Polar Biol (2000) 23: 121–128

ORIGINAL PAPER

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Distribution of organic carbon and nitrogen in surface soils in the McMurdo Dry Valleys, Antarctica

Accepted: 2 August 1999

Abstract The organic carbon and nitrogen contents of sediments in the upper 2 cm of the soils surrounding several lakes in the McMurdo Dry Valleys were measured in a relatively high-density sampling grid, in order to better understand the present-day distribution of organic matter in the ecosystem that is most readily transportable via aeolean processes. Carbon and nitrogen contents of the bulk sediments and size-differentiated sediments decreased in a series according to lake basins oriented along the Taylor Valley's main axis (Lake Fryxell > Hoare ≥ west lobe Bonney ≥ east lobe Bonney). Samples were also obtained around Lake Vida and showed this basin to contain less organic matter than those in the Taylor Valley. This regional spatial analysis supports the emerging view that each basin provides distinct environments for *in situ* microbial activity, lithogenic weathering, aeolian deposition and sorting that can be detected through synoptic sampling.

Introduction

The McMurdo Dry Valleys form the largest ice-free expanse of land on the Antarctic continent. Low annual precipitation (5–10 cm year^{-1}), low temperature (annual average −20°C) and low humidity (< 50%) make this region among the coldest and most xeric terrestrial environments on earth. Despite the extreme aridity and cold, functioning biological communities exist in unique habitats in what would otherwise appear to be an inhospitable environment (e.g. Moorhead and Priscu 1998).

The stocks, fluxes and turnover rates of materials within ecosystems are fundamental parameters defining an ecosystem's structure, function and dynamics. Although the McMurdo Dry Valleys ecosystem is relatively simple, the magnitude of many of these parameters remains unknown (Moorhead and Priscu 1998). Therefore, quantifying the pools and turnover rates of organic carbon and associated nutrients in lakes, streams, glaciers and soils and the fluxes between these distinct units within the McMurdo Dry Valleys ecosystem is essential for understanding the overall dynamics of this polar desert.

Soils within the McMurdo Dry Valleys contain a truncated food web comprising bacteria, microalgae, fungi and a limited number of microbial feeding fauna (e.g. nematodes, rotifers and tardigrades) (Freckman and Virginia 1998). Despite the wide-spread occurrence of this low-diversity food web, the soils of the McMurdo Dry Valleys rank among the most organic-poor soils on earth with organic matter contents consistently near or below 0.1% by weight (Cameron 1972; Campbell et al. 1998). The origin of the low levels of organic matter in the soils is not easily determined, although *in situ* production, paleolacustrine deposition and present-day transport from localized sources (e.g. ephemeral ponds and streams) are all likely to have contributed to the present-day soil characteristics (e.g. Cameron 1972; Campbell et al. 1998; Burkins et al., in press).

During November and December of 1996 we conducted a survey of surface soils surrounding major lakes in the Taylor Valley (Lakes Bonney, Hoare and Fryxell) and Victoria Valley (Lake Vida) that lie within the McMurdo Dry Valleys of southern Victoria Land (Fig. 1). The specific aims of this survey were: (1) to determine the distribution of organic carbon and nitrogen in sediments within the uppermost layer of the soils surrounding the lakes; (2) to gain an understanding of the potential for material transport to other landscape units (namely the lakes, streams and glaciers); and (3) to determine if there are clear indications of sources throughout the McMurdo Dry Valleys desert. This

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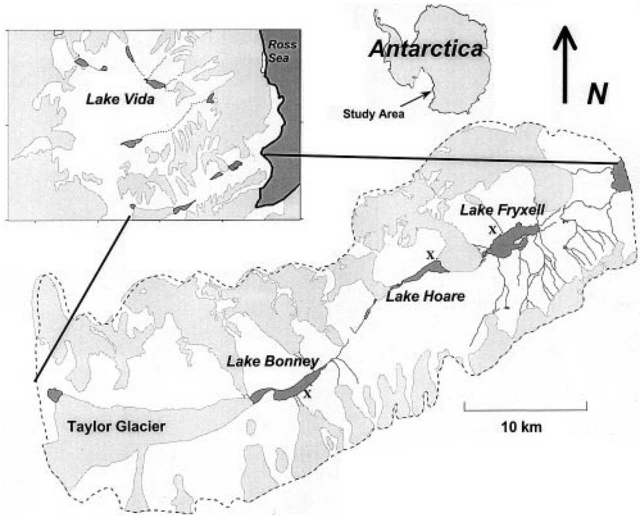


Fig. 1 Location map showing Lakes Bonney, Fryxell, and Hoare in the Taylor Valley and Lake Vida within Victoria Valley, Antarctica. *Crosses* indicate present-day location of research camps

information is pertinent to quantifying the present-day distribution of sediments and organic matter in these valleys and is highly complimentary to past (e.g. McCraw 1965; Claridge 1965; Cameron 1972; Powers et al. 1995; Freckman and Virginia 1998; Burkins et al., in press) and on-going interdisciplinary studies of the McMurdo Dry Valleys ecosystem (e.g. the McMurdo Long-Term Ecological Research Program).

Materials and methods

Study site

The Taylor and Victoria Valleys lie within the ice-free oasis of southern Victoria Land. The ice-free portion of the Taylor Valley lies on the western edge of McMurdo Sound at approximately 77°33′S, 163°25′E (Fig. 1) and is bounded by the Taylor Glacier to the west and McMurdo Sound to the east. In addition to the Taylor Glacier, there are several alpine glaciers descending the flanking mountains. These glaciers provide seasonal meltwater, which feeds the permanently ice-covered lakes that are the subjects of this study, namely Lakes Fryxell, Hoare and Bonney. The Lake Fryxell basin has a gradually sloping terrain compared to the Lake Hoare and Bonney basins. Thirteen ephemeral streams (Conovitz et al. 1998), ranging in length from 1.5 to 11 km (McKnight et al. 1998), transect the broad and open Lake Fryxell basin, whereas the Lake Hoare and Bonney basins have three and five streams, respectively, transecting their relatively steep valley sides.

Victoria Valley (containing Lake Vida; Fig. 1) lies to the north of the Taylor Valley and is bounded by the Polar Plateau to the west and the Wilson-Piedmount glacier in the east. Lake Vida is fed by ephemeral stream run-off originating from glaciers in both the east and the west.

Sampling and analysis

Five to eight samples were taken at approximately 50-m intervals along transects running perpendicular to the shoreline of each of the four lakes. The locations of the sampling sites (latitude and longitude) along the transects were determined using a Global Positioning System (GPS) accurate to approximately 10 m. Five to fifteen transects were completed at each of Lakes Hoare, Fryxell and Vida and around the east and west lobes of Lake Bonney. Transects were intentionally chosen to be in areas that did not coincide with the locations of ephemeral ponds or stream beds.

Samples were collected with a stainless steel cylindrical tube inserted 2 cm into the soils. Only the materials from the upper 2 cm of the soil (i.e. the desert crust) were collected because this layer is most readily available for aeolian dispersion. For the same reason, cobbles and stones larger than 5 mm were not sampled. Bulk samples were placed in whirl-paks and kept frozen until further processing in a laboratory at McMurdo Sound.

Processing consisted of drying (at 90°C) for 24 hours and sieving into four classes (size class A, >2000 µm; size class B, 297–2000 µm; size class C, 67–297 µm; size class D, <67 µm). Subsamples were taken from each size class, fumed in concentrated HCl (to remove inorganic carbon) and analyzed for carbon and nitrogen contents using a Carlo Erba elemental analyzer. Known amounts of acetanilide and blanks (consisting of the high purity tin foil used to contain samples) were used to generate carbon and nitrogen standard curves. Low concentrations of acetanilide standards were used (1.3–1.8 ug N and 8.7–12.1 ug C). Those values lower than the lowest standard (which amounted to only 5% of samples) were examined to determine if they were at least threefold higher than the blanks. Values lower than at least threefold the blank values were considered below the detection limits and assigned the value of zero when computing statistics.

Although we intentionally structured the survey to avoid ephemeral aquatic features, samples of aggregated cyanobacterial mats were collected on occasion. When these samples were processed the aggregated mats were collected in the >2000-µm size fraction (size class A). These samples contributed to the larger variability of the carbon and nitrogen contents of this size class relative to the smaller size classes.

Statistical analysis

Correlations among sample characteristics were assessed using Spearman-Rank Order correlation matrices. One-way ANOVA tests were performed to determine if sediments within each lake basin possessed characteristics separating them from the other basins. Significant median effects were separated using pair-wise comparisons.

Results

Size distribution of surface sediments

Correlation analysis showed that several properties of the surface sediments in the Taylor Valley were not randomly distributed. Specifically, the percentage of the total sediment weight comprising size class B (scB) increased with higher latitude and longitude following the NE-SW uphill trend of the Taylor Valley while the proportion of size class C (scC) decreased with both latitude and longitude (Table 1). The relative mass of sediments in size class A (scA) and D (scD) did not vary significantly along either the EW or NS axis.

When grouped by lake basin, the surface soils differed in their sediment composition (Fig. 2). One-way analysis of variance showed a significant difference ($P < 0.05$) in the proportion of the sediment weight in scC among the different basins. Pair-wise comparisons

Table 1 Spearman rank order correlation matrix for surface sediment properties in the Taylor Valley, Antarctica (N^x nitrogen content; C^x carbon content, where x identifies the size class; + or – indicate either a positive or negative correlation coefficient; *NA* indicates the correlation test is not applicable to these interdependent variables)

	Lat.	Long.	%A	%B	%C	%D	N^A	N^B	N^C	N^D	C^A	C^B	C^C	C^D
Lat.	–	**+	nc	***+	***+	NA	nc	***+	***+	***+	***+	***+	***+	***+
Long.		–	NA	NA	NA	NA	nc	***+	***+	***+	***+	***+	***+	***+
%A			–	NA	NA	NA	**–	*–	***–	**–	***–	nc	nc	nc
%B				–	NA	NA	nc	nc	nc	nc	nc	*–	nc	nc
%C					–	NA	*+	***+		***+	***+	***+	nc	**+
%D						–	nc			***+	nc	nc	nc	***+
N^A							–	***+	***+	***+	***+	***+	***+	nc
N^B								–	***+	***+	***+	***+	***+	***+
N^C									–	***+	***+	***+	***+	***+
N^D										–	***+	***+	***+	***+
C^A											–	***+	***+	***+
C^B												–	***+	***+
C^C													–	***+
C^D														–

nc no significant correlation ($P > 0.05$); *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

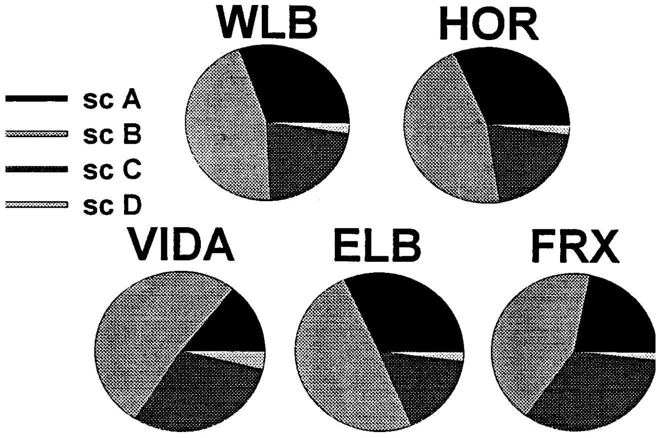


Fig. 2 Average proportion of sediment weights within each size class of sediments collected at Lakes Vida, Bonney (east lobe *ELB*; west lobe *WLB*), Hoare (*HOR*) and Fryxell (*FRX*)

showed that the significant difference among all the basins was due to the differences between the proportion of scC in the Lake Fryxell basin compared to all the other basins. Although the proportion of the sediments in scC tended to increase between Lakes Hoare and Bonney (Fig. 2), pair-wise comparisons showed no significant differences between Lake Hoare and either lobe of Lake Bonney.

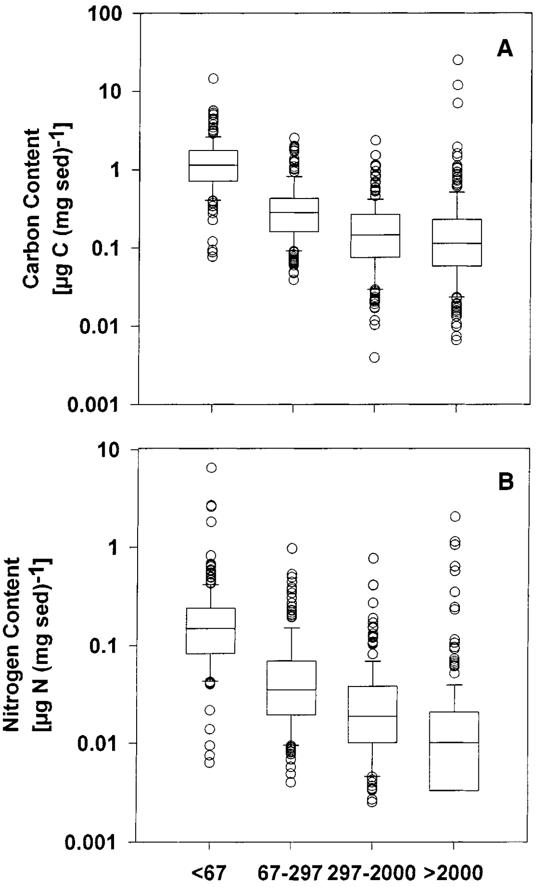


Fig. 3 Box and Whisker plots of organic carbon (**A**) and nitrogen (**B**) content of the sediments in each sediment size class in the surface soils (top 2 cm) surrounding the lakes in the Taylor Valley (all data combined). *Horizontal line* in the *box* is the median value while the *upper* and *lower* ends of the *boxes* denote the 25th and 75th percentiles. *Error bars* demarcate 10th and 90th percentiles. *Circles* are the individual data points beyond the 10th and 90th percentiles

Carbon and nitrogen content

Carbon and nitrogen contents of the surface sediments varied by over 3 orders of magnitude throughout the Taylor and Victoria Valleys (range 0.005–13 µg C mg sed^{-1}; 0.002–8.0 µg N mg sed^{-1}; Fig. 3). Carbon and nitrogen contents increased in the smaller size fractions with the median carbon and nitrogen contents being roughly tenfold higher in the sediments in the $>$67-µm fraction (scD) than in the sediments in the $>$2000-µm fraction (Fig. 3). The C and N contents of sediments in size classes B, C and D all had significant positive correlation coefficients with both latitude and longitude in

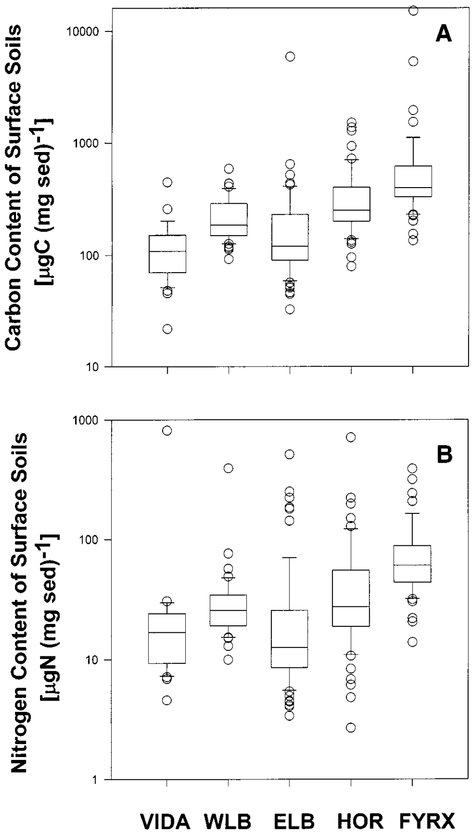


Fig. 4 Box and Whisker plots of organic carbon (**A**) and nitrogen (**B**) contents of the sediments from surface soils surrounding Lakes Fryxell (*FRYX*), Hoare (*HOR*), Vida, and the east (*ELB*) and west lobes (*WLB*) of Lake Bonney (*boxes*, *error bars* and individual data points as described in Fig. 3)

the Taylor Valley, despite the order of magnitude variability (Table 1).

Comparisons of measurements grouped according to lake basin showed that the surface soils had significantly higher C and N contents within the Fryxell basin (Fig. 4a, b; $P < 0.05$; ANOVA). There was also a general trend for C and N contents to decrease in the basins further west within the Taylor Valley. Sediments at Lake Vida contained significantly less C and N compared to all other basins (Fig. 4, $P < 0.05$; ANOVA).

Contour plots illustrate apparent localized areas of enriched C and N in the surface soils within each of the sampling grids surrounding the lakes (Figs. 5, 6). Specifically, contours show enriched areas on the southern shore of the east lobe of Lake Bonney (Figs. 5a, 6a), on the northeastern shore of Lake Hoare (Figs. 5b, 6b), on both the northern and southern shores of Lake Hoare midway along the lake's axis (Figs. 5b, 6b), and in the northeastern corner of the Lake Fryxell sampling grid (Figs. 5c, 6c). Contours of the bulk C and N within the Lake Vida sampling grid revealed relatively little horizontal variation, with an apparent trend for C and N to increase towards the northwest (Figs. 5d, 6d).

The two-dimensional contours show areas of relatively enriched C and N within each basin. Autocorrelation analysis of the bulk carbon content of the soils in the Taylor Valley shows a trend for the semi-variance (one-half of the squared difference between pair-wise combinations of samples) to increase in a near-linear fashion as a function of distance between samples up to an apparent maximum at 10–12 km (Fig. 7). Therefore, the variability of the carbon contents are maximized at distances greater than 10 km and samples less than 10 km have an increased likelihood of being similar. This result indicates that our sampling regime detected patches of organic matter on the order of several kilometers in size.

Discussion

Size distributions

This survey indicates that the size distribution of the sediments in the surficial soils decreases from south to north and from west to east within the Taylor Valley. The orientation of the Taylor Valley is generally along a northeast to southwest axis. Therefore, trends along both NS and EW coordinates are also likely to be associated with gradients along the long axis of the valley or those associated with each distinct lake basin. For instance, significant correlation coefficients between the proportion of size class B sediments (negative correlation) and the proportion of size class C (positive correlation) with latitude and longitude are likely to be due to differences between the soils in the Fryxell basin (in the northeast) compared to those in the basin of Lake Bonney (in the southwest). The survey also shows a distinct difference between the sediments in the surface soils in the Victoria Valley and those in the Taylor Valley, with those in the Victoria Valley being composed of larger-grained sand material (scB and scC).

The differences in the sizes of the sediments in the surface soils in the different lake basins within the Taylor Valley are consistent with earlier reports that the basins of the Taylor Valley contain different types of zonal moraine soils along its axis (McCraw 1967; Prentice et al. 1998). According to these pedologic surveys, the majority of the soils surrounding Lake Bonney's east and west lobes are soils of lateral moraines with moderately developed polygons and weak to moderate development of surface pavement. The soils surrounding Lake Fryxell have been classified as moraines with moderate to well-developed polygons and well-developed stone pavement over "siltball" subsoils. The differences between the sediment sizes in the surface soils in the Victoria Valley and those in the Taylor Valley are also consistent with the soils near Lake Vida being a procession of aoelian-deposited sand dunes and glacial moraines (Cameron 1972). Such sand dunes are not prevalent features in the Taylor Valley (Campbell and Claridge 1987).

Fig. 5 Contour maps of the organic carbon contents of the sediments surrounding Lakes Bonney, Hoare, Fryxell, and Vida

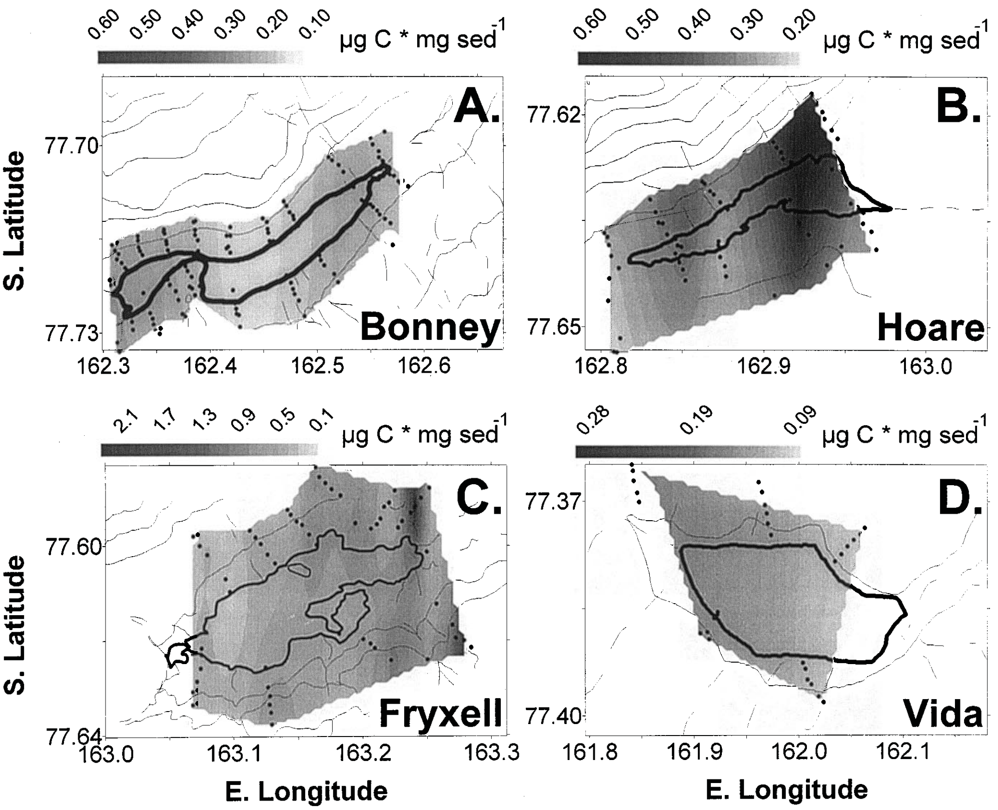
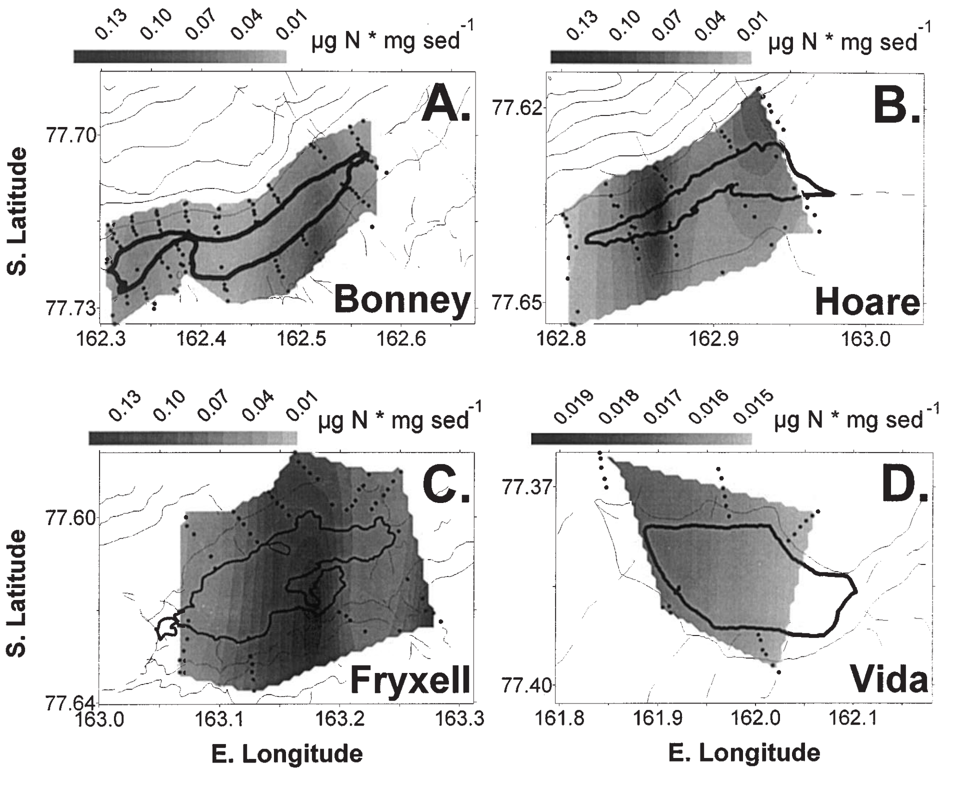


Fig. 6 Contour maps of the nitrogen content of the sediments surrounding Lakes Bonney, Hoare, Fryxell, and Vida



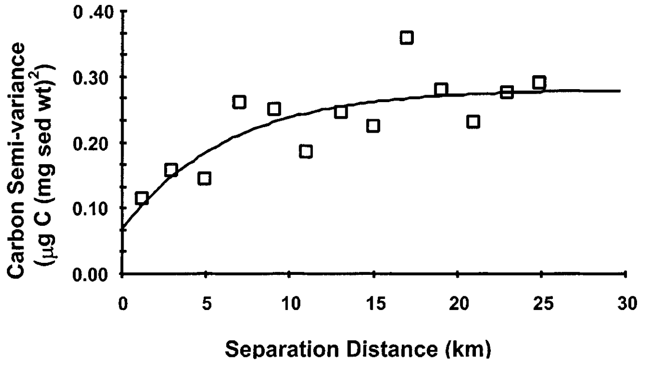


Fig. 7 Semi-variogram generated from the carbon distribution map (Fig. 5) illustrating an apparent autocorrelation of soil carbon content at scales less than ~10 km

Carbon and nitrogen contents

Organic carbon and nitrogen contents of bulk sediments are determined by the organic matter content of the different sediment size classes, as well as the proportions of the different size classes composing the sample. When both characteristics are accounted for, the median organic carbon content of the bulk surface sediments in the lake basins of the lower Taylor Valley ranged from 0.120 to 0.398 µg C (mg sed wt)$^{-1}$, and the median nitrogen contents ranged from 0.012 to 0.060 µg N (mg sed wt)$^{-1}$. The lower values were at Lake Bonney and the highest values were at Lake Fryxell (Fig. 5). This pattern is a result of the relatively high C and N contents within each sediment size class (Fig. 4), as well as higher proportions of fine-grained sand (scC) (Fig. 2) in the eastern sampling locations (Fig. 3). The carbon and nitrogen contents of the Victoria Valley samples were significantly lower than those within any of the lake basins within the Taylor Valley.

The organic carbon and nitrogen contents of the surficial soils measured during this relatively high-density survey are consistent with previous measurements of organic carbon and nitrogen in shallow soil profiles (10–50 cm), which have consistently shown the organic matter to comprise $< 0.1\%$ carbon by weight [i.e. < 1 µg C (mg sed wt)$^{-1}$; e.g. Cameron 1972]. The consistency of the prior measurements and those in our extensive basin-wide survey indicates the potential for data consolidation and future construction of a present-day map of the ecosystem's landscape and biomass, which presently cannot be remotely sensed. Such mapping promises to allow a better assessment of the landscape interactions affecting the ecosystem's biomass distribution.

These carbon and nitrogen contents of the surface soils are several orders of magnitude lower than Antarctic protoranker soils with macroscopic plant life (Tedrow and Ugolini 1966; Campbell and Claridge 1987), and places these "frigic" desert soils among the most organically devoid soils on earth. The low organic matter content is recognized as a defining indicator of the extreme environment of the McMurdo Dry Valleys ecosystem (Campbell et al. 1998) and is likely to be one of the environmental factors influencing the distribution of higher trophic levels in the desert landscape (Powers et al. 1995).

Patterns and processes

Soil properties are determined by factors involving the parent materials, climate, organisms, topography and time (Jenny 1941). Variation of soil properties at scales of 1–10 m (Powers et al. 1995), isotopic signatures indicative of paleolacustrine deposition, as well as modification via *in situ* growth of the soil biota (Burkins et al., in press), in conjunction with the significant variation in organic matter content on the order of several kilometers (this study) are all consistent with a hierarchy of processes creating the present-day soil properties and patterns.

Paleolacustrine deposition of material on the valley floor over glacial and interglacial periods is likely to have determined the carbon content of parent materials throughout the desert landscape, which has left a legacy of materials within the present-day desert soil (Kellog et al. 1980; Doran et al. 1999). Subsequent weathering, transport and sorting of these materials within the valleys have lead to the redistribution and transformation of these paleolacustrine and glacial deposits. The higher proportion of sediments in size class C around Lake Fryxell is also consistent with the soils at the lower elevations being composed of smaller sediments because of their greater propensity for down-slope aeolian transport (Campbell et al. 1998). The significantly enriched organic matter content in the Lake Fryxell basin is also consistent with the deposition of organic-rich marine material during glacio-marine intrusions in the lower portion of the Taylor Valley (Kellog et al. 1980) and long-term sedimentation in paleolakes (e.g. Chinn 1993; Doran et al. 1999; Burkins et al., in press).

Present-day primary production and decomposition processes within the soils and surrounding environments produce and modify the carbon and nitrogen within the sediments in concert with weathering and sorting. Cyanobacterial mats within the ephemeral ponds and streams, as well as the mats escaping the benthos of the lakes through the seasonal moat ice, contribute to the present-day supply of organic matter to the surface soils (Wilson 1965; Parker et al. 1982). Therefore, variability in the organic matter content of the surface soils may be due in part to differences in the production of readily transportable organic material and processes leading to its transport into the surrounding landscape. Despite this possibility, the distribution patterns of carbon and nitrogen in the surface soils do not unequivocally identify material originating from present-day sources within each basin. Rather, the distribution patterns are suggestive of a few potential sources known to occur in the present-day landscape. Specifically, the patterns in the basin of the east lobe of Lake Bonney are consistent with a significant source from the ephemeral ponds located next to the Hughes Glacier along the southern slope of the basin (personal observation), and the cyanobacterial mats in the seasonal moat along the northeastern end of the lake (personal observations). The pattern of increasing carbon and nitrogen in the surface soils at the northeast shore of Lake Hoare could be due to sources originating from the ephemeral stream located next to the Canada glacier, from the mats in the seasonal moat as well as from the semi-permanent research camp. In this specific instance, the relative contribution of carbon and nitrogen to soils in conjunction with the operation of the camp appears to need further evaluation, in order to place the potential source from the camp operations in the context of the overall ecosystem dynamics. Analysis of the isotopic composition of materials within these apparent small-scale patches and comparison with their potential present-day sources may determine if these are indeed related through present-day production as opposed to transport and deposition of the legacy organic matter.

The Lake Fryxell basin contains larger areas of ephemeral stream flow, which contain thick cyanobacterial mats, than either the Lake Bonney or Lake Hoare basins (Conovitz et al. 1998; McKnight et al. 1998). Lake Fryxell also has relatively large areas within the seasonal moat ice where benthic cyanobacterial mats are incorporated into the ice, and sublimation exposes them to wind scouring (personal observation). Therefore, the significantly higher organic matter content in the Fryxell basin may also be indicative of the large potential sources of organic matter and perhaps a more clement environment for *in situ* growth by soil microbiota. However, isotopic composition of soil carbon and nitrogen does not carry a strong signal indicative of present-day lacustrine sources in the Fryxell basin (Burkins et al., in press).

The Lake Vida basin in Victoria Valley has experienced different glacial, erosional paleolacustrine and aoelian deposition sequences than those in the Taylor Valley (e.g. Prentice et al. 1998). The Lake Vida basin currently experiences a more extreme arid and low-temperature climate than the basins in the Taylor Valley (Doran, unpublished work). Hence, it is not overly surprising that the surface soil's properties are different from those in the Taylor Valley. However, it is worth noting that the organic carbon and nitrogen content of these surface soils, whether due to a different paleohistory or present-day conditions, represents an extreme end of the spectrum in organic matter content of the Dry Valley soils. This low organic matter content is likely to contribute to the factors making this soil among the least diverse in terms of invertebrate biotic diversity (Freckman and Virginia 1998).

In summary, the survey of the soils surrounding lakes within the Taylor Valley shows two ecologically and pedologically significant trends. First, the size of the sediments in the surface soils, as well as the organic matter content (C and N), within all of the size classes of sediments tends to decrease from east to west (the Lake Bonney basin to the Lake Fryxell basin). The mechanisms and processes creating this overall pattern of sediment properties are likely to be complex. However, the changes in the surface soil properties in the valley are consistent with differential paleolacustrine deposition of materials, subsequent aeolian sorting along the valley axis, increased weathering in the lower basin, as well as differential growth of the soil and lacustrine microbiota. The Lake Vida basin shows substantially lower organic matter content and larger sediment sizes, which are likely related to Victoria Valley's different depositional history and more extreme present-day climate.

Acknowledgements We wish to thank Antarctic Support Associates for the analytical, technical and logistics support making this endeavor possible. We offer our special thanks to Greta Gilbert for enthusiastically implementing the sampling regime and Birgit Sattler for additional field assistance. This work was supported by NSF grants OPP 92-11773, OPP 94-19423 and OPP 98-1551 to J.C.P. and OPP 98-14972 to C.H.F.

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