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

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.

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Scott Thomas Konley

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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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

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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

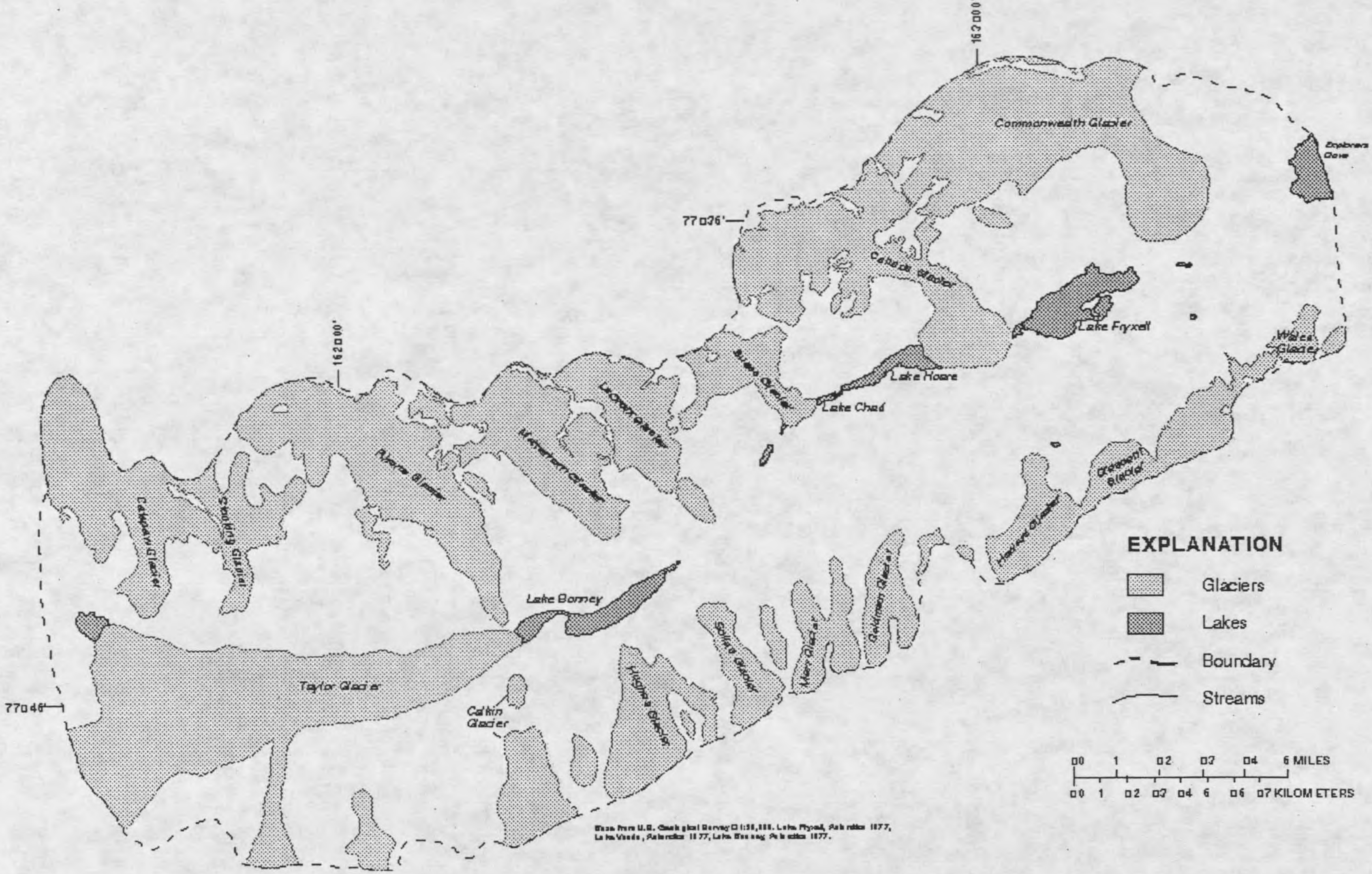

Figure 1. Base map and location of glaciers in Taylor Valley, Antarctica.

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

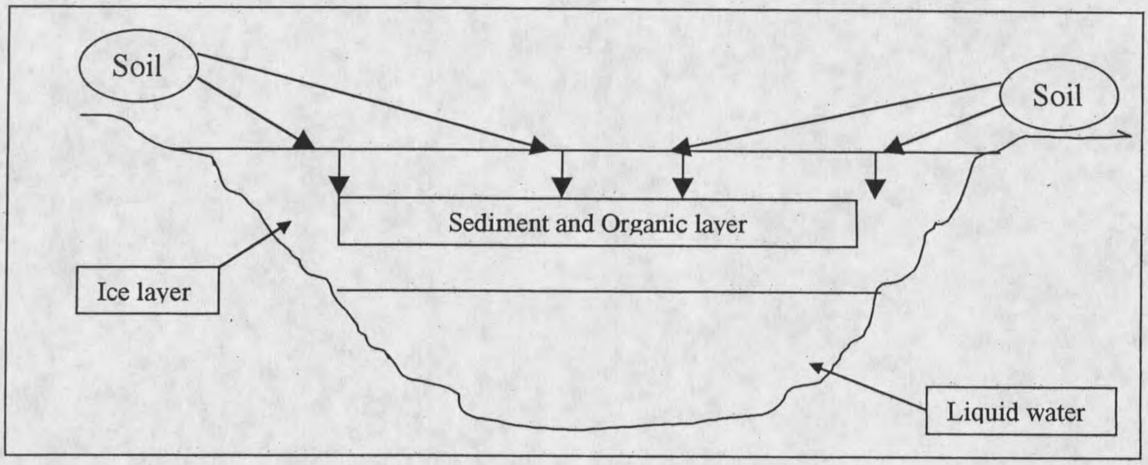

Figure 1.2. Conceptual model of processes that form the basis for my research.

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