Linkages between soils and lake ice sediments biogeochemistry : Taylor Valley, southern Victoria Land Antarctica
by Scott Thomas Konley

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Science
Montana State University
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Abstract:
I quantified ammonium (NH4+), nitrate (NO3-), soluble reactive phosphorous (SRP), organic matter and rates of primary production (PPR) associated with terrestrial surface soils and lake-ice sediments within two major lake basins [East Lobe of Lake Bonney (ELB) and Lake Fryxell (LF)] of Taylor Valley, Antarctica. Despite there relatively close proximity, dissolved inorganic nitrogen (DIN=NH4+ + NO3-), SRP ratios indicate phosphorous may limit primary production in the surface soils surrounding ELB (DIN:SRP = 35), while nitrogen may limit the soils of LF basin (DIN:SRP = 2). DIN:SRP ratios were similar between the lake-ice sediment found within the permanent ice covers of the two lakes (DIN: SRP of 2). NH4+ concentration was found to be lower, while SRP concentration was higher between surface soils and lake-ice sediments within ELB basin. In LF basin, NH4+ concentration was higher and SRP concentration was lower between the surrounding surface soil and lake-ice sediments. NO3" concentration was lower between surface soils and sediments in both ELB and LF basins. A higher organic matter content and higher rate of primary production within LF basin suggests that its terrestrial environment is relatively more hospitable. Turnover rates of DIN and SRP within both these environments are on the order of years. Differences in the biogeochemistry between lake basin's may be the result a combination of factors, including climate and palaeoenvironment. The linkage between soil nutrients surrounding these Antarctic lakes and the sediments found within the permanent ice-covers may be important to the colonization and sustainability of microorganisms known to populate the lake-ice habitat.

LINKAGES BETWEEN SOILS AND LAKE ICE SEDIMENTS BIOGEOCHEMISTRY: TAYLOR VALLEY, SOUTHERN VICTORIA LAND ANTARCTICA

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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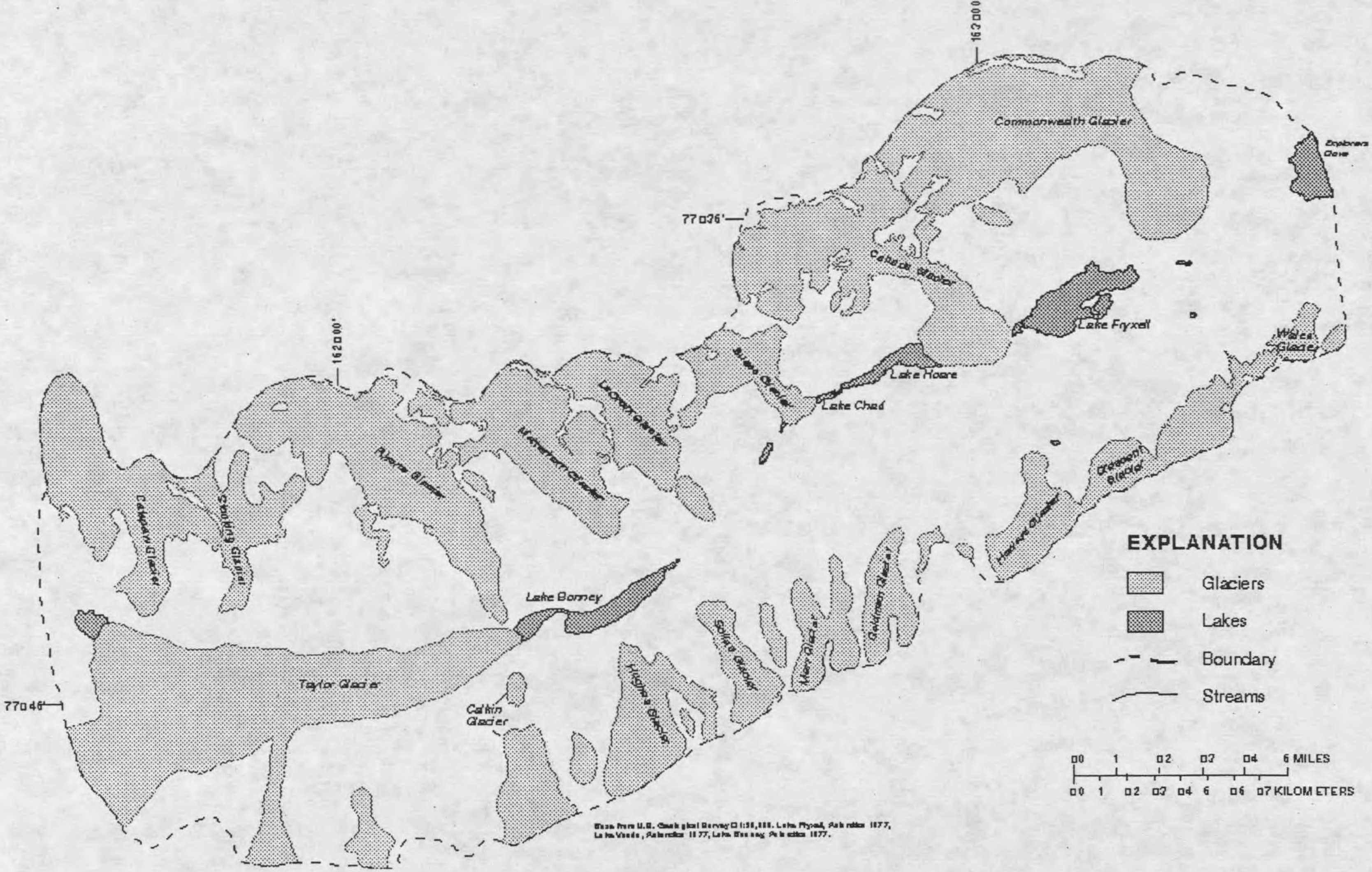
Abstract

I quantified ammonium (NH_4^+), nitrate (NO_3^-), soluble reactive phosphorous (SRP), organic matter and rates of primary production (PPR) associated with terrestrial surface soils and lake-ice sediments within two major lake basins [East Lobe of Lake Bonney (ELB) and Lake Fryxell (LF)] of Taylor Valley, Antarctica. Despite there relatively close proximity, dissolved inorganic nitrogen ($DIN=NH_4^+ + NO_3^-$), SRP ratios indicate phosphorous may limit primary production in the surface soils surrounding ELB (DIN:SRP = 35), while nitrogen may limit the soils of LF basin (DIN:SRP = 2). DIN:SRP ratios were similar between the lake-ice sediment found within the permanent ice covers of the two lakes (DIN:SRP of 2). NH_4^+ concentration was found to be lower, while SRP concentration was higher between surface soils and lake-ice sediments within ELB basin. In LF basin, NH_4^+ concentration was higher and SRP concentration was lower between the surrounding surface soil and lake-ice sediments. NO_3^- concentration was lower between surface soils and sediments in both ELB and LF basins. A higher organic matter content and higher rate of primary production within LF basin suggests that its terrestrial environment is relatively more hospitable. Turnover rates of DIN and SRP within both these environments are on the order of years. Differences in the biogeochemistry between lake basins may be the result a combination of factors, including climate and palaeoenvironment. The linkage between soil nutrients surrounding these Antarctic lakes and the sediments found within the permanent ice-covers may be important to the colonization and sustainability of microorganisms known to populate the lake-ice habitat.

CHAPTER 1

INTRODUCTION

The continent of Antarctica has provided unique opportunities for exploration and science, from the time of its discovery in 1773 by James Cook. Considered the last great wilderness on Earth, Antarctica's ecosystems are unprecedented. Perhaps the most intriguing aspect of the continent is the McMurdo Dry Valley region, a polar desert located just west of the East Antarctic Ice Sheet within the transantarctic mountain range. These dry valleys represent the only ice-free area of the continent (~2%) and have been the subject of intense study since the establishment of permanent scientific stations during the International Geophysical Year of 1957. The diverse geomorphology of the region includes coastal lowland and marine terraces, entrenched inland and coastal valleys with steep sides and long narrow floors, upland valleys, wide cirques, broad plateaus and high mountains (Campbell et al., 1998). Many of these valleys contain lakes of various physical qualities. Four basic types of lakes have been described within dry valleys, wet based lakes, where liquid water exists under a permanent ice cover, dry based lakes, which are frozen to the bottom (i.e. no liquid water), seasonally frozen lakes, and finally, lakes that never freeze because of ultra-high salt concentration (Hendy 2000). Notable features of dry valley soils include the widespread occurrence of a pebble or boulder surface pavement, a soil form that is dominated by coarse but extremely variable textures, lack of cohesion and soil



Base from U.S. Geological Survey □1:50,000. Lake Fryxell, Antarctica 1977, Lake Vanda, Antarctica 1977, Lake Bonney, Antarctica 1977.

Figure 1. Base map and location of glaciers in Taylor Valley, Antarctica.

structural development, very weakly developed chemical weathering, wide variations in salinity, and the existence of either ice-cemented or non ice-cemented permafrost at variable depth (Campbell et al., 1998).

The Taylor Valley, in particular, has received a lot of attention (Figure 1). It is the location of an interdisciplinary Long Term Ecological Research effort that provided the framework for this thesis. Located at 77°45' – 77°30' south latitude 162° – 163°40' east longitude the Taylor Dry Valley lies in the middle of the McMurdo Dry Valley system and contains three major lake basins created by advancing and retreating glaciers. The west-east trending valley broadens towards the coastline until opening into the McMurdo Sound. In addition to the terminal Taylor Glacier at the head of the valley, there are numerous alpine glaciers descending from the surrounding mountains. During the summer months when temperatures in the valley may exceed zero °C, these glaciers provide meltwater to the lakes. These feeder streams typically flow only for six to eight weeks during the summer, and streamflow is highly variable on an interannual as well as daily basis (Conovitz et al., 1998). However, the lack of precipitation (snow <10 cm yr $^{-1}$), low average temperatures (~ -20 °C), and low relative humidity (<50%) make the McMurdo Dry Valleys, Antarctica, one of the coldest, driest, and most biologically inhospitable environments on Earth (see Table 1, Priscu et. al., 1998). Despite the extreme aridity and cold, functioning biological communities do exist in many habitats (Priscu et. al., 1998). The three major lakes in the Taylor Valley (Lake Fryxell, Lake Hoare and Lake Bonney) contain liquid water under a permanent ice-cover, the existence of which is unique to the Antarctic continent. Landscape positions,

Table 1.1. McMurdo Dry Valley averages and extremes in selected meteorological parameters. Data are from 1985-2000 and represent information for Taylor, Victoria and Wright valleys (Priscu et. al. in press).

Paramater	Value
Surface air temperature (°C)	
average mean annual	-27.6
absolute maximum	10.0
absolute minimum	-65.7
Degree days above freezing	
mean annual	6.2
Soil temperature at surface (°C)	
average mean annual	-26.1
absolute maximum	22.7
absolute minimum	-58.1
Surface wind speed (m s^{-1})	
average mean annual	4.1
maximum	37.8

defined by the physical environment and glacial history of the valley have substantial impact on the local climate conditions and lake levels within the basins.

In the Taylor Valley, glaciations are subdivided into: “Taylor Glaciations”, originating from the East Antarctic Ice Sheet west of the Transantarctic Mountains, “Ross Sea Glaciations”, originating from an ice sheet grounding and filling McMurdo Sound to the east of Taylor Valley, and “Alpine Glaciations”, resulting from an expansion of local alpine glaciers on the Asgard Range and the Kukri Hills to the north and south of the valley (Hendy et. al., 1979). In high latitudes, warmer temperatures increase the activity of glaciers, providing more water to the hydrologic system, increasing lake levels (Fountain et. al., 1998). Past shorelines are preserved on steep sidewalls in the valley and attest to lake levels having been considerably higher in the recent past (Hendy, 2000). On one occasion in the past (~22,000 yr BP), it is thought that a single lake occupied the entire valley, dammed by an ice sheet occupying McMurdo Sound. This lake has been termed "Glacial Lake Washburn" and the natural legacy of its sediment is just beginning to be understood (Doran et. al., 1999). Recently Burkins et. al. (2000) concluded that isotopic signatures of Soil Organic Matter ($\delta^{13}C$ and $\delta^{15}N$) found at low-elevations in Taylor Valley, Antarctica are best explained as relict of signatures from Late Wisconsin (~ 40,000 yr BP) paleoenvironments. In other words, yesterday's mud is a component of today's soil!

Taylor Valley soils and stream sediments contain simple communities of nematodes, rotifers, and tardigrades (Freckman and Virginia 1998). Nematodes dominate the communities and are most abundant within stream channels relative to the surrounding soils (Treonis et. al., 1999). Soil respirations rates, using a maximum 60 days of productivity, are estimated to be 17.8 mg C m^{-2} d^{-1}, one of the lowest reported values for terrestrial ecosystems (Burkins et. al., 2001).

Taylor Valley is divided into an upper and lower section separated by the 800 meter high Neusbaum Regal located in the center of the valley. Meteorological data collected as part of the McMurdo Long Term Ecological Research efforts clearly show that Lake Bonney (upper section) experiences a more continental climate strongly influenced by katabatic winds, while Lake Fryxell (lower section) experiences a more marine climate (Lyons et. al., 2000; see also Fountain et. al., 1998). The difference in climatic regimes between the lake basins has important effects on glacial stream flow, surface albedo, soil biota and chemistry, and the ecology of the lakes.

My study focuses on biologically important inorganic nutrients in the terrestrial environment surrounding two principle lakes and the sediment trapped within their permanent ice-covers on the lakes within the above two basins, Lake Fryxell and the East Lobe of Lake Bonney. These two particular lakes were chosen because Lake Fryxell basin has more particulate organic carbon, streams, and moisture associated with its terrestrial environment than the East Lobe of Lake Bonney basin, providing a basis for a comparative study. These nearshore surface soils are perhaps the most important and least studied environment in this ecosystem. In general, soils exert considerable influence on the ecology and play many key rolls in terrestrial ecosystems. They provide valuable habitat for microbial life and their globally important biogeochemical reactions responsible for the cycling of biologically essential nutrients. The rate at which these and all chemical reactions proceed is a direct function of temperature and in this polar desert environment the availability of water is critical. The thermal regimes of the dry valley soil is extreme because of the absence of the sun's radiant energy for several months in the winter and its continued presence in the summer. Organic matter associated with soil is a major terrestrial pool for C, N, P, and S, while the active microbial component of soil is an essential component in the global recycling of these elements. The quantity of soil organic matter is dependent on the balance between primary productivity and the rate of decomposition. This study includes one of the first attempts to quantify primary production by photoautotrophs in dry valley, Antarctic soils.

Dissolved inorganic forms of nitrogen (DIN= NH_4^+ + NO_2^- + NO_3^-) and phosphorous (PO_4^{-3}) in soils constitute the base of essential biological components of

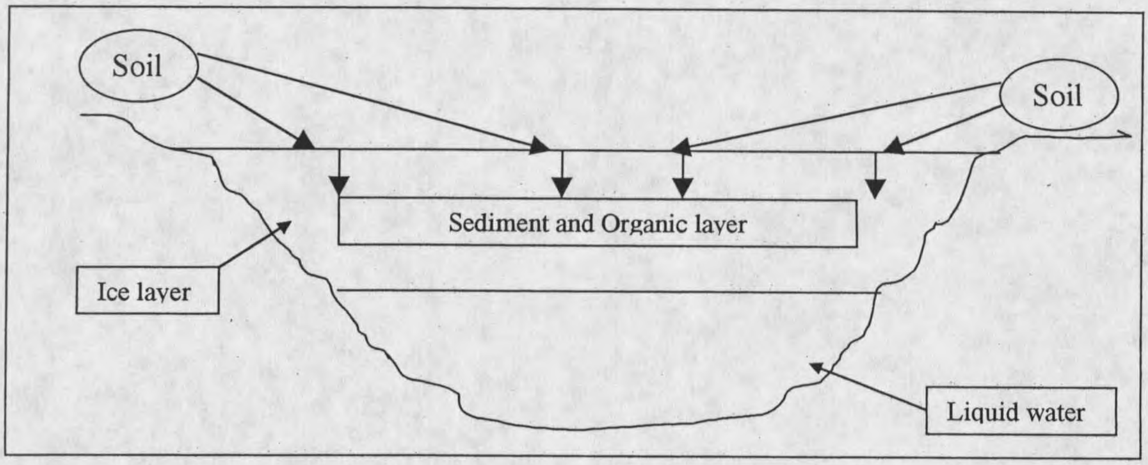


Figure 1.2. Conceptual model of processes that form the basis for my research.

soil microorganisms, including proteins, microbial cell walls, and nucleic acids. The availability of these important nutrients are necessary for life to exist in a given environment; therefore, nutrient availability provides an important indicator of environmental potential. DIN: Phosphate ratios are repeatedly used to predict nutrient deficiency in both terrestrial and aquatic systems. Furthermore, the stocks, fluxes and turnover rates of materials within ecosystems are fundamental parameters defining an ecosystem's structure, function and dynamics (Molles 1999).

In desert ecosystems, such as those found in the McMurdo Dry Valleys, Antarctica, the absence of higher plants and mosses exposes the surface soil to aeolian transport. Some of the soil blown by the wind finds its way onto the surface of lakes. The dynamic nature of the ice surface allows for the accumulation of soil in cracks, depressions, and against ridges (Priscu et. al., in press). Eventually some of this soil melts into the 4-6m thick ice cover creating a layer of sand and associated organic matter of aeolian origin, and liquid water below the surface (Figure 1.2). It is currently thought that this layer represents a dynamic equilibrium between downward movement of sediments as a result of melting during the summer and upward movement of ice from ablation at the surface and freezing at the bottom (Priscu et. al., 1998). DNA sequences of 16s rRNA within this layer of sediment in the East Lobe of Lake Bonney ice cover, showed that they most closely resemble the bacterial composition of the soils and do not resemble prokaryotic DNA signatures within the water column (Priscu et.al. 1998, Olson et.al. 1998). Gordon et.al. (2000) used oligonucleotide probes to demonstrate the presence of a diverse microbial community dominated by cyanobacteria in the lake ice, and that the dominant members of the lake ice microbial community are found in nearby terrestrial cyanobacterial mats. These molecular band results imply that the microbial populations found within the ice have terrestrial origins. Investigations into the trophic dynamics associated with the sediment aggregates revealed a complex cyanobacterial-bacterial community, concurrently conducting photosynthesis, atmospheric nitrogen fixation, decomposition, and biogeochemical zonation needed to complete essential nutrient cycles (Paerl and Priscu, 1998). Because the ultimate source of the inorganic nutrients NH_4^+ and NO_3^- associated with lake ice sediment is the surrounding surface soil, it can be assumed physical and/or biological processes are responsible for any concentration differences between environments.

The focus of this investigation is to determine the linkage between the terrestrial environment and the lake-ice habitat within Taylor Valley, Antarctica. My investigation focused on the comparison of key biogeochemical compounds essential to the survival and growth of microbial populations within both of these environments. This study logically follows from and builds on the work of pervious investigation.

Nutrient concentrations clearly affect phytoplankton productivity in Antarctic lakes (Priscu, 1995; Dore and Priscu 2001), yet very little is known about nutrient dynamics and its control on terrestrial life or that within the lake ice. With increasing interest in life beyond Earth, the McMurdo Dry Valleys, Antarctica, represent the closest Earthly analogs to Martian and Europon (A moon of Jupiter) environments (Priscu et. al., 1998). Therefore, my study is also relevant to the possibilities of life beyond our own planet. The following hypotheses focus on a comparison of inorganic nutrients and organic matter dynamics in terrestrial surface soils and lake-ice associated sediments between two lake basins.

Multiple hypotheses

Hypothesis 1

Aeolian transported inorganic soil nutrients contribute to the sustainability and colonization of the lake-ice ecosystem.

To address this hypothesis the nutrients NH_4^+, NO_3^-, and Soluble Reactive Phosphorous (SRP), within both the terrestrial surface soils and sediments contained within ice cores, were quantified. Aside from the paucity of liquid water in these environments, one or more of the above nutrients is likely to be a growth-limiting factor. The results between the two environments are compared within and between lake basins.

Hypothesis 2:

Organic matter accumulations are greater within the lake ice habitat than the surrounding soils.

Organic matter associated with soil in this environment represents both a legacy of past lakes and present-day *in situ* production. I believe that the lake-ice habitat provides a clement refuge for soil microorganisms that allows biological production to proceed at a faster rate than in the surrounding terrestrial surface soil environment

Hypothesis 3:

Photoautotrophic activity contributes to the overall carbon dynamics within Taylor Valley soils.

To address this hypothesis microbial photoautotrophic activity associated with the terrestrial soil was quantified within each lake basin and results compared. In most ecosystems, including this polar desert, sunlight provides the ultimate source of energy to power all biological activity. The production of organic molecules by microorganisms capable of photosynthesis represents the only new source of heterotrophic substrate within the ecosystem. Therefore, the potential for *in situ* production within the soils is important for understanding the carbon dynamics of this polar desert.

Hypothesis 4:

Interbasin differences in the biogeochemistry between surface soil and lake-ice habitats occur in the Taylor Valley.

This hypothesis was tested by sampling surface soils and lake-ice sediments from the major lake basin in both the upper and lower halves of the Taylor Valley were the sampled. Due to this design and the specific biogeochemical factors quantified, a reasonable inference about the different controlling constituents was made.

Materials and Methods

Sample collection and processing

Soil and ice core samples were collected during November and December 2000. Bulk (~ 4.0 kg) soil samples were collected from previously established transects (Fritsen et. al. 2000) around the East Lobe of Lake Bonney and Lake Fryxell, respectively. Samples were taken from 10 soil transects around Lake Fryxell and 11 around East Lobe of Lake Bonney. Transects were intentionally chosen to be in areas that did not coincide with the locations of ephemeral streams or ponds. Four samples were taken per transect at ~ 50 meter intervals with a plastic scoop and sealed in clean plastic bags by folding and stapling the top. All soil-sampling locations were recorded with a hand-held Garmin 45 Global Positioning System accurate to within 15 m. Only the top 2 cm of soil was collected because this is the portion most available for aeolian transport to the surface of the lake ice. After collection, soils were kept dark and frozen until processed.

Processing of soils consisted of separation by hand sieving in the field or with an automatic sieve shaker in a 4 °C environmental room, into four size classes: > 2000μm, 297-2000μm, 63-297μm, and <63μm corresponding to course, medium, fine grain sands, and silts/clays. Each fractions ambient weight was recorded. Gravel > 5 mm in diameter was removed from the >2000μm fraction (this portion is not commonly transported by wind). Subsamples of all size classes were removed and placed in 20 ml scint vials for nutrient and organic matter assays at Montana State University while the majority of the samples were placed into whirl-pac bags, kept dark and frozen (-20 °C), and shipped to the United States via a sea going vessel, then over land to Montana State University.

Ice cores were collected from 10 x 10 m plots located along a longitudinal or latitudinal transect across the ice cover of the East Lobe of Lake Bonney and Lake Fryxell. Using a 10 cm SIPRE coring device equipped with a Badger power head, five cores were taken from five plots established on both ice covers for a total of 50 cores (25 from East Lobe of Lake Bonney, 25 from Lake Fryxell). In all cases, cores were taken to a depth of 3.5 - 4.0 m to ensure the capture of all the sediment within ice cores. Only the portion of core that contained visible sediment inclusions was collected for analysis. Cores were kept frozen and shipped to the United States, then to Montana State University where they were placed in a –20 °C freezer until processing.

Processing of the ice cores consisted of cutting into 50 cm intervals from the surface followed by melting at room temperature overnight in 4 L HDPE Nalgene bottles. After all ice had melted, ~ 60 mL of melt-water was subsampled and the remaining melt-water was removed from the settled sediment with a Fisher Scientific gast lubricated rotary vane-type vacuum pump equipped with a glass tube. Following removal of excess melt-water, sediment was transferred to pre-weighed 70 mL aluminum weighing dishes and dried for 24 hours at 105 °C. After drying, dishes were reweighed and mass of sediment was quantified by subtraction. At this point, a 1-5 g subsample of sediment was removed for organic matter quantification. The remaining sample was separated by hand sieving into four size classes, >2000μm, 250-2000μm, 61-250μm, and <61μm, comparable to the separation of the soils. Size fractionated sediments were placed into whirl-pac bags and set aside for nutrient assays.

Nutrient assays

All nutrient assays (NH_4^+, NO_3^-, and SRP) followed standard protocol found in the McMurdo Long Term Ecological Research Limnological methods manual (Priscu and Wolf 1998, www.homepages.montana.edu/~lkbonney). Ammonium concentration was determined using a modified indophenol-blue method, SRP concentration was determined with a mixed molybdate method, and finally the NO_3^- procedure used was based on reduction to NO_2^- with spongy cadmium with subsequent NO_2^- analysis. For all assays 2 g of soil/sediment was leached in 50 mL DIW added to acid washed (0.1 N HCl) 125 mL Erlemeyer flasks and shaken for 1 h on a wrist action shaker. Leachate was filtered through 47mm Whatman GF/C filters using a bell-jar filter apparatus and a Fisher Scientific vacuum pump. Filtrate was captured in 50 mL polypropylene conical tubes and stored at 4 °C. No sample was stored for more than 24 hours before assaying for specific nutrient concentration. Colorimetric analysis was done with a 1 cm light path cuvette and a Varian DMS 80 UV-Visible spectrophotometer. Raw absorbance for NH_4^+, NO_3^-, and SRP were read at wavelengths of 640 nm, 543 nm, and 885 nm, respectively. Concentrations were determined using standard curve regression equations prepared the same day as analysis. Working standards were checked for variation against fresh standards several times over the course of running samples.

Organic Matter

Organic matter in 1-5 grams of dried (24 h at 105 °C) surface soil and lake ice sediment sample was determined using a modification of the Loss-On-Ignition (LOI) Method described by Ben-Dor and Banin (1989) found in SSSA's "Methods of Soil Analysis". Samples were placed in preweighed combusted (2 h at 400 °C) aluminum weighing dishes reweighed and ignited for 16 h at 400 °C. Percent organic matter in samples was determined using the following relationship:

$$\text{LOI, } (\%) = [\text{Weight}_{(105)} - \text{Weight}_{(400)} / \text{Weight}_{(105)}] * 100$$

Photoautotrophic Activity

Soils used for this portion of the study were collected in the Antarctic summer of 1995 as part of a previous study (Fritsen et.al., 2000). Samples were kept in 20 mL scintillation vials at –20 °C until used. Photoautotrophic activity was quantified using a Biological Oxidizer (R.J. Harvey model OX-300). For most of these experiments, eight one-gram soil samples from each location were placed into 20 mL scintillation vials with 2 mL DIW and 4.02 µCi $NaH^{14}CO_3$. All samples were incubated at 10 °C for 24 hours. Four of the vials were placed lying on their sides, exposed to a light source, and the other four were wrapped in several layers of tin foil and placed into a small cardboard box to insure no exposure to the light source. Following incubation, the liquid was removed from the soil with a syringe and placed into a serum vial for determination of dissolved inorganic carbon (DIC), obtained DIC was measured by acid sparging and subsequent infrared analysis of CO_2 released from the sample. Soil samples were acidified with 0.5 mL 6.0 N HCl and dried on a hot plate before running through a Biological Oxidizer (B.O.). Efficiency of the B.O. was monitored during runs by combusting mannitol with a known amount of ^{14}C-Glucose (Sigma Lot# 099F9235). Glucose was calibrated using a ^{14}C-Toluene STD (DuPont Lot# 0060686A). Samples were counted on a Beckman LS-100C Liquid Scintillation System. LS-100C counting efficiency was predicted for each sample using the channels ratios method calibrated with a quench curve prepared with acetone quenched ^{14}C-toluene standards.

CHAPTER 2

NUTRIENT CONCENTRATIONS WITHIN SURFACE SOIL AND PERMANENT ICE-COVER ASSOCIATED SEDIMENT IN EAST LOBE OF LAKE BONNEY BASIN, TAYLOR VALLEY, ANTARCTICA

Introduction

The Taylor Valley is 33 km long and runs along a SW to NE axis (Figure 1). Lake Bonney basin is approximately 30 km inland and the lake is divided into an east and west lobe separated by a 13-m deep sill that runs along a regal. The East Lobe of Lake Bonney icy surface covers ~5 km^2 and is ~4.5 m thick. Several recent investigations have focused on sediment inclusions within the ice cover of this lake showing the existence of an active microbial component with the capacity to carry out diverse metabolic processes (Priscu et. al., in press; Priscu et. al., 2000, Paerl et.al., 1998, Olson et.al., 1998; Fritsen and Priscu 1998).

The local climate of the East Lobe of Lake Bonney basin is clearly more continental (warmer, drier conditions) compared to the climate further down valley in the Lake Fryxell basin (closer to the ocean) (Fountain et. al., 1998). The majority of the soils surrounding the East Lobe Lake Bonney are soils of lateral moraines developed in sediments lain down by both ancient glaciations and ancient lacustrine stands (Burkins et. al., 2000) with moderately developed polygons and weak to moderate development of surface pavement (Fritsen 2000) and classified as Pergelic Cryorthents (Pastor &

Bockheim, 1980). Surface soils are subjected to frequent freeze-thaw cycles, while the soil below about 30 cm remains frozen. The permafrost layer is about 300m thick. There are relatively few streams entering East Lobe of Lake Bonney (McKnight et.al., 1998). Unlike other lakes in the valley, microbial mats are not abundant on the soil immediately adjacent to the lake. The large-scale spatial distribution of soil microbial life within the lake basin is uncertain, but the soils of the Taylor Valley are known to support a diverse group or organisms, including algae, bacteria, fungi, yeasts, protozoa, and nematode communities. Until recently the origins of organic matter driving these communities was unknown. Significant new evidence supports a legacy model, wherein organic matter was deposited as both entrained organic detritus in glacial till and as primary productivity in ancient glacial paleolakes (Burkins et. al. 2000; Lyons et. al., 2000). The largest assessment of surface soil organic matter to date was reported by Fritsen et. al. (2000). Fritsen et. al. (2000) addressed organic carbon and nitrogen with no emphasis on inorganic, biologically important nutrients. My study addresses the stocks of NH_4^+, NO_3^-, and Soluble Reactive Phosphorous (SRP), in surface soils

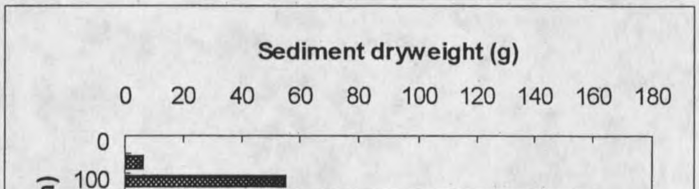


Fig. 2.1. Distribution of sediment through the ice cover of ELB. Depth is relative to surface of ice (0 cm surface). All size fractions included.

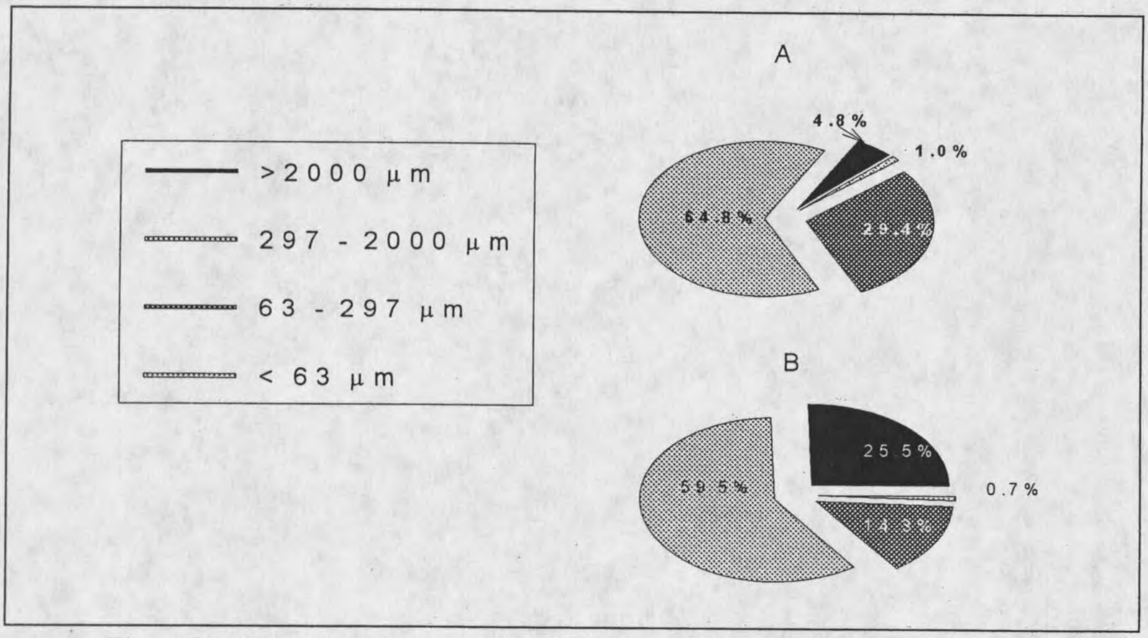


Figure 2.2. Proportion of surface soil and lake-ice sediment dryweights within each size class. (A) Lake Ice sediment. (B) Surface soil.

available for aeolian transport, therefore, potentially contributing to the nutritional requirements of microbial life within the lake-ice ecosystem. I also address the stocks of these nutrients associated with sediment inclusions within the ELB lake-ice ecosystem, allowing an assessment of factors affecting microbial nutrition between the two environments and the spatial distribution of NH_4^+, NO_3^-, and SRP throughout the environment.

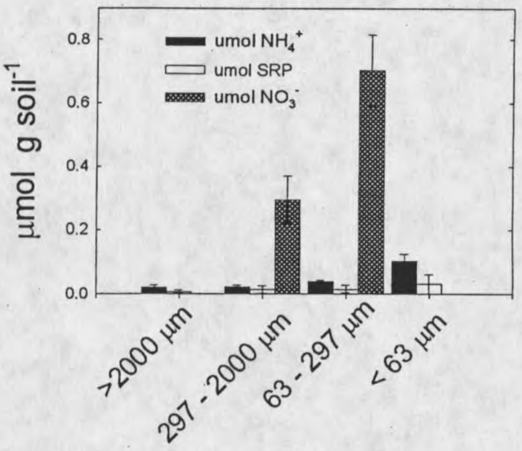


Figure 2.3: Inorganic nutrients associated with specific size classes of soil surrounding ELB. Top of bar is the mean value of all data combined. Error bar is the standard error of the mean.

Results

A majority (85%) of the sediment associated with ELB ice-cover was found 150 - 300 cm from the surface (Figure 2.1). There was no visible accumulation of sediment above 50 cm and rarely (only two cores) any found above 100 cm. These samples were from the northern most sampling site which consequently receives the least amount of direct radiation from the sun because of the steep topography and mountains to the north of the lake (personal observation). There was only one occasion were there was no visible sediment within a core taken to approximately 4.0 meters; the location of this core sample also happened to be one of the 5 taken in the northern most plot.

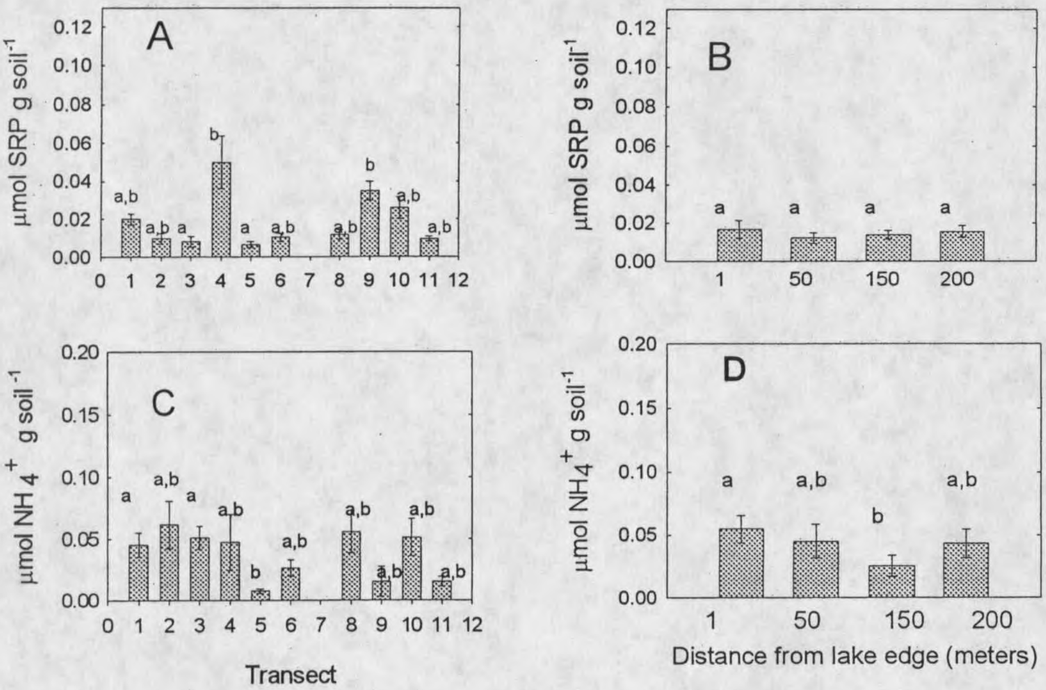


Fig. 2.4. Spatial distribution of soil nutrients by transects (A&C) or distance from lake edge (B&D). Means with the same letter are not significantly different from one another at $P < 0.05$. Error bars are one standard error of the mean.

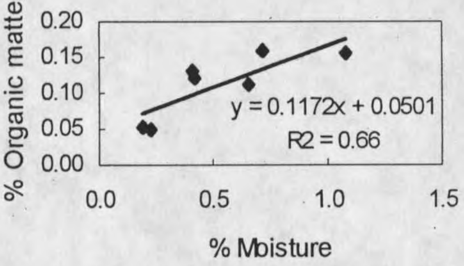


Fig. 2.5. Scatterplot and linear regression between soil organic matter and soil moisture of selected samples from the East Lobe Lake Bonney Basin.

Of the soil sampled in this study 99.3% by weight was sand with the remaining 0.7% being silts/clays (Figure 2.2). The course sand (>2000μm) fraction accounted for 25.5% of the total sand fraction of terrestrial soils. Of the sediment sampled from ice

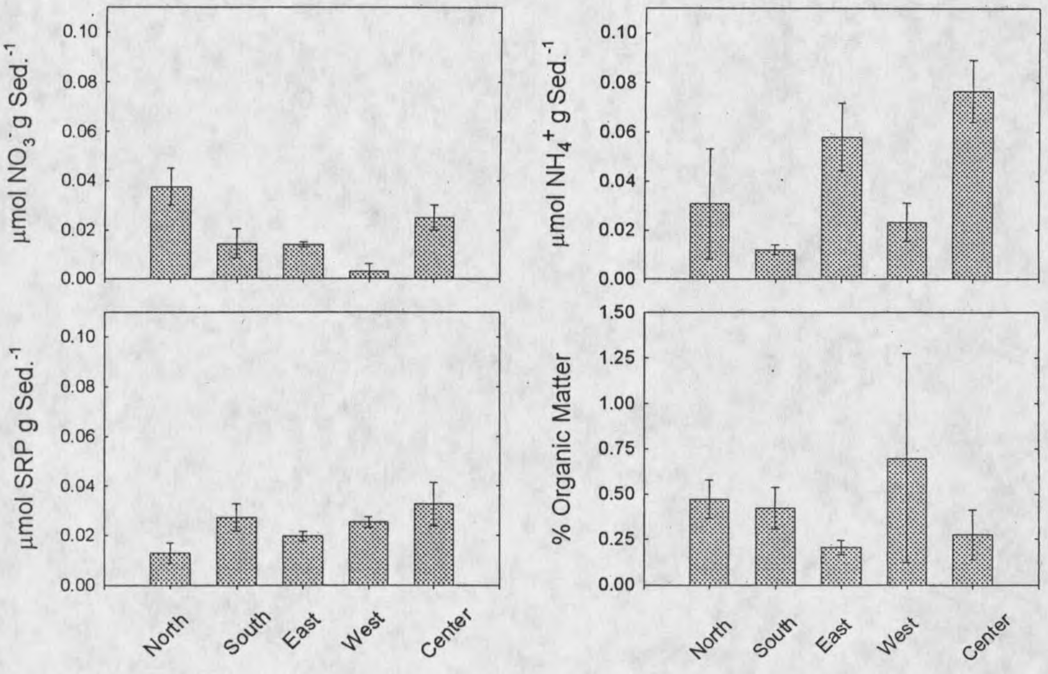


Fig. 2.6. Spatial distribution of nutrients associated with the sediment found within East Lobe Lake Bonney ice cover. The x-axis represents compass direction within 10x10m plots relative to one another across the ice cover. Means are not significantly different from one another at $P < 0.05$. Error bars are one standard error of the mean.

cores 99.0% fell within the sand fraction and 1.0% was silts/clays. Of the 99.0% sand fraction only 4.8% of it was course owing to the greater wind velocities necessary for the transport of this fraction to the surface of the lake.

The pH and electrical conductivity of terrestrial soils averaged 8.11 and 396 µmhos cm^{-1}, respectively, where the pH and electrical conductivity of the sediments are significantly different averaging 5.46 and 14.64 µmhos cm^{-1} (t-test $P<0.05$). The < 63 µm sized soil particles had significantly greater NH_4^+ concentration than the two largest size fractions, but did not differ significantly from the 63 – 297 µm size particles (Figure 2.3). SRP concentration is significantly greater in the <63 and 63 – 297 µm than the >2000 µm soil, but do not differ significantly from each other or from 297 –

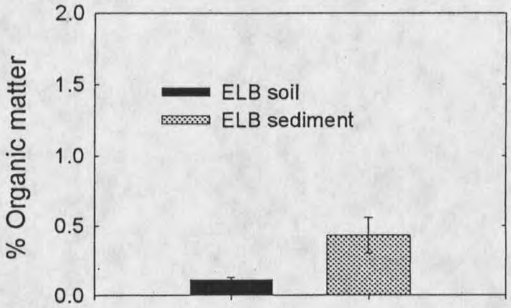


Fig. 2.7. Organic matter content between terrestrial soils and lake ice associated sediment. There is a significant difference between mean values. Error bars are one standard error of the mean.

2000 μm size fraction. NO_3^- concentrations were only determined for the 297 – 2000 μm and 63 – 297 μm soil sizes which account for 94.2% of the sediment weight associated with ice cores. Significant differences were observed between these sizes of soil with respect to NO_3^- concentration.

Concentrations of NH_4^+, NO_3^-, and SRP ranged form 0.10 - 0.020 μmol g^{-1} soil, 0.30 – 0.70 μmol g^{-1} soil, and 0.005 – 0.030 μmol g^{-1} soil, respectively. In all cases, this range is from largest to smallest sized particles. Mean NO_3^- concentrations in the two size particles assayed, was over an order of magnitude greater than the NH_4^+ concentrations observed in those same particle sizes. The DIN: SRP ratio in the 297 – 2000 μm size fraction was 24:1 and 50:1 in the 63 – 297 μm size particles.

There is no clear trend concerning the spatial distribution of either NH_4^+ or SRP associated with the soil around the lake at the scale sampled in this study (Figure 2.4 A&C). On the other hand, there is significant variation between transects with respect to both nutrients (ANOVA; Ammonium P = 0.002, SRP P = <0.001). SRP

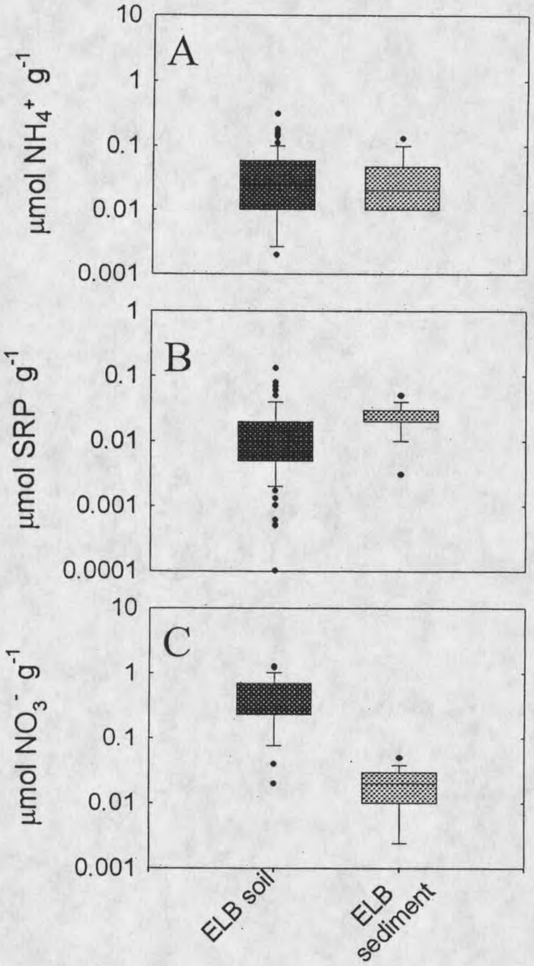


Fig. 2.8. Box and whisker plots of NH_4^+ (A), SRP (B), and NO_3^- (C), concentration between terrestrial soils and lake-ice associated sediments. Horizontal line in the box is the median, the upper and lower ends of the boxes denote the 25th and 75th percentiles, and error bars mark 10th and 90th percentiles. Circles are individual data points outside the 10th and 90th percentiles. Note that the y-axis is a log scale.

concentration did not vary with respect to distance from lake edge (ANOVA $P = 0.586$) where ammonium concentrations did (ANOVA $P = 0.035$; Figure 2.4 B&D). The highest concentrations are found closest to the shore of the lake (Figure 2.4 B & D). ANOVA revealed no significant difference in transects grouped according to the directional location (e.g. North or South side of the lake). Nitrite (NO_2^-) was undetectable in 26 of 30 samples and considered an insignificant constituent in this study. Organic matter associated with the soil is low, ranging from 0.0490 – 0.159 %. Over 66% of the variability in organic matter can be explained by soil moisture content (Figure 2.5).

Similar to the soil, there is no clear trend concerning the spatial distribution of nutrients about the ice cover of ELB (Figure 2.6). Ammonium concentrations associated with the sediments are the most variable, ranging from 0.012 – 0.077 μmol NH_4^+ g^{-1} sediment. Despite this range between plots, none of the differences are significant. Total sediment per ice core was highly variable in 24 ice cores that contained visible sediment, ranging from 0.034 – 61.925 g sediment $core^{-1}$. Ten of 24 cores taken had less than 6 grams total sediment. Combining all data across the ice cover resulted in sufficient sample sizes to draw conclusions when comparing terrestrial soils and ice-associated sediments.

NH_4^+ concentration did not change significantly between soils and sediments (t-test, $P = 0.518$; Figure 2.8A). NO_3^- concentration changed by over an order of magnitude, significantly decreasing from a mean of 0.49 μmol NO_3^- g^{-1} in the terrestrial soils to 0.018 μmol NO_3^- g^{-1} sediment (t-test, $P < 0.001$; Figure 2.8C). The mean SRP concentration in the sediment was 0.025 μmol g^{-1}, 2-fold greater than 0.015 μmol SRP g^{-1} soil (t-test, $P<0.001$; Figure 2.8B). Organic matter content increased 4-fold from soil to ice associated sediment from a mean value in the soil of 0.11 to that of 0.43 per unit weight in the sediment (Figure 2.7).

Photoautotrophic activity spanned four orders of magnitude in the 11 samples subjected to experimentation. Rates ranged from 1.25 – 0.00012 μg C g^{-1} d^{-1} with the highest rate being 2 orders of magnitude greater than the next highest rate. This value was omitted for comparisons, giving a mean value of 0.0066 μg C g^{-1} d^{-1}.

Discussion

The lack of clear trends regarding the spatial distribution of soil-associated nutrients around East Lobe Lake Bonney was not surprising; all the soils sampled have presumably been subjected to the same environmental conditions for similar periods of time. Furthermore, soil transects were intentionally chosen so environmental gradients, such as ephemeral ponds and streams, where soil moisture, pH, conductivity, organic carbon, chlorophyll *a* and total nitrogen, can change abruptly (e.g. see Treonis et. al. 1999, Barrett et. al. 2002) would not be crossed or sampled.

Significant variation between transects is apparent (Figure 2.4 A&C) - the exact nature of this variation, however, is not certain. Differential physical and/or biological processes (past and present-day) involved in the modification and sorting of materials between specific sampling locations may contribute to the differences observed.

Moreover, it is hard to draw any hard conclusions about the distribution of nutrients associated with lake-ice sediment because of the small sample sizes between plots across the ice cover. In most cases, only one or two of the 5 cores contained enough sediment to quantify all properties giving a sample size of 2 or 4 at each location. Nonetheless, if the soils surrounding the lake are indeed the source of sediments in the ice and there are no clear trends with respect to spatial distribution there, it makes reasonable sense that the sediments will all be similar in biogeochemical nature.

The presence of high NO_3^- concentrations relative to NH_4^+ in the soil around ELB is most likely due to the atmospheric deposition of marine aerosols directly or indirectly, by snow blowing into the valley from the inland ice sheet (Campbell et. al., 1998). The lack of precipitation (rain or snow) - and therefore leaching - along with the age of the soils provides the ideal situation for the accumulation of these salts. It seems clear from the data that the abiotic process of NO_3^- deposition dominates over any biological control of N-cycling in surface soils surrounding the East Lobe Lake Bonney. Biological control of N-cycling within this basin is likely restricted to ephemeral stream margins and soils adjacent to alpine glaciers where soil moisture status is greatly enhanced.

NH_4^+, being the fully reduced state of nitrogen, is biologically preferred and energetically favorable to that of NO_3^-. Present day, or more likely, historic microbial activity associated with paleolakes that covered today's soil could also be responsible for the transformation of nitrogen species. The dissolved inorganic nitrogen (DIN) ($NH_4^+ + NO_2^- + NO_3^-$): SRP ratio in the terrestrial soil around the East Lobe of Lake Bonney from the above data is estimated at 35, greatly exceeding the ratio for balanced growth (see Paul and Clark 1996, Redfield 1958). After the soil is blown onto the surface of the lake and migrates down forming a sediment inclusion within the ice cover the DIN:SRP ratio drops considerably, to 2, indicative of nitrogen deficiency; due principally to the decrease in nitrate concentration and an increase in SRP between the two environments.

There are several possible explanations for significant decrease in NO_3^-, none of which were addressed in this study: (1) Nitrogen species associated with wind blown soils are leached out and aerosolized in an initial melt-water pool before migrating to depth in the ice. (2) These ions are excluded from the ice during the freezing process. (3) Upon being exposed to liquid water, biologically activity commences and quickly consumes the nitrogen species associated with the sediment. Denitrification, assimilatory reduction, and dissimilatory reduction activities could potentially all play a role in the loss of NO_3^- between surface soil and lake ice sediment. These findings are consistent with that of others. For example, Pearl and Priscu (1998) suggest, in response to bioassay experiments with ice-associated sediment from ELB, that CO_2 fixation may be limited primarily by N, and secondarily by P availability. When added individually, nitrogen in the form of NO_3^- led to the greatest degree of stimulation. NH_4^+ was not considered as a nitrogen source in these experiments. Olson et. al. (1998) suggested that N availability might be a limiting factor in this environment based on the presence of a diverse diazotrophic community: a community that would have a distinct advantage in a N-limited environment. The decrease in pH from soil to lake-ice sediment observed in this study is further evidence of N-fixing activity. Atmospheric nitrogen fixed to NH_4^+ could be transformed by, assimilation, ammonification and nitrification activities, directly affecting the pH in the environment.

The fact that NH_4^+ concentrations are the same between environments is difficult to explain (Figure 2.6A). Because it is the more energetically favorable reduced form of nitrogen, one would expect, in a nitrogen limited environment that NH_4^+ would be preferred over NO_3^-, therefore decreasing in the more favorable lake ice environment relative to NO_3^-. Conversely, if uptake and regeneration of NH_4^+ were equal within the lake-ice a given concentration would be maintained.

The increase of SRP from the surface soil to the lake-ice sediment may result from several mechanisms (Figure 2.6B), none of which were addressed directly in my study. (1) Soil PO_4^{-3} in minerals may be mobilized by microbial activity in the sediment and more easily extracted by water. (2) Mineralization of organic PO_4^{-3} containing compounds may occur more regularly in the lake-ice habitat being made available in solution. (3) Increased organic matter and the lower pH of the lake-ice sediment may also have affects on the amount of PO_4^{-3} available. The fact that SRP concentrations increase in the lake-ice relative to the terrestrial soil is yet further evidence that nitrogen is a limiting nutrient on primary production in the lake-ice ecosystem of ELB. Although SRP concentrations are detectable in association with lake ice sediments, the concentration may be well below that necessary for maximum N_2 fixation rates. This suggestion is in concurrence with previous investigations that showed a strong stimulation of nitrogenase activity associated with sediments following the addition of PO_4^{-3} (Paerl & Priscu 1998). Indeed, indirect evidence based on DIN:SRP ratio suggests primary production within this environment may be limited by nitrogen, total ecosystem production as a whole may be limited by the PO_4^{-3} available to nitrogen fixing organisms.

The influences of surrounding terrestrial soil on the water column of lakes in this polar desert have never been explored. It is interesting however, that large DIN:SRP ratios have also been reported for East Lobe of Lake Bonney water column

(Priscu, 1995). At all but one sampling depth through the water column in the Priscu (1995) study, NO_3^- concentrations were greater than NH_4^+ concentrations.

Conclusion

The spatial distribution of inorganic nutrients associated with terrestrial soils and sediments in East Lobe of Lake Bonney ice cover showed no clear trends. The simplest explanation is the fact that all sediments within the ice come from soils surrounding the lake and the soils sampled have all been subjected to similar environmental forces for similar periods of time. Measurable rates of photosynthesis indicate that the terrestrial surface soils around the East Lobe of Lake Bonney support photoautotrophic activity not previously known to exist. Organic matter differences between the terrestrial environment and the lake-ice environment showed that the lake ice supports colonization and is capable of maintaining growth and reproduction of microbial life.

NH_4^+, NO_3^-, and SRP concentration differences between the terrestrial surface soils and lake ice sediments may only partially be explained by microbial transformation. Physical influences such as exclusion from ice during freezing of water may also play major rolls in the availability and specific form these inorganic nutrients take. There is strong enough evidence within my study to suggest that primary production within the lake-ice ecosystem is limited by lack of nitrogen, although, the availability of PO_4^{-3} may ultimately limit ecosystem production as a whole. There is little doubt that tight coupling of populations with complementary metabolic activities is likely to be responsible for the continued existence of all life in the ice as is the case in other microbial dominated communities.

There is also sufficient evidence to suggest that inorganic nutrients associated with terrestrial soils are at least partially responsible for the sustainability of this lake-ice habitat. This habitat encountered in Antarctic lake ice is truly unique so few comparisons exist. Therefore, the soil environment in Antarctica should be seen as an extremely important source of inorganic nutrients required for the growth of microbial life within the ice and even if it is only a means for the diverse life associated with the lake ice to become metabolically active, without it life may not exist or be able to colonize the ice habitat.

CHAPTER 3

NUTRIENT CONCENTRATIONS WITHIN SURFACE SOILS AND ICE-COVER SEDIMENTS IN LAKE FRYXELL BASIN, TAYLOR VALLEY, ANTARCTICA.

Introduction

Lake Fryxell is located in the Taylor Valley, 8 km inland from the McMurdo Sound. It is the closest lake to the McMurdo Sound, which is reflected in its climate relative to other lakes in the valley; wetter, colder, cloudy conditions near the coast (Lyons et. al. 2000). The frozen surface of Lake Fryxell covers approximately 7 km^2 and the thickness of the ice is ~5.0 m. The soils around Lake Fryxell are soils of moraines with moderate to well-developed polygons and well-developed stone pavement over siltball subsoils (Fritsen et al., 2000).

In contrast to the other lake basins in Taylor Valley, the broad, open, landscape of Lake Fryxell basin contains 13 ephemeral streams (Conovitz et al., 1998), most containing algal mats and mosses that persist from summer to summer (McKnight et al., 1998). Algal mats in the streams are dominated by several species of *Phormidium*, *Oscillatoria*, and/or *Nostoc* (McKnight et al., 1998) that remain desiccated and exposed to wind scouring most of the year. Lake Fryxell also has relatively well-developed algal mats on soils that surround the lake, extending in some cases, several meters from the lake edge (personal observation). The dispersal of these algal mats by wind may contribute to the soil characteristics seen today.

Recent inorganic soil nutrient data reported around Lake Fryxell tends to be spatially limited, focused in small plots or transects across streambeds (see for example Treonis et al., 2002. Barrett et al., 2002). Past investigations are few and the methodology is unclear. For example, Pastor and Bockhiem (1980) do not report nitrate concentrations because they were "negligible." Tedrow and Ugolini (1966) report "trace" amounts of nitrogen and undetectable amounts of organic carbon. My study was designed so a better understanding of the spatial distribution of inorganic nutrient (NH_4^+, NO_3^-, and SRP) associated with surface soils surrounding Lake Fryxell would be obtained. Because these soils are often transported by wind to sediment inclusions in the permanent ice-covers of Antarctic lakes, inorganic nutrients associated with the soils may also contribute to the nutritional requirements of microbial life associated with sediment inclusions in the ice. DIN and SRP were also quantified in association with sediment inclusions in the lake-ice, so nutrient transformations and the linkage between the soil environment and lake-ice environment could be assessed.

Results

Of the soil sampled around Lake Fryxell 82.4% fell within the 297 – 2000 μm and 63 – 297 μm particle size classes (Figure 3.1), while 2.4% was silts/clays and 15.2% of the soil was > 2000μm. In most cases the sample taken closest to the lakeshore was considerably more moist than samples taken farther along a given transect. Because of this moisture, separation of the < 63 μm sized particles from bulk samples while "wet" sieving did not occur (these particles formed large aggregates). The < 63 μm size particles that were recovered had significantly greater NH_4^+ and SRP

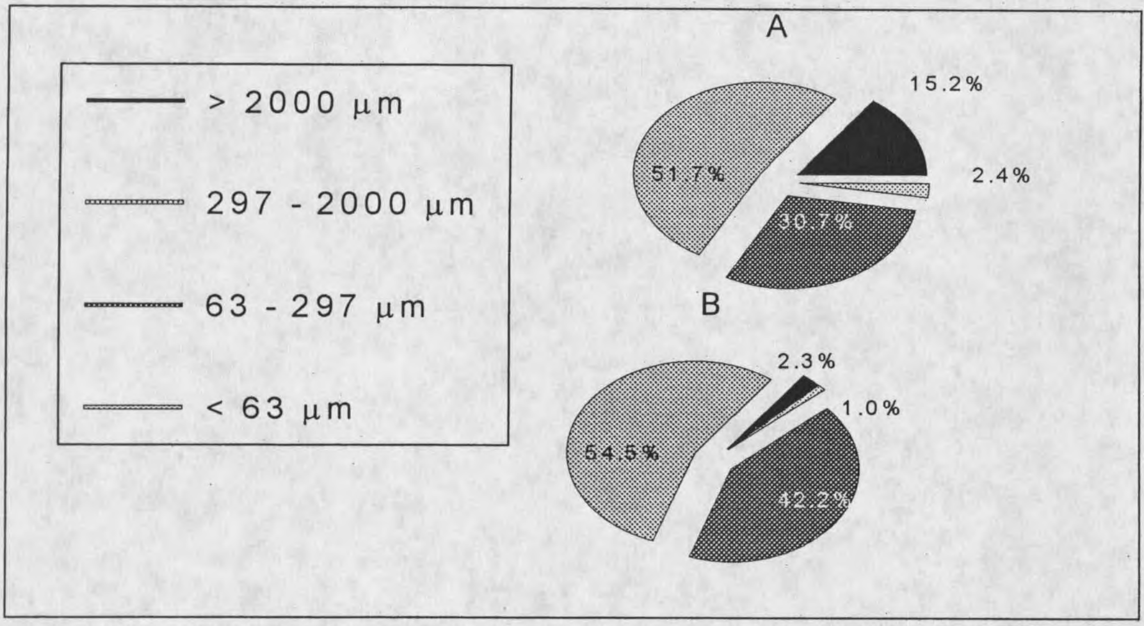


Fig. 3.1: Portion of surface soil and lake ice sediment dryweight within each size classe (g). (A) Surface soil. (B) Lake Ice sediment.

concentrations (per gram of soil) compared to the other three sizes (Figure 3.2; ANOVA, $P < 0.001$). There was no significant difference between the 297 – 2000 μm and 63 – 297 μm sized particles with respect to NH_4^+, NO_3^-, or SRP concentration (ANOVA, $P > 0.05$). The largest size particles (> 2000 μm) had the greatest range in NH_4^+ concentration, from a maximum value of 1.64 μmol g^{-1} soil to undetectable (mean = 0.07, n = 40). These samples also represent the greatest concentrations associated with any sized particles. SRP concentration in the < 63 μm sized particles ranged from 2.35 – 0.084 μmol g^{-1} soil (mean = 0.581, n = 34). The lowest SRP concentrations were associated with the largest sized particles. NO_3^- concentrations ranged from 0.004 μmol g^{-1} soil (297 – 2000 μm) to 0.762 μmol g^{-1} soil (63 – 297 μm). Mean NO_3^- concentration of both particle sizes combined is 0.207 μmol NO_3^- g^{-1} soil. Ammonium and Nitrate values from all sized particles was combined to get a DIN:SRP ratio of two.

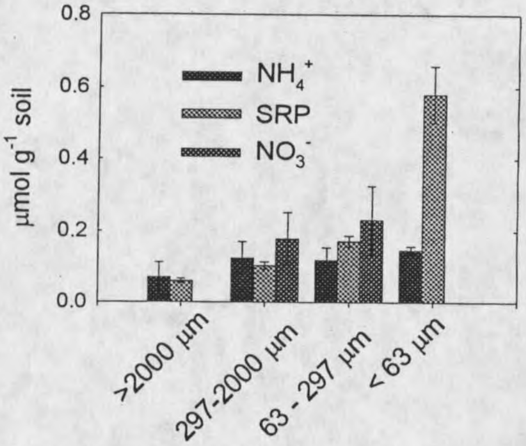


Fig 3.2. Inorganic nutrient concentrations associated with different sized particles. Top of bar is the mean value. Error bars represent one standard error of the mean.

NH$_4^+$ and SRP concentration of surface soils varied between transects and elevations, but the variation was never significant (Figure 3.3, ANOVA; $P > 0.05$). There are no clear trends regarding the spatial distribution of NH$_4^+$ or SRP concentrations about transects (Figure 3.3). Mean NH$_4^+$ concentration was clearly greater in association with the samples taken closest to the lakeshore (Figure 3.3B). Mean SRP concentration was only slightly higher at 200 m versus 1 m from the lakeshore. Organic matter varied considerably with the highest value of 2.55% being associated with a sample taken 1 m from the shore of the lake. This value was almost 4-fold larger than the next largest and eliminated for statistical analysis. Mean organic matter in surface soils (minus the outlier) was 0.324% (Figure 3.7), 58% of the variability in organic matter content could be explained by soil moisture (Figure 3.4). Electrical conductivity and pH values of surface soil surrounding Lake Fryxell averaged 76.8 μmhos cm^{-1} and 9.51, respectively.

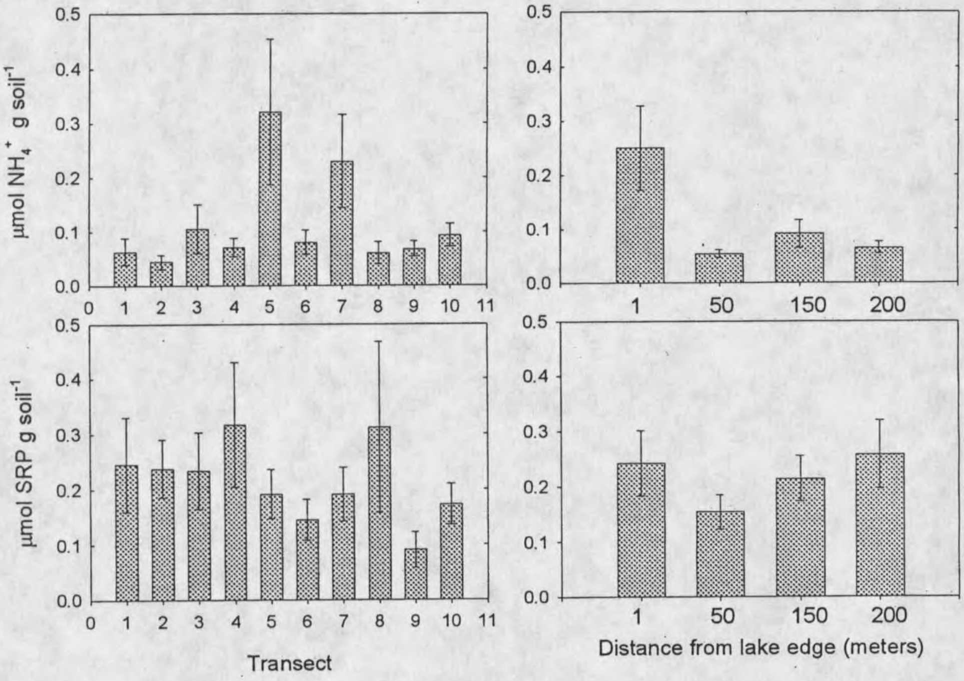


Fig. 3.3. Spatial distribution of soil nutrients by transect (A&C) or distance from lake edge (B&D). Means are the top of the bar. Error bars are one standard error of the mean. There are no statistically significant differences between means at $P < 0.05$.

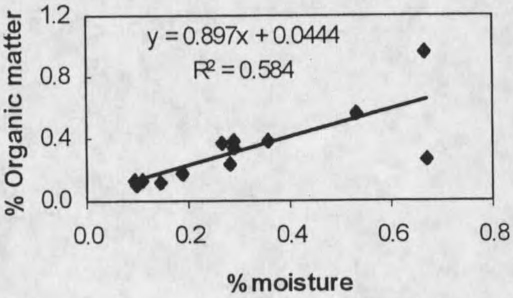


Fig. 3.4 Scatter plot and regression equation of percentage organic matter and percentage moisture in soil samples.

Photoautotrophic activity of surface soils was quantified in 7 samples, spanning an order of magnitude (0.0072 - 0.184 µg C g^{-1} soil d^{-1}). Several samples approached the maximum value obtained; so all samples were included for comparisons giving an average rate of 0.061 µg C g^{-1} soil d^{-1}.

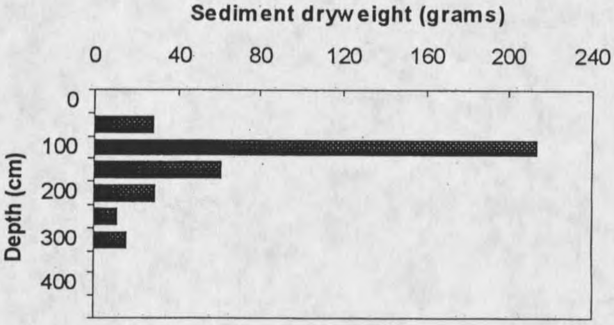


Fig. 3.5. Distribution of sediment through the ice cover of LF. Depth is relative to the surface of the ice (0 cm surcace). All size fractions included.

The majority (85%) of the sediment associated with Lake Fryxell ice cover occurred between 50 and 200 cm (Figure 3.5). There was no sediment above 50 cm and only one of the 25 cores taken contained no visible sediment. This core was taken from the farthest plot to the east. A number of cores had a "well-developed" sediment layer up to 5 cm thick at a given depth, where in other cores the sediment was distributed unevenly over a given depth interval. Most (96.7% by weight) of the sediment fell within the 297 – 2000 μm and 63 – 297 μm particle size classes (Figure 3.1). One percent of the sediments were silt/clays (<63 μm) and 2.3% was > 2000 μm. Sediment weight per core was highly variable ranging from 49.833 – 1.047 g core^{-1}. Nine of the 24 cores with visible sediment inclusions contained less than 6 g total sediment. Total sediment that fell within the > 2000 μm and < 63 μm sized particles never exceeded 1.69 g and 0.55 g core^{-1}, respectively. For this reason, inorganic nutrient concentrations were only determined for the particles that existed within the 297 – 2000 μm and 63 – 297 μm sizes (96.7% by weight of all sediment found). A smaller second peak in sediment load was distinguishable between 300 and 350 cm. None of the variation

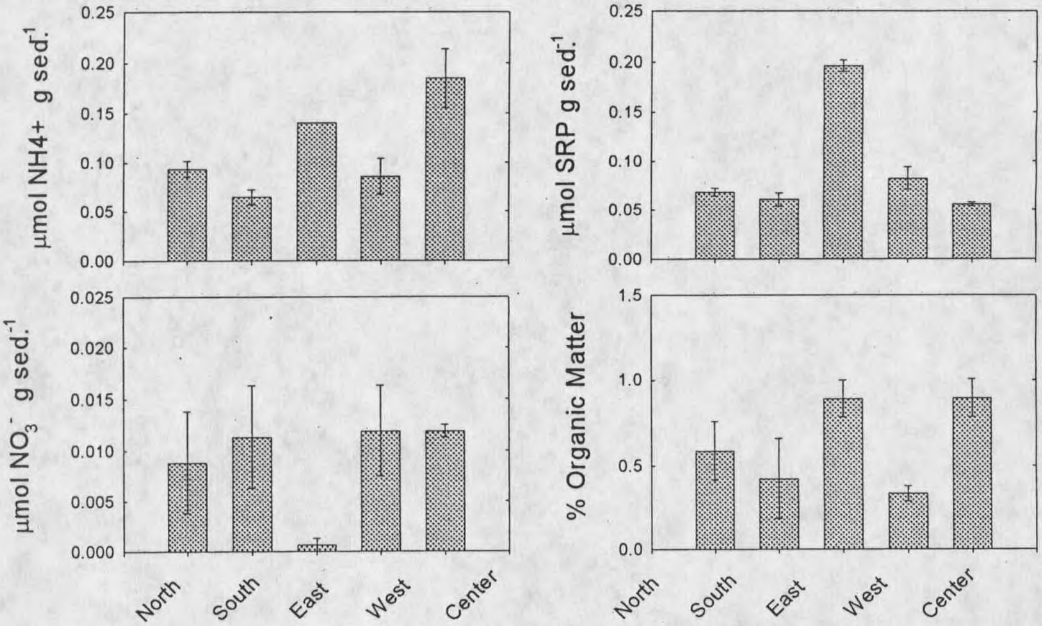


Fig. 3.6. Spatial distribution of nutrients associated with the sediment found within Lake Fryxell ice cover. Directional locations indicate the position of 10x10m coring plots relative to one another. Means are not significantly different from one another at $P < 0.05$. Error bars are one standard error of the mean.

between the sampling plots is significant and no clear trend with respect to spatial distribution of inorganic nutrients or organic matter associated with lake-ice sediment across the ice cover is apparent (Figure 3.6). NH_4^+, NO_3^-, and SRP concentrations from leached sediments range from 0.03 - 0.26 μmol NH_4^+ g^{-1}, undetectable – 0.016 μmol NO_3^- g^{-1}, and 0.04 - 0.20 μmol SRP g^{-1} sediment. The DIN:SRP ratio of sediment associated with Lake Fryxell ice cover was two.

All inorganic nutrient concentrations and percent organic matter differed significantly between terrestrial surface soils and lake-ice associated sediments (Figures 3.7 and 3.8). NH_4^+ concentration increased 2-fold, from 0.05 μmol NH_4^+ g^{-1} soil to 0.10 μmol NH_4^+ g^{-1} sediment. SRP concentration decreased almost 3-fold from 0.22 μmol SRP g^{-1} soil to 0.08 μmol SRP g^{-1} sediment. There was a 23-fold decrese in NO_3^-

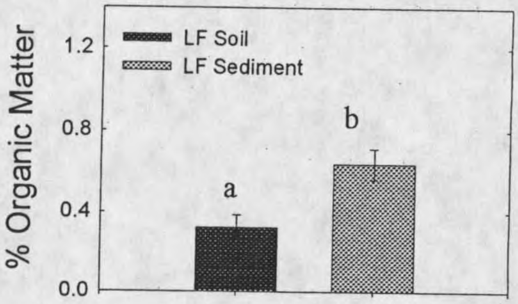


Fig. 3.7. Organic matter content between terrestrial soils and lake ice associated sediment. Letters indicated a significant difference between mean values. Error bars are one standard error of the mean.

concentration, from 0.20 to 0.009 μmol NO_3^- g^{-1}, respectively. Organic matter increased 2-fold from 0.324% g^{-1} soil to 0.637% g^{-1} sediment.

Discussion

My data did not allow me to determine the factors controlling the spatial distribution of inorganic nutrients surrounding Lake Fryxell. It is clear, however, that the majority of the soils that blow onto and melt into the ice cover are particles between the sizes of 63 – 2000 μm (Figure 3.1). The simplest explanation is larger particles are rarely moved by wind events and smaller particles are not abundant in surface soils available for aeolian deposition.

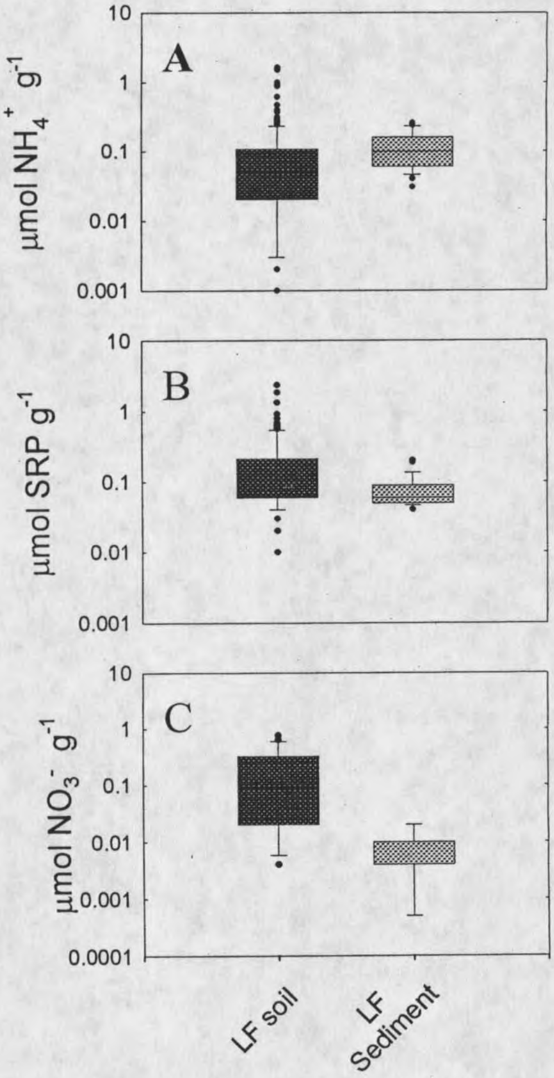


Fig. 3.8. Box and whisker plots of NH_4^+ A, SRP B (SRP), and NO_3^- C, concentration between terrestrial soils and lake-ice associated sediments. Horizontal line in the box is the median, the upper and lower ends of the boxes denote the 25th and 75th percentiles, error bars mark 10th and 90th percentiles. Circles are individual data points outside the 10th and 90th percentiles.

Because of greater ion exchange capacity, it was not surprising the < 63 μm particles had greater nutrient concentrations on average than larger particles. The greatest range in NH_4^+ concentration and the largest values, however, were seen in association with the largest sized particles (> 2000 μm). This is most likely due to the relatively "well-developed" surface microbial mats that surround the lake edge; sampling of these mats was often unavoidable. During the sieving of samples the majority of this material remained in the > 2000 μm size with a little breaking apart and falling into the 297 – 2000 μm size. The mat material did not appear to break into smaller size and, therefore would not have influenced nutrient concentrations in the smaller sized particles. Further supporting this idea, are the relatively greater NH_4^+ concentrations associated with all samples collected closest to the lakeshore (Figure 3.3B).

Variation in nutrient concentration between transects occurred but is difficult to explain. Topographic features, moisture regimes, proximity to ephemeral streams and ponds, or differences in microbial mat cover between transects were not assessed in this study and may influence the characteristics of the soil. Past or present production could also be involved in the differences. Because of the broad, gentle sloping nature of the basin, it is possible many small lakes or ponds occupied the landscape during warmer periods in history. Transects were intentionally chosen to avoid present-day ephemeral streams and ponds, but the past location of these features is not completely known, so unavoidable.

The DIN:SRP ratios suggest nitrogen would limit primary production in this terrestrial ecosystem if water supply were enhanced. The greater mobility of nitrogen than phosphorous within the soil is the simplest explanation for the low ratio (2:1). Brief summer snowfall events often moisten the soil surrounding Lake Fryxell, which may act to mobilize nitrogen species, eventually leaching them from surface soils.

Confounding this loss of nitrogen is the relative absence of biological processes involved in soil nitrogen retention. Nitrogen limitation to primary production is widespread in terrestrial ecosystems throughout the world. Differences in the biogeochemical cycles of nitrogen and phosphorous, are arguably, largely responsible for this phenomenon (Vitousek & Howarth 1991).

The differences in inorganic nutrient concentrations between terrestrial soil and lake-ice sediment are likely a result of a more favorable habitat for growth and reproduction of microbial life, as well as regeneration of nutrients. Kennedy (1993) showed that water should be seen a primary factor limiting terrestrial life in Antarctica. However, liquid water is known to be present within the lake-ice habitat for at least 150 days during the summer (Fritsen et. al., 1998) and would not limit life associated with lake-ice sediment at this point. The lower boundary of the in-ice aquifer coincides with the location of the in ice sediment layer (Adams et. al., 1998). Assuming the terrestrial soil surrounding the lake is the sole source of inorganic nutrients and microbial life to the lake ice habitat, significantly greater NH_4^+ concentrations associated with ice sediment should be the result of increased microbial activity. A greater potential for atmospheric nitrogen fixation and microbial mediated mineralization of organic nitrogen in excess of utilization could both be responsible for the increase in NH_4^+ between soil and sediment environments. Much of the organic nitrogen associated with soils surrounding Lake Fryxell (Fritsen et. al., 2000) may be unavailable to soil microbes because of energetic constraints inherent in its breakdown (Vitousek & Howarth 1991). These energetic constraints may be overcome in the lake ice environment, therefore, making more NH_4^+ available to microbial life and leaching.

Increased rates of dissimilatory reduction of NO_3^- and/or the exchange of bound NH_4^+ associated with sediment would also contribute to greater NH_4^+ concentrations relative to soils.

The 23-fold decrease in NO_3^- concentration from terrestrial soil to lake-ice sediment presents an interesting dilemma and may be the result of abiotic processes, although biological processes cannot be ruled out. The expulsion of ions during the downward freezing of the in-ice aquifer should result in their accumulation at the lower boundary (i.e. sediment layer) as demonstrated in the study of a dry based lake in the Taylor Valley (Sleewaegen et. al., 2002). Conductivity values for the lake ice sediment were consistently lower than those for the terrestrial soil (average; 7.81 and 76.8 μmhos cm^{-1}, respectively), so other process must explain the differences seen. Leaching of soils may occur in an initial meltwater pool on the surface of the ice followed by loss to the atmosphere. Enhanced water availability in these same meltwater pools may activate microbial life associated with the soil and processes such as denitrification, assimilatory reduction, or dissimilatory reduction to NH_4^+ could all play a role in the removal of NO_3^-. The complete reduction of $NO_3^- \rightarrow NH_4^+$ (dissimilatory reduction) can also help explain greater NH_4^+ concentrations associated with the lake ice sediment.

Although phosphate shows neither extensive biologically induced fluxes to and from the atmosphere or is it used as a primary energy source, as nitrogen shows and is, it makes the SRP concentration differences seen between terrestrial soils and lake ice sediments no less complicated to explain without further investigation. The relative decrease in SRP concentration associated with the lake-ice sediment is consistent with its immobilization by microbial organisms. Despite the fact that indirect evidence based on nutrient ratios are indicative of nitrogen limitation on primary productivity, microorganisms associated with sediment may still lack sufficient P for optimal growth. If, for instance, atmospheric nitrogen-fixing organisms were limited by P, a reduction in fixed N_2 would directly affect primary producers ability to fix carbon. In this instance, primary production would be limited by the ability of nitrogen fixers to obtain phosphorous. This or the plethora of other possibilities were not the objectives of this study and additional experimentation is required to better understand the exact nature of factors limiting microbial production in both terrestrial and lake ice habitats in this polar desert. However, the significantly greater organic matter associated with lake ice sediment relative to surface soil implies conditions within the ice-cover of this Antarctic lake are much more suitable for the growth and reproduction of microbial organisms than conditions associated with the terrestrial environment surrounding the lake.

Conclusion

Variation in nutrient concentrations among transects surrounding Lake Fryxell show no consistent spatial pattern. Relatively well-developed surface soil microbial mats that surround the lake are likely responsible for the greater NH_4^+ concentrations in samples taken 1 m from the shore of the lake where their avoidance was not possible. Further supporting this idea, are the elevated NH_4^+ concentrations associated with the largest sized particles of soil where mat material is most likely to accumulate during sieving and the large difference in organic matter in samples from near shore locations. Despite this, the smallest sized soil particles (<63μm) had significantly greater median NH_4^+ and SRP concentrations. The < 63μm sized soil particles may indeed be the most important component of the surface soils for the supply of inorganic nutrients to the lake ice, but their appearance is limited. Clearly, the majority of terrestrial surface soil and the portion of surface soil being blown onto the surface of Lake Fryxell are particles 63 – 2000 µm in size.

Most of the sediment found within ice cores was located between the depths of 100 and 150 cm. The smaller peak in sediment load between 300 and 350 cm may be the result of periods when sufficient solar radiation existed to melt sediments to deeper depths (Figure 3.5).

Specific changes in biogeochemistry from terrestrial soil to lake-ice associated sediment appears to be the result of more favorable conditions for metabolism of microbial life in the ice. Greater accumulations of organic matter, increase in NH_4^+ concentration, and decrease in SRP concentration per unit sediment are all consistent with this idea. However, abiotic processes cannot be ruled out. Evidence based on inorganic nutrient ratios suggests primary production in both the terrestrial and lake-ice environment of Lake Fryxell basin is nitrogen limited. Aside from the microbial mats surrounding the lake and those within ephemeral stream channels, primary production is most likely limited to microhabitats and is not widespread throughout the surface soil. Clearly, the potential for *in situ* primary production exists in the soils surrounding Lake Fryxell when water availability is enhanced.

There is sufficient evidence to suggest inorganic nutrients associated with terrestrial soils are necessary for the survival and maintenance of the lake ice ecosystem. Once established, tight coupling of complementary metabolisms may alleviate the need for subsequent inputs, but without the initial nutrients associated with wind blown surface soil, colonization of this habitat by microbial life is unlikely.

CHAPTER 4

AN INTERBASIN COMPARISON OF SURFACE SOILS AND LAKE-ICE ASSOCIATED SEDIMENTS BETWEEN THE EAST LOBE OF LAKE BONNEY AND LAKE FRYXELL BASIN

Introduction

Approximately 22 km separates the two lake basins with Lake Fryxell being closer to the ocean. Landscape position has recently been used to explain the great physical and chemical variations between the water columns of these lakes (Lyons et. al., 2000), and can be employed to explain variations in biogeochemistry between terrestrial soils and lake-ice sediments across the landscape. Organic carbon and nitrogen have both been shown previously to vary considerably between the soils of these two lake basins (Fritsen et. al., 2000, Burkins et.al., 2001), with higher concentrations of both occurring in soils surrounding Lake Fryxell, yet very little is known about inorganic nutrient concentrations.

The spatial variation in glacial history and climate forcing throughout the Taylor Valley may provide the simplest explanation for differences in present-day soil biogeochemistry. Lake Bonney basin, being farther inland from the McMurdo Sound, experiences a more continental climate, while a marine climate prevails in the Lake Fryxell basin (Lyons et. al., 2000). This results in a change from wetter, colder, cloudy conditions at Lake Fryxell, to warmer, drier conditions at Lake Bonney (Lyons et. al., 2000), as well as strong precipitation gradients (Fountain et. al., 1998). These subtle but measurable differences in climate may strongly influence the biogeochemical nature of the soil environment. Aside from distinct climatologically differences, there are many physical and biological differences between the two lake basins.

The East Lobe of Lake Bonney is surrounded by a much steeper topography compared to the broad open nature of Lake Fryxell basin. Glacial meltwater streams are relatively abundant within the Lake Fryxell basin, most of which contain algal mats and mosses (McKnight et. al., 1998). "Well-developed" surface soil microbial mats that surround Lake Fryxell, are virtually absent from the surface soils surrounding the East Lobe of Lake Bonney. Furthermore, frost polygons are regular features in Lake Fryxell basin, owing to greater soil moisture content and perennially frozen ground subjected to freeze thaw cycles. Finally, there are relatively larger areas within the seasonal moat ice of Lake Fryxell where benthic cyanobacterial mats have become exposed (Fritsen et. al., 2000).

The soils surrounding the lakes represent the largest pool of organic matter in the Taylor Valley (Burkins et. al., 2001). Biological activity in this environment relies primarily on the availability of liquid water (Kennedy, 1993) and secondly on the availability of inorganic nutrients. One purpose of my study was to quantify inorganic nitrogen (NH_4^+, NO_3^-) and soluble reactive phosphorous (SRP) stocks in surface soils and lake-ice associated sediment, firstly, to gain a better understanding of what is there, secondly to determine what factors may limit primary production when liquid water availability is enhanced and finally, to better understand the linkage among soils and the viable microbial community that seems to be thriving in the permanent ice covers of these Antarctic lakes.

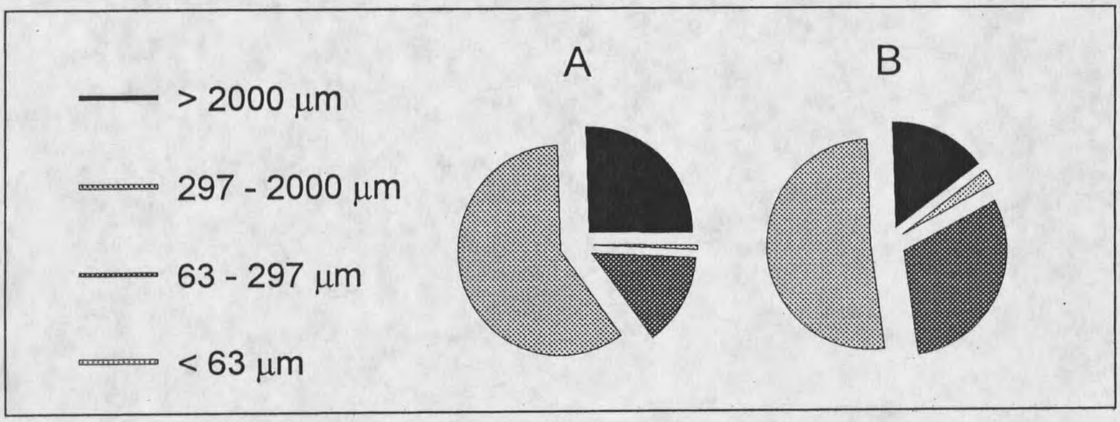


Fig. 4.1. Portion by weight (g) of terrestrial soils surrounding the East Lobe of Lake Bonney (A) and Lake Fryxell (B) within each size class. All pairwise comparisons between portions are statistically different at $P<0.05$.

Results

Surface soil comparison

Statistical analysis showed that all surface soil particle size classes are significantly different between the two lake basins (t-test $P<0.001$). The relative mass of the two largest size class particles (> 2000μm, 297 – 2000μm) significantly decreases from the East Lobe of Lake Bonney basin to Lake Fryxell basin, where the relative mass of the two smallest size class (63 – 297μm, <63μm) particles significantly increases (Figure 4.1).

Comparisons of inorganic nutrients grouped by lake basin showed that surface soils had significantly greater NH_4^+ and SRP concentrations within the Lake Fryxell basin (Table 4.1; t-test $P<0.05$). The mean NH_4^+ value was 2-fold greater, where the

Table 4.1. Mean values of Soil and Sediment Properties Between Two Antarctic Lake Basins.

	East Lobe of Lake Bonney		Lake Fryxell	
	Surface Soil	Lake Ice Sediment	Surface Soil	Lake Ice Sediment
NH_4^+ (μmol g^{-1})	0.042	0.035	0.114	0.119
NO_3^- (μmol g^{-1})	0.49	0.018	0.207	0.009
SRP (μmol g^{-1})	0.016	0.025	0.215	0.077
DIN:SRP	35	2	2	2
PPR (μg C g^{-1} d^{-1})	0.7×10^{-2}	*9.6×10^{-2}	6.1×10^{-2}	*11.8×10^{-2}
Turnover of C (days)	100	---	33	---
Turnover of DIN (days)	6408	44	424	86
Turnover of SRP (days)	3084	331	4483	830
% organic matter	0.111	0.430	0.324	0.637

* from Priscu et. al. in press.

mean SRP value was over an order of magnitude greater within the Lake Fryxell basin. NO_3^- concentration was significantly greater in the East Lobe of Lake Bonney basin, differing by a factor of two (Table 4.1; t-test $P<0.05$). DIN:SRP ratios are drastically different between surface soils of the East Lobe of Lake Bonney and Lake Fryxell basins, 35 and 2, respectively. These ratios imply that the soil environment changes from phosphorous limitation to nitrogen limitation on primary production along the SW to NE axis of the valley. Comparison of surface soil organic matter content also showed significant changes along the axis of the valley with greater organic matter content within soils of Lake Fryxell basin (Table 4.1). Mean organic matter content in surface soil of Lake Fryxell basin and the East Lobe of Lake Bonney basin was, 0.324

and 0.111%, respectively (t-test $P<0.05$). Electrical conductivity along with pH of surface soils changes significantly between lake basins, with Lake Fryxell basin showing relatively lower conductivity values and higher pH values (average values for LF, 76.8 μmhos cm^{-1} & 9.51, for ELB 396 μmhos cm^{-1} & 8.11).

Surface soil photoautotrophic activity between basins was an order of magnitude different, averaging 0.061 μg C g^{-1} soil d^{-1} in Lake Fryxell basin and 0.007 μg C g^{-1} soil d^{-1} in the East Lobe of Lake Bonney basin. This may be the result of microhabitats where growth conditions are more suitable; rates were highly variable among samples within respective basins. Using the above rates of primary production and assuming an element ratio of 106:16:1 (C:N:P) the turnover time of DIN and SRP in the East Lobe of Lake Bonney basin is 18 and 8 yr, respectively. Within Lake Fryxell basin, it takes just over a year to turnover DIN and 12 yr to turnover SRP. These turnover times are very high to begin with and given the extremely cold, arid environment these values are likely to be an order of magnitude greater.

Lake-ice associated sediment comparisons

The depth at which the majority of sediment within the ice covers was found varied between Lake Fryxell and the East Lobe of Lake Bonney. Sediment associated with East Lobe of Lake Bonney ice-cover was mostly (66%) located 150 to 250 cm below the surface, where the majority (60%) of sediment associated with Lake Fryxell ice-cover was found between the depths of 100 and 150 cm below the surface. Particle distribution between the ice covers was similar with approximately 95% of all sediment found in both ice covers falling between 63 – 2000 μm and 1.0% <63 μm.

Water leachable inorganic nutrients associated with sediments were highly variable between ice covers, following similar trends seen in association with surface soils. NH_4^+ and SRP concentrations are both significantly greater in Lake Fryxell sediments compared to those found in East Lobe of Lake Bonney's ice cover (Table 4.1; t-test $P<0.001$). There was no significant difference between lake ice sediments with respect to NO_3^- concentration (Table 4.1; t-test $P=0.105$). DIN:SRP ratios are similar, averaging two, indicating primary productivity within both ice covers is limited by nitrogen. Organic matter content, again, was relatively greater in association with Lake Fryxell sediment (Table 4.1).

Discussion

Spatial variation in soil properties and geochemistry

Soil organisms, together with other factors, such as climate, topography, parent material, and time interact in the process of soil formation (Paul & Clark, 1996). Contemporary soil organisms probably participate very little in the formation these Antarctic soils because of very low activities. Therefore, physical and chemical processes, along with past biological activity are the major factors in the formation of these soils. Strong katabatic winds originating on the polar plateau actively move soil particles down valley and are most likely responsible for the differences in particle distribution between the two lake basins in this study. This phenomenon is particularly evident on a much smaller scale, where finer particles and softer ground are encountered on the leeward side of superficial topographic features on the valley floor (personal observation). Landscape position, therefore, may be largely responsible for a greater accumulation of smaller soil particles around Lake Fryxell compared to East Lobe Lake Bonney.

Significant differences in biogeochemical constituents between the lake basins are likely the result of several factors, none of which were addressed experimentally in this study. NO_3^- in Antarctic soils is ultimately derived from the sea, where it is deposited directly as salts or indirectly by snow blowing into the valley from the inland ice sheet (Campbell et. al., 1998). The lack of precipitation, biological activity, and age of the soils further inland in the Taylor Valley (ELB basin) provide an ideal environment for its accumulation. Closer to the coast (LF basin) the soils receive appreciably more moisture in the form of snowfall that may leach NO_3^- from surface soils. Although it appears that physical processes dominate the nitrogen budget, biological transformations, particularly within Lake Fryxell basin where an enhanced moisture regime makes the soils more hospitable, may be significant at least during the warmest time of year.

Significantly greater NH_4^+ concentrations associated with the soils around Lake Fryxell also may originate in the sea, added to the atmosphere as protein fragments in sea foam (Campbell et. al., 1998, Burkins et. al., 2000) and not fully oxidized when deposited into the coastal lake basin. This situation may be unique to the Taylor Valley because it is the only valley within the McMurdo Dry Valley system that opens directly to the sea. Differential deposition of NH_4^+ present in microbial detritus from ancient paleolakes (Burkins et. al., 2000) cannot be ruled out, nor can contributions from present-day *in situ* soil atmospheric nitrogen fixing or nitrification activity, neither of which has recently been addressed.

As with the differences in concentrations of other inorganic nutrients between the lake basins, there is no simple explanation for the order of magnitude difference in SRP. One explanation relates to the greater rates of photoautotrophic activity associated with the soils of Lake Fryxell basin. An increase in organic acids (not measured in this study) may be responsible for the chelation of cations that bind to inorganic P, thereby increasing its availability (Vitousek and Howarth, 1991). Of course, differences in soil age, climate, topography, parent material, history, and location between the lake basins may in part help explain these results. The differences may be great enough to have significant effects on the ecology and overall ecosystem dynamics within this polar desert, so the nature of these differences would be worthy of future research efforts.

Organic matter content in the soils follows a similar trend as inorganic nutrients, with relatively more associated with soil in Lake Fryxell basin (Table 4.1). Because organic matter content was determined on bulk soil samples, differences may in part be due to the portions of different sized particles that compose the sample (Figure1). My finding are consistent with that of others (e.g. Burkins et. al., 2001, Fritsen et. al., 2000) who found greater organic carbon content associated within soils surrounding Lake Fryxell compared to those surrounding the East Lobe of Lake Bonney. The most obvious explanation for this observation is the greater number of ephemeral streams, most of which contain thick microbial mats (McKnight et. al., 1998), relatively well-developed mats adjacent to the lake edge (personal observation), as well as, relatively large areas within the seasonal moat ice of Lake Fryxell where benthic cyanobacterial mats have become exposed (Fritsen et. al., 2000). Microbial mats in all these locations within Lake Fryxell basin are exposed to the scouring affects of wind throughout the year and are believed to contribute to organic matter content in the surrounding soils. Furthermore, the potential for *in situ* primary production is almost an order of magnitude greater in Lake Fryxell basin.

Spatial variability in lake-ice sediment properties

The depth to which sediment settles in the ice cover is a function of incoming and absorbed solar radiation (Priscu et. al., 1998). More frequent snowfall events within Lake Fryxell basin increase lake-surface albedo and are responsible for the shallower depth at which sediment is found in Lake Fryxell ice cover relative to the East Lobe of Lake Bonney ice cover. The degree to which this affects microbial processes within the ice is unknown. The majority of published physiological studies involving ice aggregate associated microbes in Antarctic lakes have focused mostly on those found in ELB (e.g. see Priscu et. al., 1998, Paerl and Priscu 1998, Olson et. al., 1998, Fritsen and Priscu 1998). Although one would expect to find similar results in Lake Fryxell ice, clear physical and biological differences between basins may influence reaction rates and biogeochemical nutrient status.

Similar DIN:SRP ratios of 2 indicate primary production in both ice covers may be limited by nitrogen availability, but as with the surrounding terrestrial soils, there is relatively more NH_4^+ and SRP within LF sediment. At first glance, this seems logical: the surrounding soils are the source of sediments. However, there is a fundamental difference in the transformation of these nutrients from terrestrial soil to ice sediment between the lake basins. Median NH_4^+ concentration, though not statistically different, actually drops between surface soil and lake ice sediment, while SRP concentration significantly increases between surface soil and lake ice sediment in the East Lobe of Lake Bonney basin (Figure 2.8). In Lake Fryxell basin, the opposite occurs between the transition from surface soil to lake ice sediment, NH_4^+ concentration significantly increases, while SRP concentration significantly decreases (Figure 3.8). Because these macronutrients are essential to growth, biological activity is probably responsible for the differences. That is to say, the difference in nutrient concentrations between the surface soils may encompass some threshold where physical control over the cycling of nutrients within the ice is relinquished to biological control. Relatively greater SRP concentration within Lake Fryxell basin may be large enough so atmospheric nitrogen fixers can compete effectively for it with primary producers. This in turn results in the accumulation and greater availability of fixed N_2 for primary producers because of relatively more atmospheric nitrogen-fixing activity. Conversely, SRP concentration in East Lobe of Lake Bonney surface soil and sediment may not reach the critical value needed for effective competition by atmospheric nitrogen fixers, therefore, immobilization of NH_4^+ exceeds the rate at which it is generated. If this is the case, the physical flux of nutrients into the East Lobe of Lake Bonney's ice-cover may control the biogeochemical nature of the lake ice ecosystem. Where in the Lake Fryxell ice-cover the biogeochemistry is controlled by relatively more activity by microbial populations. Although organic matter content and primary production within both basins significantly increased from surface soil to lake ice sediment, indicating both ice covers support *in situ* microbial production of organic material, the biogeochemical nature of the surrounding soil is likely to have profound effects on the biological component found within.

Conclusion

It is clear from this investigation of the Taylor Valley that distinct lake basins have different biogeochemistry's despite their close spatial locations. Historical legacy and subtle, but measurable differences in climate could theoretically cause differences between the basins. However, differences in the transformations of NH_4^+ and SRP from surface soil to lake ice sediment among the lake basins, implies a biological influence at some level. Whether or not the systems are controlled by physical or biological processes, the stocks of inorganic nutrients associated with the terrestrial soil surrounding these lakes seems to have a profound impact on active biological processes associated with lake ice sediment. Moreover, a critical SRP concentration may be reached within Lake Fryxell basin, which allows atmospheric nitrogen fixers associated with lake ice sediment to effectively compete with primary producers for phosphorous. The true nature of biogeochemical differences between lake basins and its effect on biological processes may prove to be a difficult question to answer. However, comparing long-term physiological studies between these two lake basins would surely prove to be a rewarding experience.

CHAPTER 5

Summary and Conclusions

East Lobe of Lake Bonney basin

1. There are no clear trends in the spatial distribution (on a scale of 100's to 1000's of meters) of NH_4^+ or Soluble Reactive Phosphorous (SRP) concentrations within the terrestrial surface soils surrounding the lake. The simplest explanation for this is that all the soils sampled in this study have a similar history and have been exposed for similar time.
2. The DIN:SRP ratio of surrounding surface soil is estimated at 35. A ratio indicative of a phosphorous limitation on primary production.
3. Total dissolved inorganic nitrogen in the surface soil surrounding the East Lobe of Lake Bonney is dominated by NO_3^-. There are probably many source of NO_3^- in this lake basin, but atmospheric deposition of marine derived organics is seen as a major one (Burkins et. al., 2000). Therefore, abiotic processes probably dominate over any biological control of N-cycling in the soils of this lake basin. Biological control of N-cycling is probably restricted to surface soils found within stream margins or adjacent to alpine glaciers where water availability is enhanced.
4. Measurable rates of photoautotrophic activity in terrestrial surface soils indicate the surface soil environment has the potential to contribute to the overall carbon dynamics within this lake basin.

5. Over 95% of the sediment found below the ice surface of the East Lobe of Lake Bonney are particles 63 – 2000 μm in size. Winds strong enough to move larger particles are rare and silt/clay particles (<63μm) are not abundant in surface soils.

6. Soil NH_4^+ concentrations do not statistically differ from those found in association with lake ice sediment. However, NO_3^- and SRP concentrations are statistically different between the environments in Lake Bonney basin. NO_3^- concentration is lower while SRP concentration is higher in sediments compared to soils. There is no simple explanation for these differences; a combination of both physical and biological processes are likely responsible.

7. DIN:SRP ratio of lake ice sediment is two, a ratio indicative of nitrogen limitation on primary production. Previous investigations have shown a strong stimulation of nitrogenase activity with the addition of PO_4^{-3} (Paerl & Priscu 1998), so ecosystem production as a whole may be limited by the amount of PO_4^{-3} available to atmospheric nitrogen fixing organisms, despite the indirect evidence provided by nutrient ratios.

8. A significantly greater accumulation of organic matter togather with greater rates of primary production associated with lake ice sediment indicates the habitat supports the colonization and proliferation of primary producers much more so than the surface soil habitat. This is most likely the result of enhanced water availability within the lake ice allowing for the "rapid" growth of microorganisms during the short summer season.

9. Finally, because the surrounding surface soils are the ultimate source of lake ice sediment, inorganic nutrients associated with surface soils are at least partially responsible for the successful colonization of the lake ice habitat. Complementary metabolic processes known to be active within the lake ice of ELB (Paerl & Priscu 1998, Olson et. al. 1998) are probably at the center of the communities continued existence.

Lake Fryxell basin

1. Data clearly show that NH_4^+ concentrations in terrestrial surface soils surrounding Lake Fryxell are relatively higher closer to the lakeshore (Figure 3.3B). The most logical explanation for this occurrence is the existence of surficial microbial mats immediately adjacent to the lakeshore that probably fix atmospheric nitrogen. In most cases, these mats extended several meters from the lake edge, making their avoidance during sampling impossible. The bulk of the material remained in the > 2000 µm size fraction after sieving, which is an explanation for the relatively high NH_4^+ concentrations seen in association with these sized particles. Although none of the variation between transects or elevation is statistically significant, differences do exist.
2. The DIN:SRP ratio of surface soil surrounding Lake Fryxell is two, indicative of primary production being limited by nitrogen. Nitrate species make up a relatively small portion of the total dissolved inorganic nitrogen in these soils and conductivity values are relatively smaller. Increased moisture

within this basin probably results in NO_3^- and other ions being leached from surface soils surrounding the lake.

3. Measurable rates of photoautotrophic activity indicate the surface soil environment surrounding Lake Fryxell has the potential to contribute to the overall carbon dynamics within this lake basin.

4. Significant differences exist with respect to all inorganic nutrients assayed and organic matter when terrestrial surface soil is compared to lake ice sediment. All results indicate that the lake ice is a much more suitable habitat for the growth and proliferation of microbial life than the surrounding surface soils. Specifically, the 2-fold increase in NH_4^+ concentration in ice sediments compared to terrestrial soils indicates, among other possibilities, a much more active population of atmospheric nitrogen fixing organisms.

5. The DIN:SRP ratio of lake ice sediment found is estimated at two, indicative of nitrogen limitation. Despite significant modification of nutrients involved, this ratio is the same as that estimated in the surrounding surface soils. An unequivocal explanation is beyond the scope of this project, but microbial generation of NH_4^+ and immobilization of PO_4^{-3} along with the physical exclusion of NO_3^- from the ice provide the simplest explanation.

6. The data I collected imply that the surface soils surrounding Lake Fryxell contribute substantial amounts of essential inorganic nutrients to the lake ice ecosystem. Without this contribution, the initial colonization of this seemingly inhospitable habitat may not be possible. Although there are no previous investigations into the microbial diversity associated with sediments found

within Lake Fryxell ice-cover, it is probably similar to the community known to exist within ELB ice-cover. The tight coupling of diverse complementary metabolic activities is likely the ultimate reason why these communities continue to persist.

Interbasin comparison: East Lobe of Lake Bonney and Lake Fryxell

1. Significant differences exist among all but one (NO_3^-) of the parameters compared across the landscape of Taylor Valley. The majority (95%) of the sediment found within both ice covers consisted of particles 63 – 2000 μm in size and NO_3^- concentrations associated with these sediments are statistically similar. Although biological activity may be partially responsible, because of the great NO_3^- concentration differences between terrestrial surface soils (Table 4.1), the physical exclusion during the freezing process and leaching of NO_3^- from soils before or while their migrating in the ice is more likely.
2. Surface soil textures vary significantly between basins, with a greater portion of fine particles found surrounding Lake Fryxell. This is consistent with the idea that strong winds originating on the polar plateau differentially transport finer soil particles down valley (Campbell et. al. 1998).
3. There is significantly more NH_4^+ and SRP per gram of surface soil and lake ice sediment associated with Lake Fryxell basin. However, fundamental differences in the transformation of these nutrients exist between basins. In the East Lobe of Lake Bonney basin NH_4^+ concentration falls slightly from surface soil to lake ice sediment, where it significantly increases within Lake Fryxell

basin. SRP concentrations, on the other hand, significantly increase and decrease from surface soil to lake ice sediment in East Lobe of Lake Bonney and Lake Fryxell basin, respectively. It is possible that a critical concentration of one or both of the nutrients is reached within Lake Fryxell basin that allows for a greater biological influence over the cycling of nutrients. Although SRP concentration falls from soil to sediment within Lake Fryxell basin, the concentration maintained within the sediment is still significantly greater than that found in East Lobe of Lake Bonney sediment. This concentration could be large enough for atmospheric nitrogen fixers to effectively compete with primary producers for its use, therefore, increasing the NH_4^+ available to other community members and in solution. Diazotrophic activity by cyanobacteria is known to exist in association with the East Lobe of Lake Bonney lake ice sediment (Paerl & Priscu 1998, Olson et.al. 1998), but this activity may be limited by the availability of PO_4^{-3} as the Paerl and Priscu (1998) and Olson et.al. (1998) studies suggest. This need for P may result in the immediate consumption of any fixed N_2, which explains the relative lack of accumulation in the East Lobe of Lake Bonney sediments.

4. Finally, based on the data collected, these two lake basins within the same Antarctic dry valley show clear biogeochemical differences. The specific effects on the biology between the two basins is difficult to explain based on my study, but it seems clear that Lake Fryxell basin supports more biological activity. This is likely a result of both relatively more moisture and the greater availability of inorganic nutrients.

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