such as electromagnetic induction and ground–penetrating radar could be used to map the hyporheos. Collection of continuous records of water levels in wells that intersect the hyporheos and continuous measurement of specific conductance would help define the effect of seasonal and diel variations of streamflow on the solute flux. Solute–injection experiments provide an approach for determining residence time and volume of storage in the hyporheos (Bencala *et al.* 1984; Stream Solute Workshop 1990).

2. Determine sensitivity of streamflow to small variations in climate

Streams in the dry valleys of Antarctica are temporally intermittent, and variations in the discharge are closely coupled with air temperature and solar radiation. Temperature excursions above 0°C generate the glacial meltwater that feeds these streams. As a result, streamflow markedly reflects deviations from this 0°C threshold. The streamflow responses tend to be nonlinear and magnify small changes in regional temperature. Summertime temperatures have both diel and seasonal responses that frequently result in transitions both above and below the 0°C threshold. These transitions produce intermittent streams, commonly flowing from late November to early February, that are often characterized by large diel fluctuations in discharge exceeding one order of magnitude. The hydrograph is therefore relatively predictable as to the period of flow but highly variable in the annual quantity of discharge and in day–to–day peak and minimum flows.

Streams in warm xeric environments commonly amplify small changes in total precipitation with large changes in discharge. In more mesic environments, a change in precipitation generates a linear increase or decrease in streamflow and water yield. In more arid regions, streamflow responds nonlinearly with small changes in precipitation producing a nonlinear amplified response within the stream. It is hypothesized that, similarly for streams fed by glacial meltwaters in the cold dry deserts of Antarctica, streamflow will respond nonlinearly to slight temperature shifts either above or below the 0°C threshold. Slight cooling will result in a large decrease in water yield while small temperature increases will add substantially to total discharge and the areal extent of stream habitat.

Hydrograph responses to small temperature fluctuations near the critical 0°C transition point need to be evaluated with existing and future data. This analysis should be overlaid on indices of regional climate that show their impact on a seasonal and annual basis. A temperature/flow–response curve for various hydrographs should be constructed and the degree of nonlinearity assessed. Comparisons of hydrograph records across various streams in the area should be done.

Addressing this research priority requires measurements of stream discharge and temperature, air temperature, and solar radiation. A network of weather stations and stream gauges would allow this research to address issues of regional climate and year–to–year variability within the dry valleys. Such a network would contribute both to an evaluation of regional changes in climate and to estimates of water budgets, geochemical mass balances, and nutrient fluxes to the lake ecosystems. An array of shallow ice cores (ca. 10 m depth) from glaciers over a wide geographic range within the dry valleys should also be sampled. These would provide information, with subannual resolution, of variables such as the concentrations, sources, and pathways of atmospheric constituents, and provide a baseline record of recent variability (100 yrs) in temperature. Maintenance of present long–term records for the region would be critical, as would the establishment of new gauges in those basins targeted for intensive interdisciplinary studies of terrestrial and aquatic ecosystems. Compilation and examination of existing climate and streamflow records would help in the determination of what additional information is needed. Other aspects of the effects of climatic variables on stream–flow generation that require investigation are: (1) the threshold at which climate variables affect streamflow generation, and (2) the cumulative effects of climatic variables on streamflow generation.

3. Investigate biogeochemistry of trace metals and elemental budgets in nonimpacted catchments

The dry valley streams are among the few flowing waters on the Earth's surface that are minimally influenced by human activity. Thus, they act as a window to preindustrial stream environments and as a baseline from which possible future human–induced impacts can be assessed. The sources, acquisition processes, concentrations, biogeochemical pathways, and fluxes of major ions, nutrients, and metals in meltwater and streams should be defined. The rigorous testing of evolution models of dry valley lakes requires major ion mass–flow data. While there is some information on nitrogen and phosphorus, there have not been long–term loading studies of these nutrients in Antarctic lakes. The precise sources of these nutrients and their transformations throughout the stream environment are also unknown. Data on metal concentrations and information on metal partitioning between dissolved and particulate phases are limited in these pristine waters (Green *et al.* 1986, 1989; Masuda *et al.* 1982). Knowledge of metal sources and of metal interactions with the biotic communities and with inorganic substrates is also limited.

Linkage between the soil and lake ecosystems should be emphasized. The soils and bedrock are the major sources of dissolved and suspended material. Understanding the composition of these materials will make it easier to interpret the variability of stream composition both in and among the dry valleys. The lakes serve to integrate stream inputs over time and their compositions and biological activity are, in part, a reflection of these inputs. Any understanding of lake chemistry and biology must also be linked to stream fluxes.

Addressing this research priority will require extensive collection of water samples during flow from glacial meltwater, along longitudinal stream gradients, in the hyporheic zone, and at stream gauging stations. Sampling should involve rigorous use of ultraclean techniques such as those outlined by Boutron and Patterson (1987). Partitioning of metals operationally defined as being in the dissolved and particulate phases requires that special attention be given to the filtration process while avoiding contamination. Nutrient species and major ions are more easily identified using either standard wet or instrumental techniques, and accurate analyses of ultra–low concentrations of these elements may require return to institution laboratories. Modeling strategies include partitioning the stream to quantify internal sinks and sources, as well as the use of metal speciation and residence–time models.

4. Investigate production, consumption, and export of perennial microbial mats

The abundance of microbial mats in temperate streams is controlled by a variety of biotic and abiotic processes, with macroinvertebrate grazing and flood scouring being quantitatively most important. Dry valley stream mats are subject to different removal processes because of the nature of the biotic community and physical environment. Biotic processes causing removal of mat material include protozoan and micrometazoan grazing, and possibly active drift from the mat. Physical removal processes include wind ablation (when streams are dry) and flood scouring. Understanding the relative importance of, for instance, wind ablation versus *in–situ* grazing is desirable because the material may be either transported from the stream to terrestrial or lake ecosystems or transferred within trophic levels of the stream ecosystem. Because these mat communities are not nutrient or light limited, removal processes may well regulate biomass accumulation. Microbial mats are likely to be significant in the removal of nutrients and other ions from solution and in transformations of nitrogen. Therefore, understanding controls on mat abundance will be helpful in studying the dynamics of these elements.

The new knowledge most needed to evaluate loss processes is that concerning the heterotrophic community. Even quantitative assessments of abundance are lacking. No information exists on the composition of the heterotrophic community. In addition to providing key information about quantitatively important ecosystem–level processes, research on mat dynamics in dry valley streams offers the opportunity to examine herbivory by nontraditional grazers in the absence of traditional grazers (e.g., insects, snails).

Several approaches are recommended for addressing this research priority. An autecology/inferential approach would involve identification of community structure and an examination of relative abundance of algal grazers, omnivores, detritivores, etc., within the consumer community. The importance of grazers may be inferred by overall abundance of this community and covariation with the biomass of autotrophs in the mats. Potential research methods include the use of stable and radioactive isotopes and/or photosynthetic pigments as tracers of organic matter. These techniques would require collection and analysis of the microheterotrophic community. Grazing could also be assessed by looking at shifts in isotopic signal, pigment degradation, and fluorescent bead techniques.

Microbial mat turnover can be examined by eliminating eukaryote grazing through the use of inhibitors. In addition, mats may be relocated to differing scouring regimes in artificial channels, and their disappearance measured through time. This could best be accomplished in streams where discharge is being monitored. Samples of desiccated mat can be protected from wind scour, making it possible to measure overwinter abundance relative to that in unprotected areas.

Benchmark stations could be established to measure mat abundance at frequent intervals in order to estimate fluctuations in abundance. These measurements should be made before and after winter winds or floods to estimate wind and scour removal. Downstream transport of microbial material under natural flow variation can be determined using netting techniques to quantify drift of algal material and thus assess loss rates.

5. Characterize survival strategies and adaptations of organisms to freeze–drying and elevated UV–B

The extremes of alternate freeze–drying and thawing are particularly accentuated in antarctic streams with their high variability in flow. Although some metabolic responses to freeze–drying and subsequent rewetting have been measured, knowledge at the cellular and membrane levels is limited.

Of all antarctic communities, those of the streams are probably the ones most affected by the high springtime UV–B levels of recent years. Where not covered by drifted snow, the mats are completely exposed on the dry streambed in spring before glacier meltwater fills the stream channels. The responses of these communities and their protective mechanisms to UV–B will be of particular interest to areas where ozone depletion is as yet not as severe as in the Antarctic. Because of the mutagenic effects of ultraviolet radiation, there is also an increased chance of change in DNA. Research into the UV–B effects at the cellular and membrane levels – linking genetics, biochemistry, and whole–system ecology – would be helpful in understanding adaptations seen in the terrestrial and lake ecosystems.

To evaluate adaptation, detailed genetic investigations of the stream organisms will be required in order to measure change from related species in other ecosystems. Phenotypic plasticity will involve a combination of field experimentation in Antarctica together with laboratory–based biochemical assays including radiotracer experiments and chromatographic separations.

6. Establish sources, sinks, and redistribution patterns of nitrogen and carbon in dry valley catchments

Studies of nitrogen and organic carbon in antarctic ecosystems may provide important insight into nitrogen and organic carbon dynamics in temperate ecosystems. Although the dry valley ecosystems are simple in structure (e.g., absence of higher plants), their flux and cycling of nitrogen and organic carbon are dynamic. Relatively large inputs of nitrogen (mostly NO_3^-) enter the ephemeral streams from glacial meltwater (Howard–Williams *et al.* 1986). The source of these compounds in the glaciers is thought to be atmospheric input. Moreover, nitrogen is removed from the stream by microbial mats as the water moves downstream. In contrast, concentrations of dissolved organic carbon (DOC) often increase downstream. This inverse relation between NO_3^- and DOC is currently being studied in temperate streams and lakes.

During periods when there is no water flow (March–October), microbial mats may be ablated and potentially transferred to glacial, terrestrial, and lentic locations by wind. An important question is, do these aeolean transfers represent quantitatively significant fluxes? In an environment with such limited quantities of nitrogen and organic carbon present, are these fluxes important to the maintenance of ecosystems? During relatively high flow periods, the mats may be scoured, thereby transferring nitrogen and carbon downstream.

To address this research priority, a combination of approaches such as those described in research priorities 1–4 above will be needed. Detailed field sampling with laboratory analysis of water, sediment, and mat will be required. A wide range of dry valley glaciers should be sampled at varying altitudes. Natural ^{15}N isotope abundance in the meltwater from the glaciers should be measured to examine marine vs. terrestrial origin of the NO_3^-. In addition, there should be estimates of the rates of aeolean losses of nitrogen and of organic carbon and particulate nitrogen and carbon losses in flowing stream waters on a diel and seasonal basis.

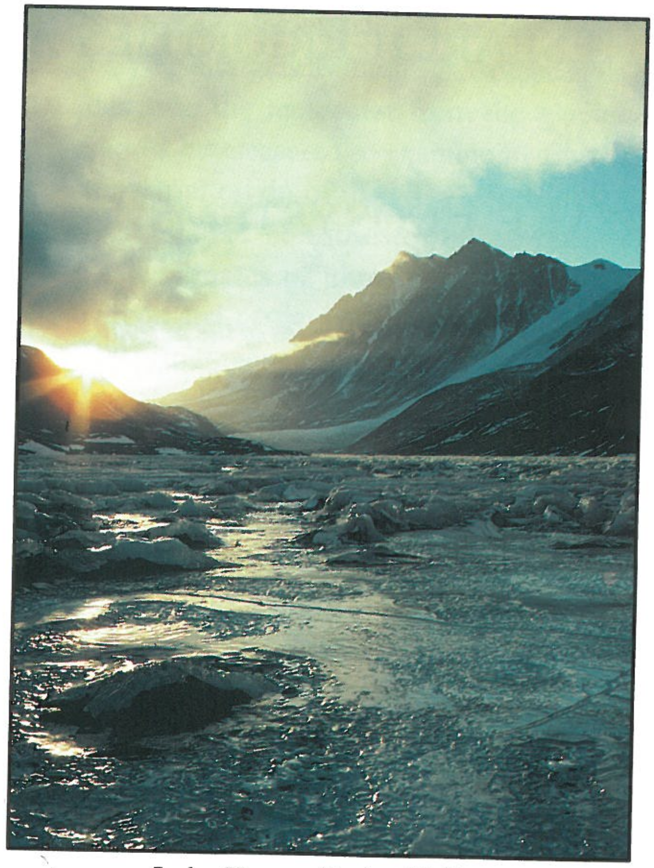
Research Priorities and Approaches for Lake Ecosystems

1. Determine how properties of the perennial ice cover and continuous light/dark regimes control the structure and dynamics of the lake ecosystems

Lakes in the dry valleys are distinguished by both the presence of a thick perennial ice cover and large variations in photoperiod. The ice cover has a pervasive influence, specifically limiting the transfer of mechanical energy from the wind, gas exchange with the atmosphere, the transfer of solar radiation internally to the lakes, and the introduction of diverse species. However, the magnitude and extent of these processes have not been adequately quantified or fully evaluated. Quantification would generate new insights to fundamental lake catchment processes such as stream–lake coupling, spatial patchiness in planktonic community structure, and water circulation. The approach to understanding these ice–cover effects will demand a three–dimensional perspective for sampling and modeling.

The annual light regime has four recognizable periods: constant light, constant dark, and the two transitions. This facilitates the study of transitions between autotrophy and heterotrophy. Potentially these light regimes allow for the study of microbial production dynamics ranging from whole–lake responses to smaller–scale comparisons of horizontal and vertical gradients within the lakes.

To account for the effect of moats, streams, and abutting glaciers, the sampling strategy should assess lateral and depth variations and allow for comparisons among the lakes. Deployment of sensors to measure parameters such as temperature, conductivity, turbidity, and current velocities will provide information on the diversity and extent (spatial and temporal) of mixing processes, including the impact of stream–lake interfaces. Tracer experiments using solutes such as lithium, bromide, or chloride have the potential to generate major new insights into local and basin–wide transport processes, but such tracers must be selected with caution to minimize environmental impact. The influence of extreme photoperiods on autotrophy/heterotrophy will require a combination of continuous in–lake measurements with specific production assays. In addition to devices for basic light measurements, in–lake instruments could include wavelength–specific detection systems, oxygen and pH sensors, fluorescence and transmittance detectors, and autosamplers for plankton and sediment. The long–term deployment of such instruments will require careful evaluation of the potential artifacts due to biofouling of the detectors and changes in the local environment indicated by the instrument. The production assays will need to combine traditional techniques with novel approaches developed for specific conditions.



Lake Hoare, Taylor Valley

2. Determine the underlying chemical and physical processes that generate the diversity in major ion composition and physical structure of the lakes

Geochemical controls on the major ion composition of the dry valley lakes include: (1) physical and chemical weathering processes, (2) the role of marine–derived salts, (3) the importance of physicochemical processes that fractionally precipitate salts within an evaporating lake, (4) selective dissolution of salts from adjacent saline soils and other evaporite lake deposits, (5) weathering processes that reflect lithologic differences among parent materials that make up the bedrock in specific lake watersheds, and (6) influence of ground–water input to the lakes.

Fractional precipitation of salts under conditions of extreme cold and salinity results in a set of unique waters that differ from those influenced by comparable evaporative processes in hot deserts (Herut *et al.* 1990). The major ion chemistry of the more saline waters in the dry valleys has been documented since the 1960s. Comparisons of the major ion contents of these waters relative to those in temperate deserts have not been performed. Knowledge of the relationship between stream input and lake composition is much improved (Green *et al.* 1988), but an understanding of the major geochemical processes controlling the chemical evolution of the lakes and ground water over longer periods of time is less certain. A systematic effort is needed to relate all of the diverse water chemistries observed in the dry valleys.

Despite considerable work on individual lakes, relatively little is known of the common processes, especially the hydrologic and hydrogeologic ones, that have led to the compositional diversity of the lakes (Lyons and Mayewski 1993; Matsumoto 1993). Observations of saline discharges at the Taylor Glacier and temporally incoherent changes in lake levels among the dry valley lakes suggest that the hydrology of lakes may be influenced by other factors in addition to climate change.

An approach to address this research priority includes the development of an improved base of comparable lake chemical data and the analysis of potential source waters of these lakes. Source waters include ice from local glaciers (e.g., Canada, Commonwealth, Taylor, Ferrar, and Blue Glaciers), supra– and periglacial streams, ponds, active–zone meltwater, snowfall, and possibly deep ground water.

Stable isotopes of hydrogen and oxygen should be used more extensively to evaluate source waters for lakes and to improve quantification of the evaporative processes that affect the lakes. Mineralogic and chemical study of sediment cores would lead to a better understanding of past variations in source waters and the evaporative history of these lakes. Also, long–term records of precipitation and stream and lake chemistries should be established to improve understanding of interannual variability in the lakes and water fluxes that control lake hydrology.

To invoke chemical weathering of local source rock substantial enough to provide the required amounts of solutes for saline lakes implies that recognizable weathering products should be detected. The existence and mineral composition of these weathering products need to be investigated to test this hypothesis. New methods for mineralogical investigation of minute amounts of material now allow direct study of parent lithic materials that weather in the arid, antarctic environments. Such techniques include high resolution transmission electron microscopy, improved scanning electron microscopy, and electron microprobe techniques.

Comparable studies of lithic fragments and mineral weathering products in lake sediment cores need to be carried out. The lack of lake macrofauna in the dry valley lakes allows for undisturbed, fine–scale accumulation of inorganic and organic materials from within the lake. Wind–blown dusts may contain appreciable amounts of these weathering products, and for that reason the aerosol minerals need more extensive collection and study.

Substantial evidence points to sea water as a primary source of the major solutes in the dry valley lakes, but these pathways are not well understood. Several lines of geologic evidence seem to rule out or severely limit direct input of these salts to lakes, but indirect pathways have been suggested. Marine salt may be transported by salts dissolved in precipitation or by dry aerosols. Systematic collection of long–term records of atmospheric precipitation chemistry and aerosol dusts is needed. Identification of the processes by which salts are transported to higher land elevations and later reworked through fractional precipitation and/or dissolution requires a better understanding of salt water generation through freezing/melting of permafrost in soils containing soluble salts derived either from chemical weathering or marine sources.

The infrequent discharges of large quantities of saline waters from the Taylor Glacier terminus is still not satisfactorily understood, despite the obvious role such a phenomenon could play in the salt budget of

Lake Bonney. A major, aperiodic solute flux to the lakes, especially Lakes Bonney and Vanda, has been ignored in models of the chemical evolution of these lakes.

The possible existence of deep ground waters beneath the existing permafrost has been suggested (Cartwright and Harris 1981). The potential role of deep ground waters needs further exploration. Higher solute and nutrient concentrations in these waters could exert considerable leverage on the chemical evolution of some of the deeper dry valley lakes (e.g., Lake Vanda). Improved understanding of dry valley lake hydrology and the coupled solute fluxes could point to the importance of these waters. Straightforward hydrogeologic techniques (e.g., nested piezometers) are available that would allow determination of the direction and flux of ground water movement in the bottom and margins of these lakes.

3. Characterize the adaptation and response of organisms to extreme physico–chemical conditions

Studying adaptations in the dry valley lake ecosystems will yield answers relevant to biology as a whole. The extreme conditions encountered in these ecosystems would be expected to accentuate the adaptations that both individual organisms and communities must have undergone to develop there. The range of parameters to which organisms and communities have adapted is very broad even within the same water body, from cold to warm, fresh to salty, supersaturation of oxygen to anoxia, high UV–B influx during spring to no light in winter. The great stability of parameters in the large lakes would give time for selection of organisms best adapted to these environments. Shallow ponds in the dry valleys represent extremely fluctuating environments, and the organisms that reside there must be adapted to warm, fresher water during summer, and, with saltout upon freezing, a cold and high–salt environment during winter. The supersaturation of oxygen in lake epilimnia provides an opportunity to study adaptations to high dissolved–oxygen concentrations. Increasing UV–B light associated with ozone depletion should act as an accentuated selective force for all organisms in antarctic ecosystems. Increased mutagenesis resulting from DNA damage by UV–B may result in increased UV–B tolerance of these species. The extremes of N:P ratios found in these lakes may provide useful experimental opportunities for understanding nutrient uptake processes and resource competition. With constant light through the summer, do the photosynthetic organisms in the dry valleys have a unique switch from photosynthesis to "dark respiration"? Finally, adaptation cannot be addressed without knowing the taxa present. Evolutionary change can be measured only in relation to related taxa in other ecosystems. Do the adaptations of the organisms to the extremes of the dry valley lakes represent modifications of morphology and physiology of related species, or are the adaptations unique? Do different taxa converge in adapted traits or are there numerous ways to evolve the same adaptation?

Adaptation and response to environmental extremes in this microbially dominated community should be investigated at the community and molecular levels, which makes necessary the use of laboratory cultures. Enrichment using continuous culture techniques can yield organisms most adapted to a set of selection conditions. Efforts to obtain representatives of most microbial groups in culture should be made. Phenotype and physiology of these groups should then be analyzed in response to specific environmental gradients (e.g., salinity, temperature, UV–B, and oxygen supersaturation). Phylogenetic characterization (probably through 16S rRNA sequencing) should be performed to evaluate the uniqueness of the organisms and their evolutionary relationships to organisms from other habitats or geographical areas. This would also make possible the development of specific oligonucleotide probes for specific taxa. These probes can be used on environmental samples to assess the contribution of each taxon to biomass and its seasonal and environmental change. Adaptation to specific selective parameters should be studied at the molecular level. One example may be to investigate changes in the capability to repair DNA after ultraviolet exposure or modifications that reduce UV–B effects. Is the evolution of these genes as measured by sequence change occurring at a faster rate than the evolution of genes not under selective pressure in organisms in these environments?

4. Determine the factors controlling microbially dominated ecosystems: the mats and the plankton

One question common to all aquatic systems, both lakes and oceans, concerns the control of the microbial loop containing cyanobacterial primary producers, heterotrophic bacteria, and grazing flagellates and ciliates. The microbial loop may be responsible for the loss of a high percentage of organic matter to respiration in many systems; it is argued that only when the microbial loop is unimportant in the cold seasons of the year can large amounts of energy reach the zooplankton and fish. The current questions go beyond descriptions of the loop in various habitats to questions of control. For example, what controls the biomass of bacteria in the plankton? Is it simply the amount of energy available or does it involve higher–order interactions including competition and predation, the grazing by protozoa, or viruses? In the dry valley lakes these questions apply equally with respect to controls of the biomass of the microbial mats that cover the sediments.

The dry valley lakes are one of the few places on Earth where microbial mats are presently forming without the interference of metazoans. The diversity, mat morphologies, and chemical conditions found in the dry valley lakes provide an excellent opportunity to investigate the ways in which physical and chemical processes govern the formation, burial, and preservation of microbial mat communities. An investigation of how sediment processes, light, and major ion concentrations control rates of carbonate deposition, stable isotope fractionation, species composition, chemical composition, pigments, and morphology of mats in the dry valley lakes is needed.

One reason that the lakes are a natural laboratory for studying the controls of the microbial loop is the lack of metazoan animals. When analyses are carried out with experiments and measurements in other aquatic systems, there is always the complication of grazing by metazoa such as copepods and other crustaceans in addition to grazing by protozoa. The peaks and valleys of a graph describing the numbers of protozoan flagellates over time may, for example, be obscured by this grazing.

The absence of the metazoans raises other questions about the microbial webs and their interactions. Does this absence lead to an unusual build–up of organic matter and an eventual reduction in the efficiency of microbial decomposition in the ecosystem? Does the lack of higher animals cause a lack of stirring of the sediments that leads to a reduction of the benthic–pelagic exchanges? Are nutrients and chemicals severely reduced in the water column, but bound up in the microbial mats?

A major gap in our knowledge of the lake ecosystems is the rate of primary production occurring in the microbial mat. Because of the very low rates, and the presence of a thick mucilage layer, current methods may not be adequate. A seasonal cycle of biomass and activity (primary production, grazing rates, bacterial production, nitrogen fixation, heterotrophic uptake) of the organisms from each trophic level needs to be recorded. These biomass and activity measurements should be made in conjunction with assessments of other basic biological and physicochemical parameters (e.g., pigments, DOC, light, temperature, nutrients, dissolved gases, major ions, ATP). Important insights on process–level controls should come from a comparison of lakes of different trophic status within the dry valleys. Optimally, these studies would be compared to similar studies from polar lakes at lower latitudes where more trophic levels are present. This study would require a team approach so that simultaneous measurements could be made over the season on a single lake. Several lakes could be sampled serially.

Very little is known about sedimentation rates and the contribution of the microbial mat biomass to sediment accumulation. Measurements of short–term sedimentation rates could be made using sediment traps. Long–term sedimentation rates can be calculated from sediment cores using ^{14}C dating if reservoir effects could be discerned.

5. *Investigate the role of dry valley lakes as sensitive indicators of climatic change*

Global climate models suggest that the greatest warming due to increased atmospheric CO_2 will occur in polar regions. The resilience of species and communities to these changes is unknown. The dry valley lakes may represent an important and sensitive area in which to monitor such predicted changes, acquire useful data for modeling these changes, and determine their effects on ecosystem processes.

Historical data on lake levels show rather dramatic increases, certainly since 1960, and possibly since 1911 (Chinn 1993; Wharton *et al.* 1992, 1993). Serious investigation, coupled with long–term monitoring, is required to determine the underlying cause(s) for the trend. Because the air temperature in the dry valleys is near 0°C during the austral summer, small changes in temperature result in major changes in the quantity of liquid water, derived from glacial melt, in streams, and in soils. Measurements of such changes — as lake level, lake ice thickness, and streamflow — have been made (Chinn 1993; Wharton *et al.* 1992, 1993) and should be continued on a routine monitoring basis, incorporating improved techniques if appropriate. It is important to monitor the levels and ice thicknesses of lakes that are in direct contact with glaciers, as well as those fed only by meltstreams. This would improve our determination of the role of glacial advance and retreat vs. that of glacial melt as controlling factors for the observed lake–level fluctuations. Bathymetric and hypsographic maps of the lakes should be made if they are not already available so that lake–level measurements can be converted to measures of actual changes in lake volume. Recent work suggests that there is not a one–to–one correspondence between lake level and climate change (Wharton *et al.* 1992, 1993). The different lakes do not respond in the same way to these changes. What now is needed is a better understanding of the heat and water budgets of several important lakes in the dry valleys.

Paleolake sediments in the dry valleys contain records that may be useful in reconstructing ancient lake levels (Denton *et al.* 1989). In addition, lake sediments provide records that reflect both in–lake and integrated watershed–scale processes, thus potentially supplying an ecosystem–level record of past and future changes in the dry valleys. To improve reconstruction of the climate history these sediment records can be compared to both the ice cores from surrounding glaciers and the marine sediment records from McMurdo Sound.

Automated meteorological stations are needed in various locations to monitor important parameters such as temperature, relative humidity, wind speed and direction, solar radiation, and albedo. Annual variation in lake ice ablation and bottom ice accumulation need to be better quantified. Direct measurements of freezing rates could be made and compared with models based on oxygen and hydrogen isotopic composition of the waters to contrast the relative importance of lake evaporation, sublimation, and surface ice melting.

Hydrologic lake models based on isotopic measurements (H/D and $^{18}O/^{16}O$) could be used to estimate the relative importance of meltwater from either local valley glaciers or polar cap outlet glaciers (e.g., Taylor Glacier) and of potential evaporation and sublimation from the lake and other inputs such as subpermafrost ground water or saline discharges. Such models would require periodic measurements of the isotopic composition of meltwaters, lake ice, lake water, moat water, runoff water from the ice surface, and active–zone meltwater from the surrounding soil systems.

Landscapes and Time/Space Relationships

Elucidating the factors controlling element cycling and biological processes in the McMurdo Dry Valleys will require data collection on several spatial and temporal scales, and interpretation at many levels of organization as listed below.

1. Hierarchical level of resolution
   a. Populations within communities
   b. Communities within ecosystems
   c. Ecosystems within the landscape
   d. Landscape
2. Spatial location and/or extent
   a. Maps of fundamental geomorphic features (e.g., soil types, stream locations)
   b. Characterization of ecosystem types for selection of specific sites for comparative assessments
   c. Paths of material flows between hierarchical levels
3. Temporal patterns (frequency and persistence)
   a. Long–term continuous measurement of the physical environment
   b. Determination of historical environmental patterns
   c. On–site processes
   d. Intersite linkages

The processing of such information requires intensive data management, the establishment of relational databases, and the implementation of a geographical information system (GIS). The difficulty of modeling such widely differing scales is a problem common in microbial ecology and presently inadequately addressed. The McMurdo Dry Valleys — characterized by low biodiversity, restricted community development, and limited interactions among communities — offer an excellent opportunity, compared to more complex temperate ecosystems, for developing new analytical methods that integrate microbial to landscape scales of hierarchical organization.

Logistics and Field Work Considerations

Ecosystem structure and processes in the McMurdo Dry Valleys have traditionally been studied during the mid–summer period, October to January. It is appropriate to continue a major portion of the research effort during this period, which encompasses near–shore meltout and early freezing. However, for some studies (e.g., autotrophy/heterotrophy relationships and microbial loops) it is critical to extend the field season to include the important transition periods, namely, early spring and late fall, and, whenever possible, to use instrumentation instead of manpower to monitor the critical parameters. In addition, interdisciplinary research would be facilitated by conducting concurrent studies of soils, streams, and lakes in the same catchment(s). It is not thought appropriate or necessary to leap into an overwintering commitment at this time, though it could become desirable in the future on the basis of data as yet unavailable.

Currently, field operations begin in October and end in late January. Extension of the field season would enhance research in several important ways. Soil biota do not stop growth and metabolic activity at the end of January, and the extension would allow studies of biota as they go through important physiological transitions as winter approaches. The stream research outlined above requires an extension of the summer field season to allow for work on the stream communities during the springtime depletion of atmospheric ozone and the critical period of cessation of flow and final freeze–up of the streambed, which occurs in early to mid–February. An extended season is also needed to follow the response of the planktonic and benthic communities to the onset of light and the onset of darkness.

Infrastructure is required to support the continuous operation of monitoring instrumentation on a year–round basis. This requirement includes the capacity for remote assessment of data. Examples of needs for the three ecosystems are outlined below.

Soil Ecosystems. The need for soil ecology studies of no less than three years' duration is of primary concern. Because of the need for microclimatic data at the community level, year–to–year variations in microclimate and macroclimate must be included. A major constraint for studying soil ecosystems is a lack of winter–season data for the dry valley soils, including both abiotic and biotic variables.

Stream Ecosystems. Continuous measurements of streamflow and general stream water–quality parameters (e.g., specific conductance and temperature) are required, as well as measurement of climatic variables to determine the effect of climate on the onset and cessation of streamflow.

Lake Ecosystems. Continuous measurements of ice thickness and lake level are critical to following responses to changing climate. Continuous measurements of water–column parameters (e.g., light, temperature, dissolved oxygen, and chl *a*) would also be extremely valuable.

In addition, there is the growing international aspect of the logistics of, and need for, maintaining long–term data sets such as streamflow (e.g., Onyx River) and climate recordings. Provision for continued update of these data sets does not always fit within research funding requirements, and yet the data sets provide essential background information for a wide range of specific studies. There is a need now for a look at how such data sets can be funded, perhaps outside of traditional research funding agencies. An internationally accessible database (both computerized and in hard copy) for routine measurements should be considered. The database could be located in McMurdo Station, with regularly updated copies made available at the Antarctic Centers in New Zealand, Australia, and the United Kingdom.

U. S. Navy Helicopter, Taylor Valley.

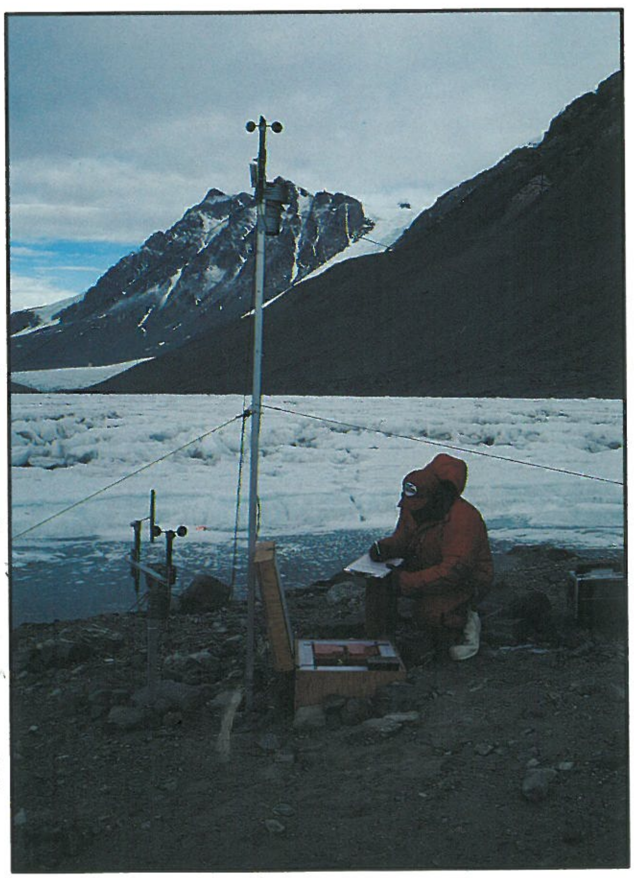
TECHNOLOGY NEEDS

Research in the dry valley ecosystems will require improvements in remote sensing capabilities, geographic information systems, and on–site laboratory facilities. These are broad needs that are difficult to justify and fund on the basis of individual, single–investigator projects.

The definition of the aerial extent and the spatial arrangement of the ecosystem types identified earlier will require the use of aerial photography and perhaps satellite remote sensing. Much of this information may already be available. The ability to use remotely sensed data to estimate soil surface temperature and moisture content could provide the basis for estimating the potential biological activity of soil ecosystems on large scales.

An interdisciplinary team approach to the study of the dry valleys will require information best organized, manipulated, and retrieved via a geographic information system (GIS). Relevant data layers include elevation, geology, soil type, landforms, surface age, and location of surface waters and streams. An important benefit of the GIS is that it could be used to locate past studies and their impacts on the environment, allowing researchers to identify areas previously disturbed. The GIS should be available to researchers at McMurdo for data analysis, and through a computer network to investigators in the U.S.A. and other countries.

Facilities should be available in the dry valleys to support microbial ecology research. For example, a soils lab would allow immediate processing of field samples and minimize potential contamination of field samples during transport to McMurdo and/ or the U.S.A. There are already some field laboratories that are used by individual research projects. These laboratories should be upgraded and so managed that the facilities are available to more than one research project.



Weather Station, Lake Hoare

ENVIRONMENTAL IMPACTS

The dry valley ecosystems should be protected during any research program. Perturbations and major accidents (e.g., chemical and radioisotope spills) are perceived to be the most significant environmental threats. Therefore, all research operations should evaluate the potential for environmental accidents and take precautions to minimize risks. Human impact and instrument deployment constitute the common, low–level impact. Low–level disturbance of the environment from the deployment of instrumentation is likely to be highly localized, and would include instrumentation acting as foci for settlement, the release of contaminants, physicochemical modification of the environment, or disruption of natural gradients. In addition to the environmental impacts common to most general field and laboratory activities in Antarctica, research in the dry valley environment may result in additional problems, for which precautionary measures are outlined below.

1. Manipulative experiments and field sampling
   a. Removal of biomass (e.g., mosses, microbial mats, endolithic rocks) should be minimized.
   b. Material additions to soil, streams, and lakes should have minimum long–term impacts and detectability. For example, additions to soils should have low probability of reaching aquatic environments. For streams and lakes, all chemical additions should be at low concentrations and involve naturally present or biodegradable chemicals.
2. Waste soils and waters from various assays (biological and chemical) should be sterilized and properly disposed of in McMurdo.
3. Use of radioisotopes should be undertaken within enclosures and radioactive wastes removed.
4. Field camp activities should be minimized by restricting the number of field camps.
5. The number of fuel transfers and spillages should be minimized.
6. Contamination from helicopters during landings at field camps and remote sites should be minimized.

Other important environmental concerns are the introduction of exotic species and intersystem species transfers. To minimize the risk, researchers should ensure that aseptic techniques are employed whenever feasible or that separate sampling equipment is used for each site. Deliberate transfers among systems should be avoided.

Potential impacts specific to stream studies are those involved with installation and operation of stream gauges. Installations of flumes and weirs should be at sites judiciously selected to minimize sediment transport. Also, walls should be constructed with sandbags filled with soil from the surrounding stream channel, and concrete-constructed installations should be used only if all other possibilities prove inadequate. Designated paths and crossings should be established at frequently visited gauging sites to minimize disturbance.

Areas of concern for lake studies include maintenance of the chemical and biological regime currently present, especially fine resolution gradients, and the avoidance of biological or chemical contamination. A conservative approach should be adopted. In view of current regulations regarding perturbation of environments in the antarctic, whole-lake manipulations will have to be avoided and any use of enclosures (mesocosms) rigorously designed. A comparative approach involving several lakes is desirable to address certain critical questions, and may, in any event, be necessary in order to fulfill impact-minimization requirements.

Canada Glacier and Lake Hoare, Taylor Valley.

INTERNATIONAL/BIPOLAR ACTIVITIES

The Antarctic Treaty of 1959, establishing scientific inquiry as the principal activity in the antarctic, has resulted in many international research collaborations. This collaboration should continue and be enhanced in the following ways:

1. Workshops should be held periodically for scientists working in the McMurdo Dry Valleys; these should include scientists who work on other antarctic, arctic, and temperate ecosystems.

2. A catalogue of polar deserts in antarctic and arctic regions should be assembled to encourage polar desert research by other scientists in many countries and to create opportunities for cross–fertilization of ideas and collaborative research.

3. A database of long–term data from the antarctic should be created and made available through an international organization such as Scientific Committee on Antarctic Research.

4. An international reference collection of antarctic organisms from both terrestrial and aquatic environments should be established to enhance taxonomic research and to establish a baseline for study of biological invasions that may occur in the future.

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