Isotopic evidence for the provenance and turnover of organic carbon by soil microorganisms in the Antarctic dry valleys

D.W. Hopkins[A,B], A.D. Sparrow[C], E.G. Gregorich[D], B. Elberling[E], P. Novis[F] and L.G. Greenfield[G]

[A]Scottish Crop Research Institute, Invergowrie, Dundee DD2 5DA, Scotland UK. david.hopkins@scri.ac.uk
[B]School of Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, Scotland UK.
[C]CSIRO Sustainable Ecosystems, Alice Springs Northern Territories 0871, Australia.
[D]Agriculture and Agri-Food Canada, Central Experimental Farm, Ottawa, K1A 0C6, Canada.
[E]Institute of Geography and Geology, University of Copenhagen, Øster Voldgade 10, DK-1350, Copenhagen K., Denmark.
[F]Manaaki Whenua - Landcare Research, PO Box 69, Lincoln 8152, New Zealand.
[G]School of Biological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.

Abstract
The extremely cold and arid dry valleys in the Southern Victoria Land region of Antarctica are one of the most environmentally harsh terrestrial ecosystems supporting organisms. The dry valleys are characterized by a combination of low temperatures and lack of liquid water that severely limit the abundance and activity of terrestrial organisms. Nevertheless, the soils contain organic C and N, a relatively large proportion of which is inorganic N, emit CO_2 produced by heterotrophic respiration and support active communities of heterotrophic soil organisms. The biogeochemical transformations of carbon and other nutrients in the dry valleys soils are exclusively driven by microorganisms. The dry valleys lack vascular plants and the cryptogamic vegetation is both sparse and inconspicuous. In situ primary production by mosses, lichens, terrestrial cyanobacteria and algae, including production in cryptic microbial communities that grow endolithically (literally growing in the interstitial spaces in fissured rock, where there may be more liquid water and where they are protected from the radiation and the abrasive and drying effects of the wind), is very limited. However, there are several other potential sources of organic C and N to support terrestrial heterotrophs, including redistributed detritus from modern lacustrine cyanobacteria, marine detritus, and the remnants of ancient organic deposits from palaeo-lakes, which is also believed to be of algal and cyanobacterial origin. The natural abundance of ^{13}C and ^{15}N in source organic materials and soils have been examined to obtain evidence for the provenance of the soil organic matter. The organic matter in soils remote from sources of liquid water or where lacustrine productivity was low had isotope signatures characteristic of endolithic (lichen) sources, whereas at more sheltered and productive sites, the organic matter in the soils that was a mixture mainly lacustrine detritus and moss-derived organic matter.

Key Words
Antarctica, Dry Valleys, $\delta^{13}C$, $\delta^{15}N$.

Introduction
The Antarctic dry valleys in the Southern Victoria Land region of Antarctica are characterized by a combination of low temperatures and lack of liquid water that severely limit the abundance and activity of terrestrial organisms. However, the soils contain organic C and N, a relatively large proportion of which is inorganic N (Burkins *et al.* 2000; Barrett *et al.* 2002; Barrett *et al.* 2005; Elberling *et al*. 2006), emit CO_2 produced by heterotrophic respiration (Burkins *et al.* 2002; Parsons *et al.* 2004; Barrett *et al.* 2006a; Elberling *et al.* 2006; Hopkins *et al.* 2006a, 2006b) and support active communities of heterotrophic soil organisms. The dry valleys lack vascular plants and the cryptogamic vegetation is both sparse and inconspicuous. *In situ* primary production by mosses, lichens, terrestrial cyanobacteria and algae, including production in cryptic microbial communities that grow endolithically is very limited. However, there are several other potential sources of organic C and N to support terrestrial heterotrophs, including redistributed detritus from modern lacustrine cyanobacteria (Parker *et al.* 1982; Greenfield 1998; Elberling *et al.* 2006; Hopkins *et al.* 2006b, 2008a), marine detritus (Burkins *et al.* 2000), and the remnants of ancient organic deposits from palaeo-lakes, which is also believed to be of algal and cyanobacterial origin (Burkins *et al.* 2000; Hendy 2000; Hall *et al.* 2000, 2001; Hall and Denton 1995; Moorhead 2007). Burkins *et al*. (2000) used the natural abundances of ^{13}C and ^{15}N of organic C and N in soils from the Taylor Valley and various organic materials as signatures for organic C and N from different sources to show that sites at greater altitude had isotopic signals approaching that of endolithic autotrophs whilst those at lower altitudes had signals approaching that of lacustrine detritus (see also Barrett *et al.* 2006b). This is consistent with the organic C contents of the soils being greater close to the edges of lakes and ponds (Moorhead 2007;

Elberling *et al.* 2006; Hopkins *et al.* 2008a) and these areas being hot-spots of biological activity in the dry valleys (Elberling *et al.* 2006; Gregorich *et al.* 2006; Hopkins *et al.* 2006a, 2006b, 2008a). Based on indirect geomorphic evidence, Burkins *et al.* (2000) also proposed that there is an additional source of organic matter derived from palaeo-lake sediments that has been redistributed in the landscape by subsequent glacial processes. This proposition has become assimilated as one of the elements of the so-called "legacy" hypothesis that contributes to ecosystem processes in the Antarctic dry valleys (Barrett *et al.* 2006b). However, estimates of the turnover time of soil organic C for the dry valleys are in the range of a few decades to about 150 years (Burkins *et al.* 2002; Elberling *et al.* 2006; Barrett *et al.* 2006a, 2006b) which suggests that legacy C can only make a minor contribution to contemporary C cycling.

Our objectives were to examine natural abundance isotope evidence for different sources of organic matter in dry valley soils and estimate the relative contributions from the principal organic sources to the soil organic matter, to extend the number of locations for which isotopic data for the soil organic C and N have been collected, and to estimate the decomposition rate of the soil organic C.

Methods

Soil and sites

Soil samples were collected from sites in the Garwood, Wright, Victoria and Taylor Valleys from the 0 to 5 cm depth. Three types of identifiable organic matter were collected at different sites in the dry valleys and used as reference source materials for ^{13}C and ^{15}N signatures: (1) Lacustrine detritus comprising cyanobacterial mat from the littoral region of the lake floating foam from the lake surface produced as cyanobacteria and algae decayed, cyanobacterial detritus stranded at high–water marks around the lake edge, wind-blown organic detritus caught in sediment traps, and surficial mats of the cyanobacteria, *Nostoc commune* and *Phormidium* sp. (2) Cyanobacterial beds buried between 8 and 20 m above the current level of Lake Vanda from the region where preserved cyanobacterial beds have been dated to between 3000 and 1900 ^{14}C years BP. (3) Moss samples were obtained by separating moss (*Bryum* sp.) growing hypolithically in soil. (4) Samples of endolithic communities were obtained from rocks.

Isotopic analysis

The $\delta^{13}C$ and $\delta^{15}N$ values of the soils and organic materials were determined by isotope ratio mass spectrometry after acidification to remove inorganic C. Isotopic comparisons were expressed in parts per thousand (‰) depletion of ^{13}C or ^{15}N (negative δ values) relative to the conventional standards, Vienna Pee Dee Belemnite (V-PDB) for $\delta^{13}C$ and atmospheric N_2 for $\delta^{15}N$ values.

Results and Discussion

The $\delta^{13}C$ values of the mosses and endolithic materials are consistent with that of C3 photosynthesis (typically -25 to -30‰). In contrast, the less ^{13}C-depleted signal for the cyanobacterial material agrees with fractionation associated with CO_2 concentration mechanisms in cyanobacteria and the diffusion limitations of dissolved inorganic C which leads to relatively less ^{13}C-depletion in the biomass. Our $\delta^{13}C$ values for lacustrine detritus were in the range -8 to -15‰, which fits well with the value of -10 to -11‰ for coastal ponds in the Garwood Valley. The $\delta^{15}N$ values of the lacustrine materials, relatively close to 0‰ indicate a contribution from biological N fixation. The possibility of biological N fixation in endolithic communities cannot be excluded, but N fixation is thought to be exceptional in these communities. The $\delta^{15}N$ values of the endolithic materials and mosses were strongly ^{15}N-depleted, which may indicate assimilation of ^{15}N-depleted sources such as soil nitrate, which can be strongly depleted in the dry valleys and elsewhere in Antarctica. In the absence of a conspicuous source or sources of organic matter from *in situ*, contemporary primary producers, the provenance of organic matter in dry valleys soils is complex (Figure 1). Based on positions in the isotope bi-plot, the organic matter in the Garwood Valley soils had the largest proportion derived from lacustrine detritus compared to soils from the other valleys. Our previous studies (Elberling *et al.* 2006; Hopkins *et al.* 2008a) indicated an important contribution from lacustrine detritus, but the present study confirms that the lacustrine material subsidises the terrestrially-derived organic matter arising from either endolithic organisms or mosses, or both. The Wright Valley soil organic C and N appeared to be derived principally from endolithic material. The Victoria Valley soil had $\delta^{15}N$ value close to that of the moss, but the variation associated with the $\delta^{15}N$ value Victoria Valley soil was large and the idea that mosses made a major contribution to this soil cannot be reconciled with the conspicuous absence of mosses, so it is more likely that endolithic materials contributed to the Victoria Valley soil. In the Wright Valley and Tayleo Valley soils, the $\delta^{15}N$ values were close to that of the endolithic materials, which is consistent with the $\delta^{13}C$ values for these soils.

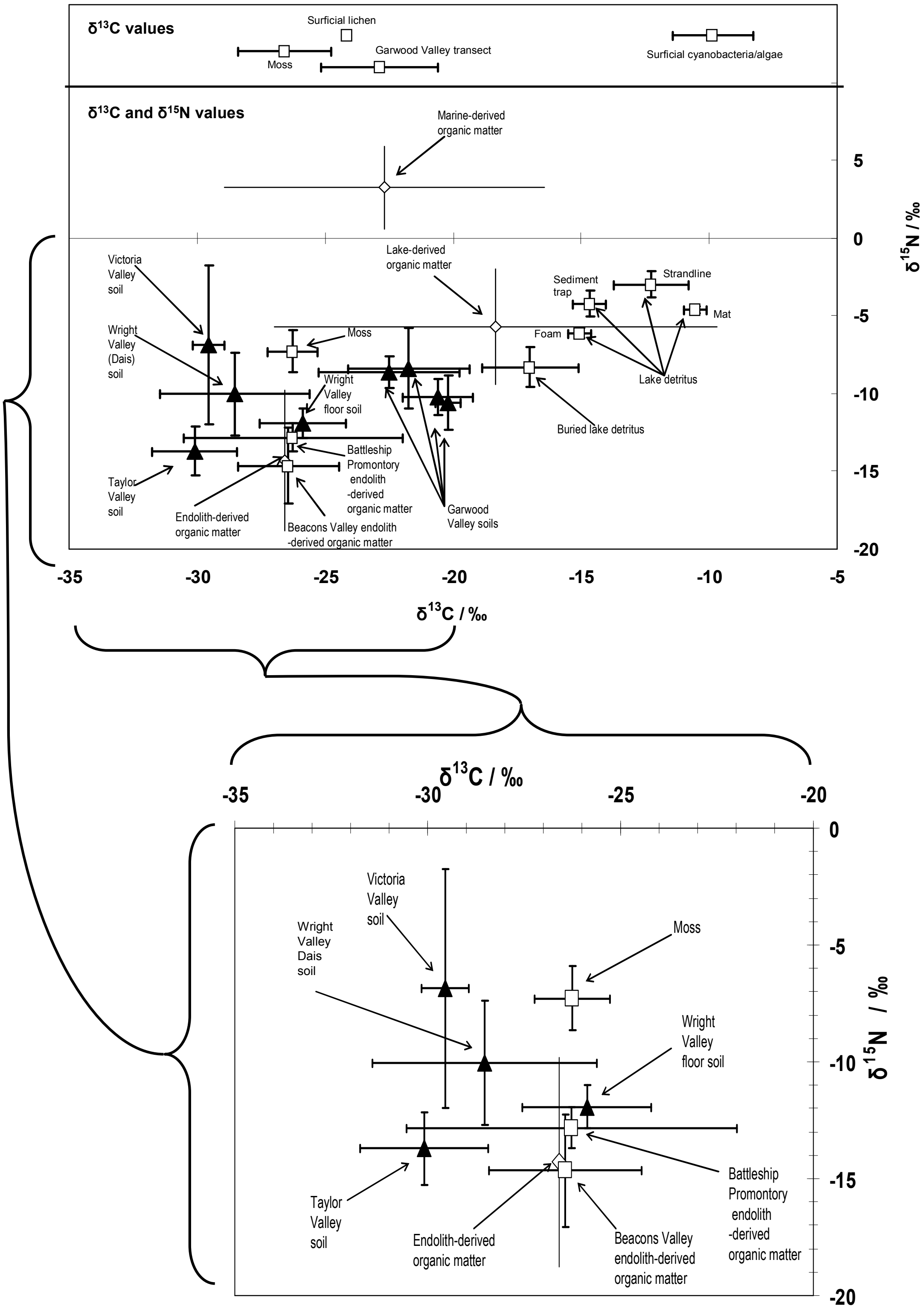

Figure 1. Isotope bi-plot for organic materials of different biological origins and soils from the dry valleys. The values plotted are the mean δ^{13}C and δ^{15}N values and the bars are ± standard deviations. The open squares (□) with bold bars are the values for the source organic materials from this study; the open diamonds (◊) with regular, uncapped bars are the values for the source materials from Burkins *et al.* (2000); the triangles (▲) with regular bars are the values for the soils. The lower panel shows the δ^{13}C- and δ^{15}N-depleted part of the isotope bi-plot expanded for clarity, and the δ^{13}C values of samples for which we only have ^{13}C data at the top of the figure.

1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Conclusion

Under the sheltered conditions of the Garwood Valley, where there is relatively abundant modern lacustrine detritus, this material makes a significant contribution to the soil. In the Garwood Valley, the soil organic C and N contents are greater than the other valleys, perhaps suggesting that lacustrine productivity subsidises soil resources above that of the indigenous, terrestrially derived organic matter. We have commented previously about the dual role of the lacustrine detritus, contributing both exploitable resources and possibly viable organisms to soils that would otherwise be even more impoverished than they are currently, and the present results provide further evidence to support this internal redistribution of resources. We propose that depletion ^{13}C and ^{15}N in the soils is associated both with increasing recalcitrance of the source material entering the soils and increasing dryness such that the lacustrine materials which are apparently relatively labile make a progressively smaller contribution to the soil organic matter at dry compared to wetter sites. These hypotheses may be tested by increasing the range of soils analysed to include soils from valleys or sites within valleys that fall at intermediate positions of the wetness gradient between the Garwood Valley at the wet (and relatively productive) extreme and the Wright Valley, Victoria Valley and Taylor Valley sites we have examined at the dry (and less productive) extreme and by a comparative study of the decomposition kinetics of the different organic material.

References

Barrett JE, Virginia RA Wall DH (2002) Trends in resin and KCl-extractable soil nitrogen across landscape gradients in Taylor Valley, Antarctica. *Ecosystems* **5,** 289-299.

Barrett JE ,Virginia RA, Parsons AN, Wall DH (2005) Potential soil organic matter turnover in Taylor Valley, Antarctica. *Arctic Antarctic & Alpine Research* **37,** 108-117.

Barrett JE, Virginia RA, Parsons AN. and Wall, D.H. (2006a) Soil carbon turnover in the McMurdo dry valleys, Antarctica. *Soil Biology & Biochemistry* **38,** 3065-3082.

Barrett JE *et al.* (2006b) Terrestrial ecosystem processes of Victoria Land, Antarctica. *Soil Biology & Biochemistry* **38,** 3019-3034.

Burkins MB, Virginia RA, Chamberlain CP, Wall DH (2000) Origin and distribution of soil organic matter in Taylor Valley, Antarctica. *Ecology* **81,** 2377-2391.

Elberling B *et al.* (2006) Distribution and dynamics of soil organic matter in an Antarctic dry valley. *Soil Biology & Biochemistry* **38,** 3095-3034.

Greenfield LG (1988) Forms of nitrogen in Beacon Sandstone rocks containing endolitihic microbial communities in Southern Victoria Land, Antarctica. *Polarforschung* **58,** 211-218.

Gregorich EG *et al*. (2006) Biogenic gas emission along a lake shore in an Antarctic dry valley. *Soil Biology & Biochemistry* **38,** 3120-3129.

Hall BL, Denton GH (1995) Late Quaternary lake levels in dry valleys, Antarctica. *Antarctic Journal of the United States* **30,** 52-53.

Hall BL, Denton GH, Hendy CH (2000) Evidence from Taylor Valley for grounded ice in the Ross Sea, Antarctica. *Geografiska Annaler* **82A,** 275-303.

Hendy CH (2000) Late Quaternary lakes in the McMurdo Sound region of Antarctica. *Geografiska Annaler* **82A,** 411-432.

Hopkins DW *et al.* (2006a) Controls on the distribution of productivity and organic resources in Antarctic dry valley soils. *Proceedings of the Royal Society of London B* **273,** 2687-2695.

Hopkins DW *et al.* (2006b) Carbon, nitrogen and temperature controls on microbial activity in soils from an Antarctic dry valley. *Soil Biology & Biochemistry* **38,** 3130-3140.

Hopkins DW *et al.* (2008a) Redistributed lacustrine detritus as a spatial subsidy of biological resources for soils in an Antarctic dry valley. *Geoderma* **144,** 86-92.

Hopkins DW *et al.* (2008b) Enzymatic activities and microbial communities in an Antarctic dry valley soil: Responses to C and N supplementation. *Soil Biology & Biochemistry* **40**, 2130-2136.

Moorhead DL (2007) Mesoscale dynamics of ephemeral wetlands in the Antarctic dry valleys: Implications to production and distribution of organic matter. *Ecosystems* **10,** 86-94.

Parker BC *et al.* (1982) Removal of organic and inorganic matter from Antarctic lakes by aerial escape of blue-green algal mats. *Journal of Phycology* **18,** 72-78.

Parsons AN *et al.* (2004) Soil carbon dioxide flux in Antarctic Dry Valley ecosystems. *Ecosystems* **7,** 286-295.