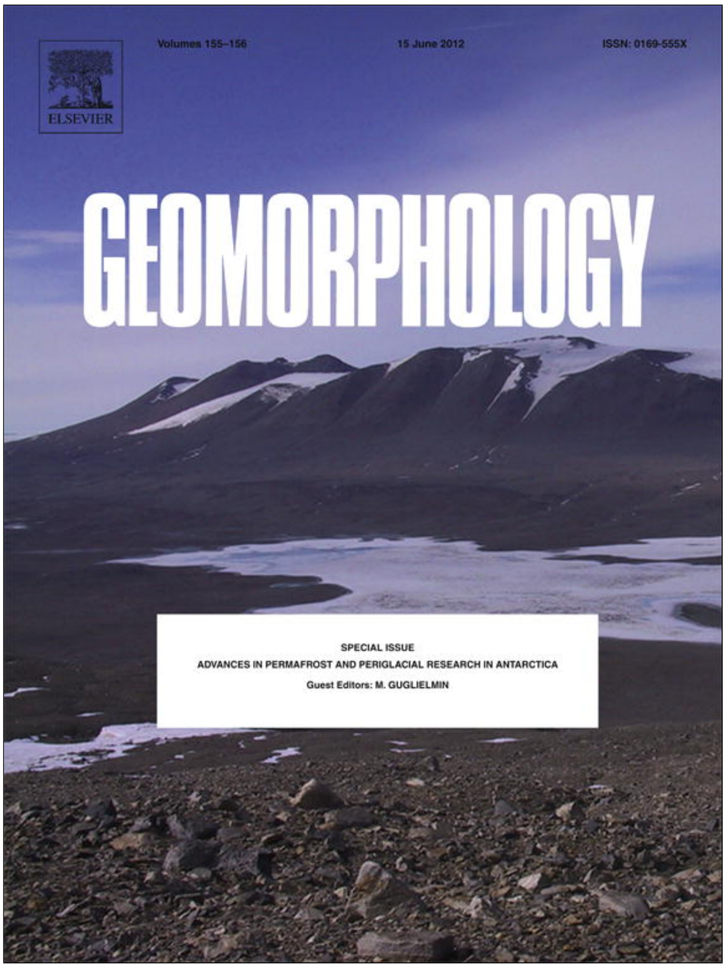
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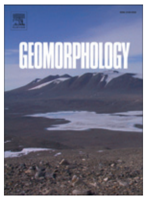

Aeolian flux of biotic and abiotic material in Taylor Valley, Antarctica

Marie Šabacká [a], John C. Priscu [a,*], Hassan J. Basagic [b], Andrew G. Fountain [b], Diana H. Wall [c], Ross A. Virginia [d], Mark C. Greenwood [e]

[a] Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, 59717, USA
[b] Department of Geology, Portland State University, Portland, OR, 97207, USA
[c] Department of Biology and Natural Resource Ecological Laboratory, Colorado State University, Fort Collins, CO, 80523, USA
[d] Environmetal Studies Program, Dartmouth College, Hanover, NH, 03755, USA
[e] Department of Mathematical Sciences, Montana State University, Bozeman, MT, 59717, USA

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ABSTRACT

We studied patterns and mechanisms controlling wind-driven flux of soils and associated organic matter in Taylor Valley, Antarctica over a 10-year period using passive aeolian traps and dynamic mass erosion particle counters. Deployment of the particle counters near meteorological stations allowed us to compare the magnitude of soil flux with data on prevailing wind. Particulate organic C, N and P measurements on transported sediment allowed us to examine connectivity of wind dispersed organic matter among landscape units.

Most sediment entrainment occurred within 20 cm of the soil surface during "saltation bursts" that occupied <3% of the total time within a year. These bursts corresponded to periods of strong föhn winds where wind velocities were ≥ 20 m s^{-1}. Sediment movement was highest in the up-valley reaches of Taylor Valley and transport was down-valley towards McMurdo Sound. The general paucity of biological organic matter production throughout the McMurdo Dry Valleys, in concert with low fluvial transport, makes aeolian distribution or organic C, N and P an important factor in the distribution of organic matter throughout this polar desert ecosystem and increases connectivity among the ecosystem components.

1. Introduction

The McMurdo Dry Valleys (MDV) located in Southern Victoria Land comprises the largest (~4800 km^2) ice free area on the Antarctic continent. The landscape of the MDV is dominated by a mosaic of bare soils, perennially frozen lakes, ephemeral streams and glaciers (Moorhead and Priscu, 1998; Priscu et al., 1998). Sub-zero temperatures throughout the year (average air temperature ~ −17 °C) and low snowfall (<50 mm $year^{-1}$ water equivalent) make the MDV region one of the coldest and driest deserts on Earth.

Physical processes are the primary ecosystem drivers within the MDV ecosystem and biological activity is controlled mainly by spatial and temporal distribution of liquid water. Additionally, life in the MDV is constrained by the availability of organic matter and nutrients which are often present in concentrations that are too low to support balanced growth (Dore and Priscu, 2001; Zeglin et al., 2009). Despite the dry and cold conditions, microorganisms persist in soils, lakes, streams and on glaciers (Wall, 2005; Foreman et al., 2007; Stingl et al., 2008). The majority of liquid water in the MDV results from glacial melt during the austral summer (Fountain et al., 1999; 2010). Water that flows from glaciers via ephemeral streams transfers nutrients and particulate organic matter (including microorganisms and metazoans) to the lakes (McKnight et al., 1999). Additionally, aeolian transport distributes sediment, nutrients and organic material throughout the area (Lancaster, 2002; Nkem et al., 2006; Lancaster et al., 2010).

Winds in the MDV are strong and persistent (Doran et al., 2002). Strong down-valley föhn winds, resulting from topographic modification of flow in the lee of the mountain barriers, are frequent in the winter and can increase air temperatures by 30 °C within a few hours (Nylen et al., 2004). Molecular comparison of organisms in stream and lake microbial mats, and cryoconites, sediment melt holes on glacier surfaces, showed that eroded biological material can seed other environments in the MDV with biological material (Christner et al., 2003). Similarly, microorganisms living within lake ice and glacier ice may form when sediment with associated biota is deposited on the glacier or lake ice surface via wind dispersal (Priscu et al., 1998; Gordon et al., 2000). Nematodes, rotifers and tardigrades are also successfully transported via wind and colonize lake-ice and glacier ice surfaces (Treonis and Wall, 2005; Nkem et al., 2006). We investigated the significance of aeolian transport on the dispersal of sediments and associated organic matter across the MDV landscape to test the general hypothesis that the strong föhn winds play a key role in the distribution of organic matter and nutrients within the Taylor Valley. Past research has shown that much of the organic matter in the MDV landscape is attached to lithic particles (e.g., Fritsen et al., 2000). The Taylor Valley was chosen for this study because it is the primary study site for the McMurdo Dry Valleys Long Term Ecological Research program (LTER—www.lternet.edu)

* Corresponding author.
E-mail address: jpriscu@montana.edu (J.C. Priscu).

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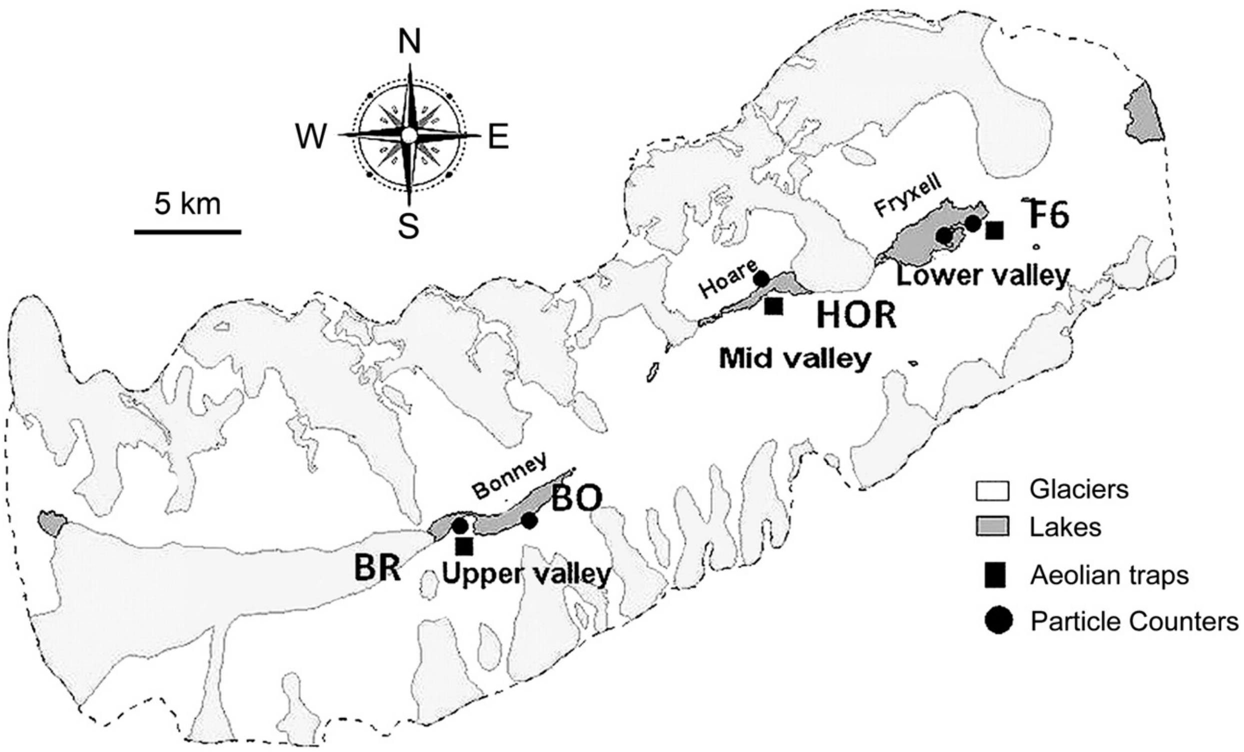

Fig. 1. Map of the Taylor Valley with locations of wind erosion mass particle counters (circles) and passive aeolian sediment traps (squares). BR = Bonney Riegel particle sensor and passive trap; BON = Bonney particle sensor; HOR = Hoare particle sensor and passive trap; FRX = Fryxell particle sensor; F6 = Lake Fryxell particle sensor and passive trap.

that focuses on physical, chemical and biological connectivity across this landscape.

2. Regional setting

The MDV is located in Southern Victoria Land in Eastern Antarctica (Fig. 1). The Ross Sea bounds it to the east and the East Antarctic Ice Sheet to the west. Taylor Valley (~163° E, 77.35° S) is a steep-walled coastal valley extending 33 km from the Taylor Glacier to the Ross sea coastline in a W–E direction. The valley contains three major lakes (Fryxell, Hoare and Bonney), each of which occupy distinct closed drainage basins (Lyons et al., 2000). Summer melt from the surrounding glaciers supplies ephemeral streams and provides the majority of liquid water for the Taylor Valley ecosystem. Approximately 95% of the glacier ice-free landscapes below 1000 m are covered by soils.

3. Materials and methods

3.1. Sampling

Approximately 50 samples of surface (upper 2 cm) sediments were collected from glacier surfaces, streams channels, lake ice and soils throughout the Taylor Valley during the austral summers 2005–2006 and 2006–2007. Sediments in this layer are directly available for wind dispersion. To ensure that the bi-modal wind patterns typical to the Taylor Valley did not impart bias to our data, we collected samples in a weighted fashion across all axes of the sampling sites (e.g., samples were collected across N, S, E and W transects). Cryoconite samples were collected from Commonwealth, Canada and Taylor Glaciers (Fig. 1) along with unconsolidated glacial sediment. Wind dispersed sediment was also collected from the surface of permanent lake ice within each lake basin. Soil samples were collected from 1 km^2 plots along the shoreline of each lake to obtain a representative collection of soils for each basin.

3.2. Dynamic wind mass erosion particle counters

Seven Sensit™ H11B acoustic wind mass erosion particle counters were deployed in close proximity to each passive aeolian trap site (see below) during January 2007 to obtain temporal data on wind dispersion events. Five particle counters were mounted to meteorological station tripods at a height of ~20 cm above the soil surface; additional counters were deployed at 100 cm at 2 sites to measure the vertical distribution of particle flux (Table 1.). Particle counters

Table 1
Location of particle counters and deployment intervals when data were collected within Taylor Valley. msl = mean sea level; N/A = data not collected.

Name	Location	GPS	Elevation (m above msl)	Counter deployment 2007	Couner deployment 2008–09	Particle counter height (cm)
FRX	Lower valley	S: 77.17665 E: 163.16961	18	N/A	N/A	Met data
F6	Lower valley	S: 77.6083 E: 163.2519	20	30 Jan–3 Dec	29 Jan–4 Dec	20 100
HOR	Middle valley	S: 77.02421 E: 162.90041	78	N/A	9 Apr–23 Jan	20
BON	Upper valley	S: 77.714443 E: 162.46416	64	27 Jan–31 Oct	30 Jan–30 Jul	20
BR	Upper valley	S: 77.7248 E: 161.3249	109	29 Jan–28 Oct	30 Jan - 3 Jan	20 100

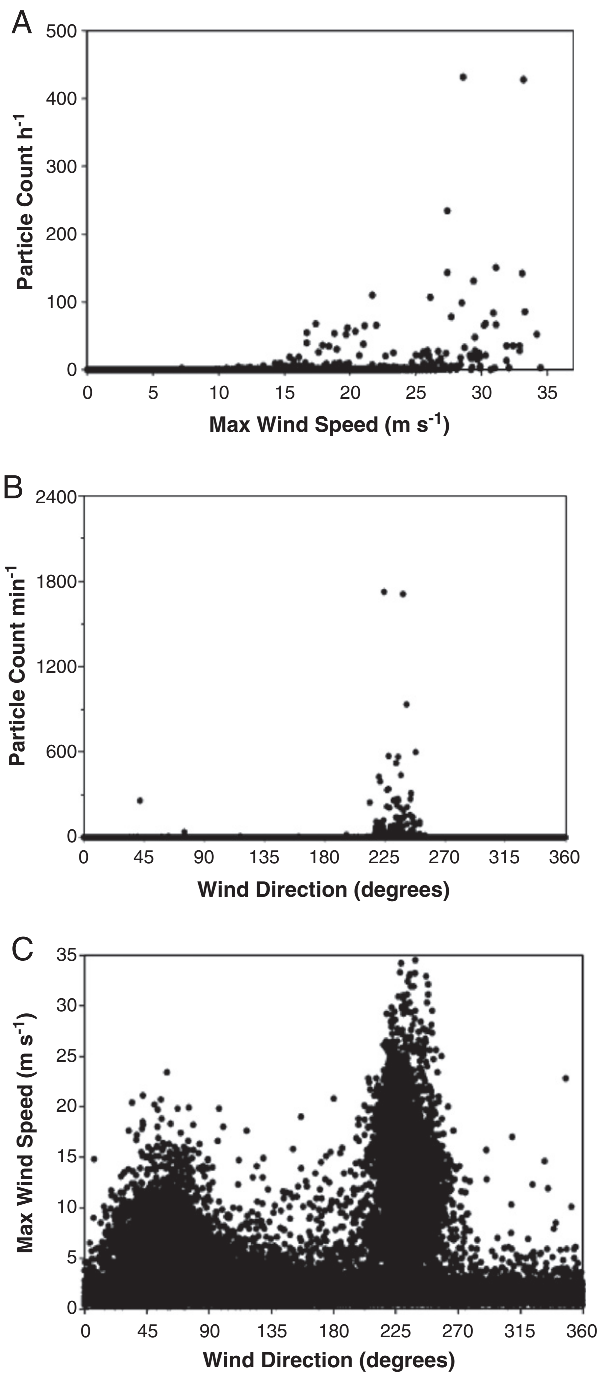

Fig. 2. Example of data collected using wind erosion mass particle counters at F6 site located in lower valley in 2007: A) particle counts versus wind speed; B) particle counts versus wind direction; C) wind speed versus wind direction. The particle counters collected data for discrete 1-minute intervals every 15 min and represent an average over the 15 min period.

were set up to produce a pulse signal proportional to the number of sediment/soil grains that impacts it. The counters were programmed to sample for 1 min every 15 min, a frequency that was required to conserve battery power for year-round deployment. This 1 minute measurement window may have missed short sediment-transport "bursts". Data were stored in Campbell CR10x data loggers and downloaded during the austral spring and summer (November/December 2007 and January 2009).

For the purpose of this study we defined föhn winds as winds that were blowing from the 180–315° and reached maximum wind speeds ≥ 5 m s^{-1} (Nylen et al., 2004). Simple linear regression models were used to test the null hypothesis (H_0) that there is no significant relationship ($\alpha = 0.05$) between frequency of föhn winds and the magnitude of sediment transport. Wind direction, and maximum, minimum and mean wind speed, was obtained from meteorological stations along the shores of Lakes Fryxell, Hoare and Bonney, and on the Bonney Riegel, the latter of which was located between the east and west lobes of Lake Bonney. Wind direction was recorded every 30 s and wind speeds every 4 s at ~3 m above the ground surface with the exception of the Bonney Riegel station where the wind speeds and direction were measured at 1.15 m. It is important to note that the difference in sensor height between Bonney Riegel and the other sites may influence comparisons between stations and between wind velocity and particle flux among stations. The data were averaged at 15 min intervals and recorded by a Campbell CR10x data logger equipped with a solid-state storage module.

3.3. Passive aeolian flux

Three series of nine passive aeolian traps were deployed at different locations within the Taylor Valley (Nkem et al., 2006). Each series of traps formed an elevation transect perpendicular to the south shore of Lakes Fryxell (F6), Hoare (HOR), and the south shore of the west lobe of Lake Bonney (BON) (Fig. 1). This deployment enabled us to capture the flux in the upper (Bonney), middle (Hoare) and lower (Fryxell) parts of valley. The traps were mounted ~30 cm off the ground on a PVC post and consisted of 19.6 cm diameter 8 cm high bundt pans containing 2–3 layers of 2 cm diameter glass marbles covered with a ~3 mm mesh screen. The marbles create an effective boundary layer keeping trapped particles within the pan once deposited there (Lancaster, 2002). From 1999 to 2008, material from the traps was retrieved annually during the austral summer months and stored in the dark at −20 °C in sterile Whirl-Pak®. Samples were weighed and size fractioned into 3 sediment size classes: coarse/medium sand (>250 μm); fine sand (63–250 μm); and silt and clay (<63 μm). Chemical and biological analyses were made on samples collected in 2005 and 2006.

The quantity of material collected from the aeolian sediment traps at each lake basin was used to calculate annual fluxes of sediment between 1999 and 2008. The aeolian flux was calculated as the mass or elemental content of material collected from the sediment trap per year divided by the area of the sediment trap. Fluxes of particulate organic carbon (PC), particulate organic nitrogen (PN) and particulate organic phosphorus (PP) were calculated following the same equation and using data obtained from the aeolian material collected from sediment traps in 2005. Because our data did not meet the requirement of normality for one-way ANOVA, we used Kruskal–Wallis non-parametric comparison (Conover and Iman, 1981) to make statistical comparisons among samples.

3.4. Physical and chemical characteristics of the aeolian sediments

Thawed (4 °C in the dark) sediment samples were size-fractioned into three size classes: coarse/medium sand (>250 μm); fine sand (63–250 μm); and silt and clay (<63 μm) using soil sieves. Physical and chemical characteristics described below were measured for each size class. pH was measured in slurry made by dissolving 2.5 g of sediment in 10 mL of deionized (DI) water and measured with a Beckman "PSI 10" meter. Water content was measured on subsamples of sediments dried at 105 °C for 5 h and reported as the percent difference between dry weight (dw) and wet weight. Organic matter content (OM) was determined as the difference between dry weight and weight of samples combusted at 450° for 5 h. Particulate organic Carbon (PC) and particulate organic nitrogen (PN) were determined for each size fraction using a "Thermo Finnigan Flash 112 EA" elemental analyzer and expresses as mg of PC or PN per g of dry weight. Sediments were fumed over concentrated HCl before analysis to remove

Table 2
Monthly frequencies (% of all wind events) of foehn winds (Teale and Dale) and sea-breezes (SB) winds ≥ 5 m s^{-1} for 2007 and 2008. Frequencies were only calculated for months with full particle count datasets.

	2007						2008					
	F6		BON		F6		HOR		BON		BR	
	SB	*FW*	*SB*	*FW*	*SB*	*FW*	*SB*	*FW*	*SB*	*FW*	*SB*	*FW*
JAN	–	–	–	–	60.7	–	–	–	74.3	–	59.1	7.0
FEB	8.0	2.8	6.4	17.0	32.5	9.1	–	–	38.9	25.8	34.0	33.8
MAR	7.1	10.9	40.8	19.6	4.8	6.0	–	–	8.9	17.0	5.8	21.4
APR	2.4	17.7	13.3	26.1	5.4	12.5	3.8	20.1	3.8	27.0	3.1	32.1
MAY	6.3	19.3	6.5	34.3	4.6	17.4	1.4	25.1	6.3	27.9	6.1	32.9
JUN	8.0	23.8	4.8	38.5	10.8	23.6	4.9	36.6	11.8	48.6	9.8	57.5
JUL	6.5	27.9	6.8	44.1	5.2	14.4	3.0	18.0	8.3	26.9	5.2	31.0
AUG	6.6	25.5	7.7	44.2	3.2	6.4	4.3	11.8	8.9	18.0	5.5	24.0
SEP	7.5	25.9	8.2	40.2	12.6	38.9	7.2	52.3	13.4	64.5	10.0	71.2
OCT	14.9	6.8	16.8	21.9	18.1	4.8	4.3	11.2	30.5	19.6	21.3	28.1
NOV	30.1	5.6	32.3	–	50.9	8.1	20.8	12.1	50.6	23.2	42.5	26.7
DEC	–	–	–	–	45.6	27.3	34.1	7.2	60.0	18.6	53.6	25.6

inorganic carbon. Total particulate phosphorus was determined on combusted (550 °C for 4 h) and noncombusted samples extracted in 1 N HCl following Saunders and Williams (1955) as modified by Walker and Adams (1958) and Olsen and Sommers (1982). Particulate organic phosphorus (PP) was estimated as the difference between phosphorus extracted before and after the destruction of organic matter by combustion. A canonical correspondence analysis (CCA) was performed using the vegan package (Oksanen et al., 2009) in R (R Development Core Team, 2009) to examine the association among soil texture, pH, OM, PC, PN, PP, habitat and location.

4. Results

4.1. Dynamic wind mass erosion particle counters

Only 0.5–3% of all particle counter measurements were positive (non-zero), indicating that aeolian transport of sediments is highly episodic, a trend typical for many arid environments (Stout, 2003). Positive particle counts were highly variable throughout the Taylor Valley. In both 2007 and 2008, significantly higher particle flux ($p<0.001$) was measured in the upper valley, compared to mid and lower valley areas. The highest particle flux was measured at Bonney Riegel (BR) and the Bonney meteorological station (BON) on 28 June 2008, when particle counts reached 7000 particles min^{-1}. A Kruskal–Wallis comparison of particle flux between counters mounted at 20 cm and 100 cm both at F6 and BR revealed that significantly more particles (3–5 times) were transported near the soil surfaces than higher above the ground (F6: $p=0.002$ for 2007 and $p=0.038$ for 2008; BR: $p=0.001$ for 2007 and $p=0.002$ for 2008).

The sensor at F6, in lower Taylor Valley (Fig. 2A), revealed that the number of counts increased sharply at wind speeds approaching 20 m s^{-1}. A similar wind velocity threshold was observed at all sites with the exception of BR in 2007 where high particle flux was initiated even low wind speeds (1–10 m s^{-1}). North-easterly (down valley) föhn mobilized more particles than the up-valley sea breezes (Fig. 2B–C and 3). The monthly frequencies of föhn and sea breezes were calculated for every location in 2007 and 2008 (Table 2). Sea breezes dominated Taylor Valley during the summer months (October–February), while föhn events were more common between March and September. Föhn events were also more frequent in the upper valley Bonney area

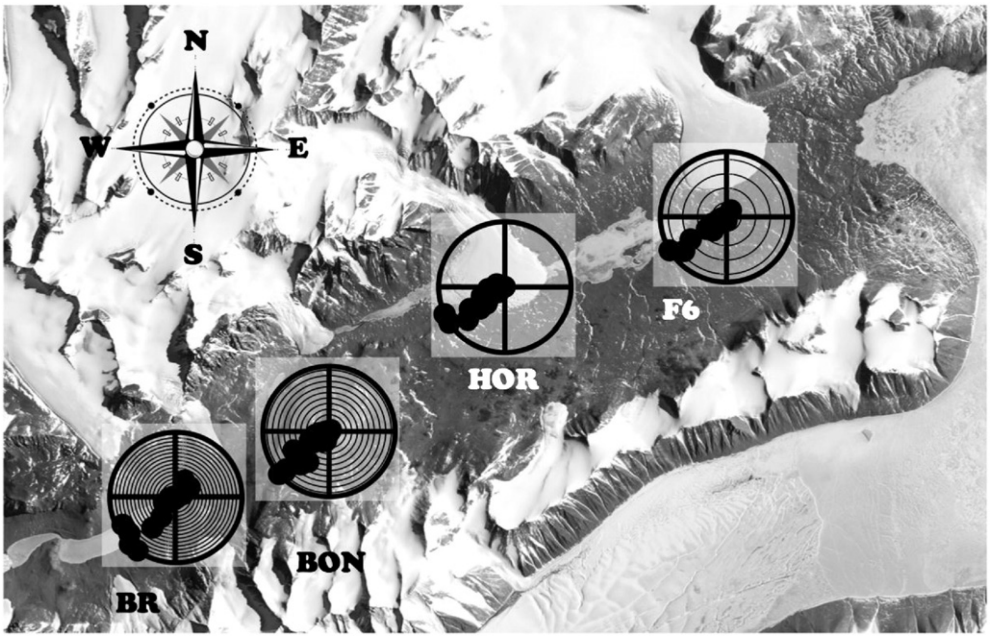

Fig. 3. Polar plots showing the direction and magnitude of particle flux superimposed on a satellite image of the Taylor Valley. The filled circle represents the direction of origin of the aeolian particles; each circle within the polar plots represents 100 particles h^{-1}. Particle counts at the Lake Hoare (HOR) site never exceeded 100 particles h^{-1}, whereas the highest particle counts occurred at the Bonney Reigel (BR) site. Note that the highest particle counts coincided with down valley winds from the southwest.

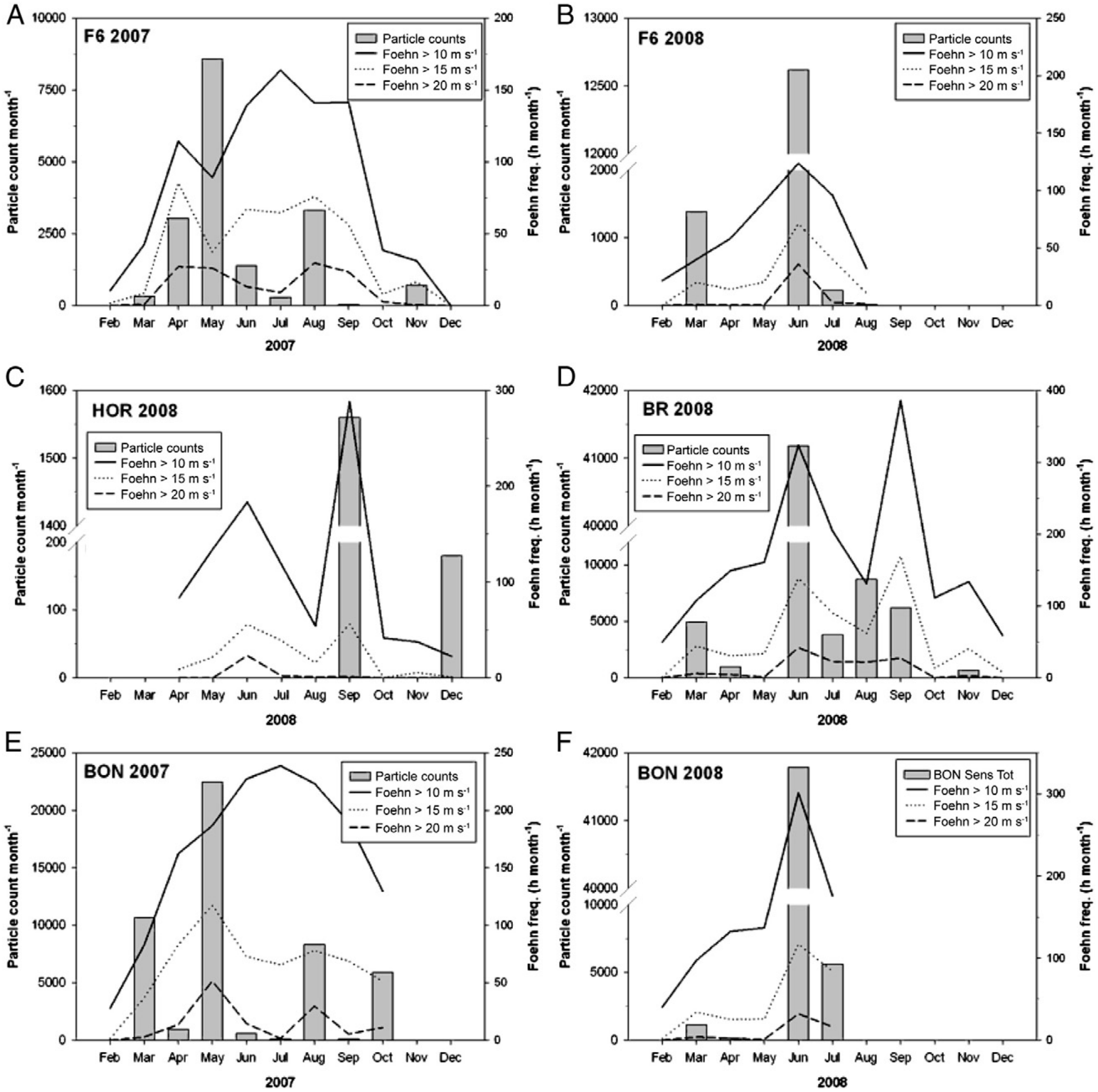

Fig. 4. Total particle counts per month (measured for 1 min every 15 min) during 2007 (A and E) and 2008 (C, D, and F) correlated with the frequency of föhn winds (in hours of föhn activity per month) with thresholds of 10 m s^{-1} (solid lines), 15 m s^{-1} (dotted lines) and 20 m s^{-1} (dashed lines). (A) F6 station in Fryxell area, 2007; (B) F6 station in Fryxell area, 2008; (C) Hoare met station, 2008, y-axis values between 200 and 1400 counts month^{-1} are omitted; (D) Bonney Riegel (BR) in Bonney area, 2008, y-axis values between 12,000 and 40,000 counts month-1 are omitted; (E) Bonney met station, 2007; (F) Bonney met station, 2008, y-axis values between 10,000–40,000 counts month^{-1} are omitted. It should be noted that, owing to logistical constraints, the wind data from the BR station were collected 1.15 m above the ground, while all other wind collections were made at 3 m. Furthermore, the particle counters may have missed short-duration wind "bursts" because particle data was collected at discrete 1 min intervals every 15 min (to conserve power) whereas wind speed and direction were recorded as averages over separate 15 min intervals.

Table 3
Results from X^2 tests for relationships between strong foehn events (wind speeds ≥ 20 m s^{-1}) and sediment transport. F6 is located in the down-valley area, BR and BON are in the up-valley area.

Site/ Year	X^2	p-value
F6/07	159.33	<0.001
F6/08	77.37	<0.001
BON/07	107.48	<0.001
BON/08	101.52	<0.001
BR/08	110.90	<0.001

compared to Lake Hoare or Fryxell areas (Figs. 3 and 4). The seasonal relationship between föhn winds and the particle counts at different locations Taylor Valley becomes more prominent when the velocity of föhn winds exceeds 20 m s^{-1} (Fig. 4).

To assess the relationship between strong föhn events (≥20 m s^{-1}) and detection of airborne sediment, föhn events were compared to daily particle counts at each site for each year. A strong relationship between wind speed and airborne sediment transport using a continuity corrected Pearson's X^2 test for a 2×2 table and 1 degree of freedom was verified (Table 3). Results were not presented for Hoare in 2008 because only four days had detected transport and thus violated the conditions for use of this statistical test. The statistical relationships

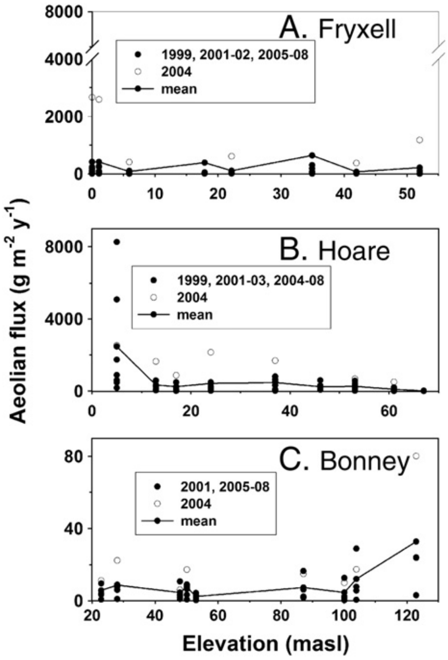

Fig. 5. Aeolian sediment flux between 1999 and 2008 versus elevation (meters above mean sea level: masl) at: (A) Fryxell, (B) Hoare and (C) Bonney. Each circle represents a one-year observation from an aeolian trap located at a specific elevation. Year 2004, when the aeolian flux was unusually high, is marked with white circles. There were no data points between 4000 and 7000 g m^{-2} year^{-1} y-axis in panel "A", thus the values are omitted. All transects were placed in locations within and between basins where visual inspection showed similar topography.

provided strong evidence for positive relationships between strong föhn events and aeolian activity.

4.2. Passive aeolian flux

The flux of airborne sediment collected varied considerably between lake basins and seasonally within any particular lake basin (Figs. 5–7). In the down-valley area near Lake Fryxell, the median aeolian flux was 72.3 g m^{-2} year^{-1}, with the lowest quantity measured in 2006 (7.5 g m^{-2} y^{-1}). In 2004, the flux at Fryxell was 2447.3 g m^{-2} year^{-1}, which was two orders of magnitude higher than the average for this location (Figs. 5A, 6A and 7A). Lake Hoare had the highest aerial flux between 1998 and 2008; the only exception was 2004, when the highest flux was measured at Lake Fryxell. The lowest aeolian flux (59.02 g m^{-2} year^{-1}) at Lake Hoare was measured in 2006 and the highest in 2004 (1260.6 g m^{-2} year^{-1}) and 2007 (1262.5 g m^{-2} year^{-1}). The median value for aeolian flux between 1999 and 2008 was 289 g m^{-2} year^{-1} (Fig. 6B). The aeolian flux in west lobe Lake Bonney was two orders of magnitude lower than at Hoare and one order of magnitude lower than at Fryxell (Figs. 6 and 7). This may reflect the location of Lake Bonney and the trap deployment elevation; Bonney is located further inland and the traps there were placed at higher elevations than at the Fryxell and Hoare basins (Fig. 5). Similar to Fryxell and Hoare, the lowest flux was measured in 2006 (0.83 g m^{-2} year^{-1}) and the highest in 2004 (20.26 g m^{-2} year^{-1}). The median flux between 1999 and 2008 was 8.5 g m^{-2} year^{-1}.

The aeolian flux at Lake Fryxell did not change dramatically from year-to-year across this transect (Fig. 5A). At Hoare, the flux decreased with the distance from the lake and corresponding elevation (Fig. 5B). The largest mass of material was deposited in the trap nearest to the

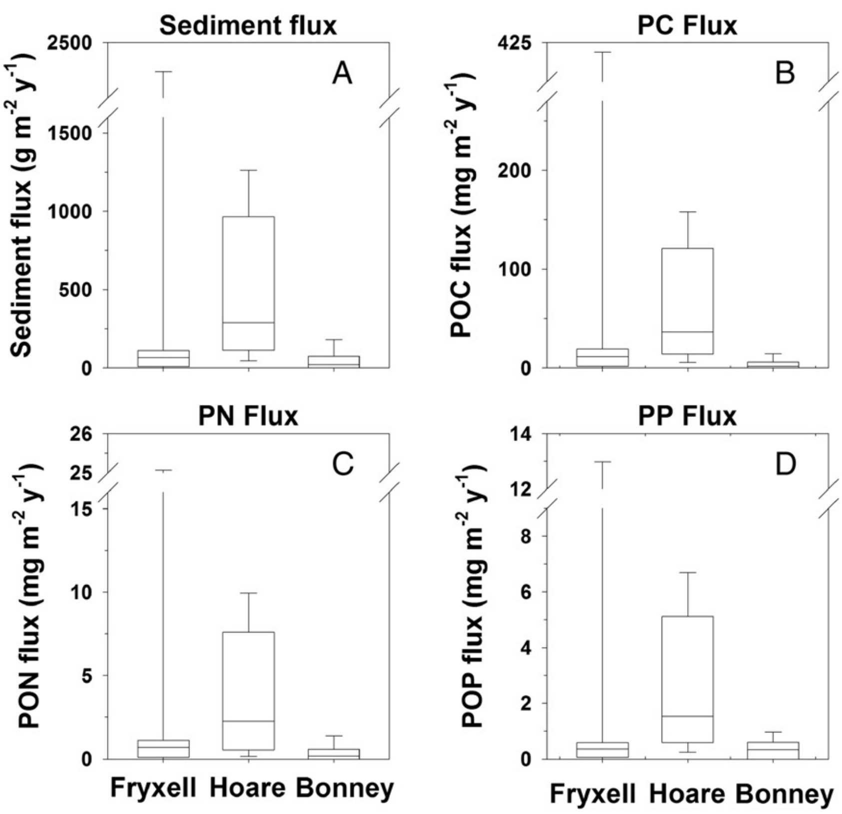

Fig. 6. Kruskal-Wallis test comparing aeolian flux among Fryxell, Hoare and Bonney basins between 1999 and 2008: (A) sediment flux on the *y*-axis values between 1600 and 2400 g m^{-2} year^{-1} are omitted; (B) PC flux on the *y* axis values between 270 and 420 mg C m^{-2} y^{-1} are omitted; (C) PN flux on the *y* axis values between 16–25 mg C m^{-2} y^{-1}; d) PP flux, on the *y* axis values between 9 and 12 mg P m^{-2} y^{-1} are omitted for better clarity. The difference among the median values of the three groups are greater than would be expected by chance ($p<0.05$). The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile of the median. Lines bellow and above the boxes mark outliers. *H* represents the variance of the ranks among the three groups (Conover and Iman, 1981).

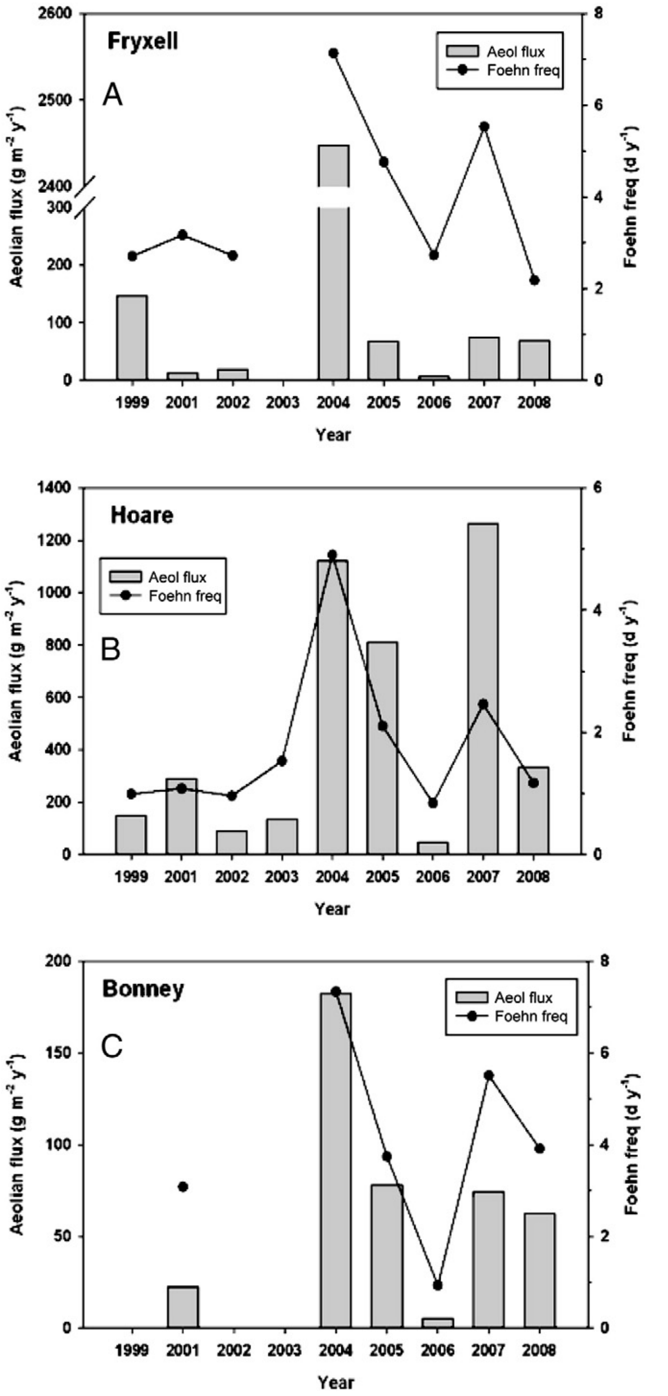

Fig. 7. Aeolian sediment flux (g m year^{-1}; grey columns) plotted against the frequency of strong föhn winds (wind direction: 180-315º, wind speed ≥20 m s^{-1}) in days of föhn activity per calendar year (black lines). (A) Fryxell – values between 300 and 2400 g m^{-2} year^{-1} are omitted on the *y*-axis. The Aeolian fluxes represent averages calculated from sediment traps along each transect.

lakeshore, and comprised one-third (34.2 ± 18.1%) of the mass of all material collected in the Hoare basin. An opposite trend occurred at Lake Bonney where the flux increased with higher elevation and distance from the lakeshore; the material collected from the highest trap accounted for about one-third (33.3 ± 13.2%) of the sediment collected in the Bonney traps (Fig. 5C). Sediment flux throughout the valley was much higher at all locations during 2004. This increase was most prominent in the Fryxell basin where it reached nearly 2500 g m^{-2} year^{-1} compared to the average 60 g m^{-2} year^{-1} for all other years. This increase is related to the 2–3 times higher frequency of strong föhn winds (≥20 m s^{-1}) in 2004 compared to 2006 when low föhn activity corresponded to low aeolian flux at all locations. Higher annual aeolian flux (g m^{-2} year^{-1}) was significantly correlated ($p = 0.01$) with higher frequency of föhn winds ≥ 20 m s^{-1} in all lake basins (Fig. 7; Table 4).

Table 4
The annual aeolian flux (g m^{-2} year^{-1}) in the Taylor Valley is positively correlated ($p < 0.05$) with the frequency of strong (≥20 m s^{-1}) foehn activity (days year^{-1}). The table shows the average magnitude of increase in annual aeolian sediment flux (g m^{-2} year^{-1}) at each lake basin when annual frequency of foehn activity increases by 1 or 24 h year^{-1}.

Location	Increase in flux after 1 h year^{-1} increase in foehn wind	Increase in flux after 24 h year^{-1} increase in foehn wind	p-values (linear regression)
Fryxell	15 g m^{-2} year^{-1}	365 g m^{-2} year^{-1}	0.030
Hoare	12 g m^{-2} year^{-1}	294 g m^{-2} year^{-1}	0.008
Bonney	1 g m^{-2} year^{-1}	26 g m^{-2} year^{-1}	0.009

4.3. Physical and chemical characteristics of the aeolian sediments

The airborne material (average +/− SD) consisted mostly of coarse sand (98 ± 2.15% consisted of particles > 250 μm) and was alkaline (pH = 8.6 ± 0.2) (Fig. 8). The sediment had low water content (0.22 ± 0.09% of dw) and organic matter (OM) content (0.25 ± 0.06% of dw). Similarly, PC (0.119 ± 0.05 mg C g^{-1} dw), PN (8.36 10^{-3} ± 0.003 mg N g^{-1} dw) and PP (2.14 10^{-3} ± 0.03 mg P g^{-1} dw) content was low. There was 1.46 ± 0.39 times more PC, 3.26 ± 1.14 times more PN and 7.8 ± 2.21 of PP in the fine sand (63–250 μm) fraction of the aeolian sediment than in the coarser fraction (> 250 μm). The aeolian material had PC:PN ratios of 13.65 ± 5.12 and PN:PP ratios of 0.72 ± 0.65. On average, the aeolian material contained less organic material and has higher pH than any of the other studied sediments (Fig. 8).

A canonical correspondence analysis (CCA) was performed to relate the physical and chemical characteristics (concentration of silt and clay, pH, water content (WC), OM, PC, PN and PP) to the habitat (aeolian, lake ice sediment, glacier ice sediment, cryoconite and soil) and location (Fryxell, Hoare and Bonney) of collection. The results from a permutation test with 10,000 permutations for each of the marginal effects showed that the habitats ($p = 0.051$) and localities ($p = 0.047$) were related to the suite of physical and chemical characteristics measured (Table 5). The CCA model explained between 30% and 54% of the variation in the different response variables. These results revealed that cryoconite, glacier sediment and Fryxell location were related to sites with higher OM, PC, PN and silt and clay (Fig. 9). Conversely, aeolian sediment was associated with low concentrations of these parameters.

5. Discussion

Strong winds are a common feature in the McMurdo Dry Valleys, Antarctica. Our results, as well as those of Nylen et al. (2004), show high down-valley föhn winds that reach speeds of 40 m s^{-1} and slower up-valley sea breezes that may reach speeds of 20 m s^{-1}. This bimodal nature of the winds is controlled by large scale valley topography and temperature. The fastest down-valley winds occur in winter when temperatures on the polar plateau and McMurdo Sound are greatest. The fastest up-valley winds occur during summer when the temperature difference between the valley floor and McMurdo Sound is greatest. These winds play an important role as a geomorphic agent (Gillies et al., 2009) and soil dispersant (Lancaster, 2002). Aeolian erosion and transport in polar regions is thought to be particularly effective due to persistent high wind speeds and high density of cold air, which increases the drag force on particles, and the general absence of plant cover (Atkins and Dunbar, 2009). Although the extent or mechanisms

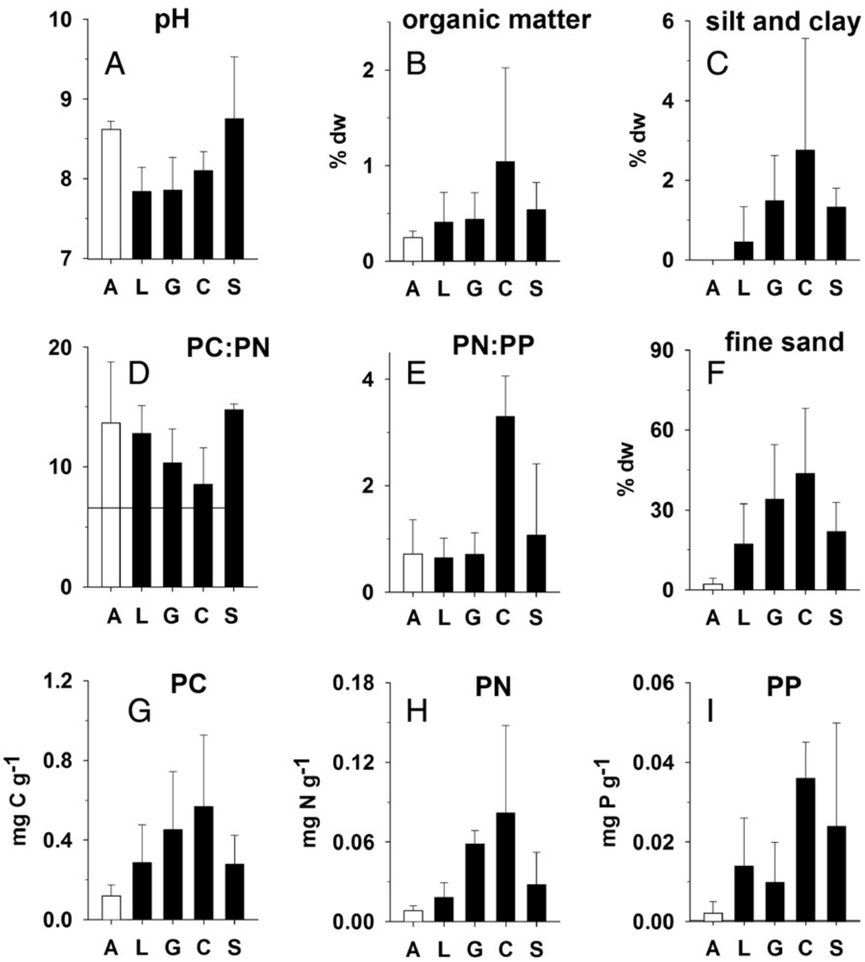

Fig. 8. Physical and chemical characteristics of the aeolian sediment (A); lake ice sediment (L); glacier sediment (G); cryoconite sediment (C); and soils (S). The horizontal line in panel (D) represents the molar Redfield ratio for cellular balanced growth for C:N; all N:P ratios shown in panel (E) are below the Redfield N:P ratio (16:1). The aeolian fluxes represent averages calculated from sediment traps along each transect. Error bars denote one standard deviation from the mean.

of wind influence on ecosystem structure and function in the McMurdo Dry Valleys is not well understood, there is evidence that aeolian deposition alters the biogeochemistry of lake habitats (Priscu et al., 2005; Barrett et al., 2007) and provides an important control over the ice melt and stream chemistry on glacier surfaces (Lyons et al., 2003).

Our data show that the movement of wind-driven sediment in Taylor Valley is controlled largely by winds in excess of 20 m s^{-1}. Wind speeds exceeded this rate only 1–3% of the time, which is typical for intermittent saltation (Stout and Zobeck, 1997; Stout, 2003; Lancaster et al., 2010). The direction of winds within Taylor Valley leads to either down-valley (SW to NE) transport or up-valley transport of material from the ocean (Doran et al., 2002; Nylen et al., 2004). The up-valley sea breezes are most persistent during the summer months, and although they can reach speeds above 20 m s^{-1}, our particle counter data together with visual observation reveal that the these up-valley winds contribute little to the overall aeolian sediment transport in the valley. More than 95% of the aeolian material is transported via strong (>20 m s^{-1}) south-westerly föhn winds, flowing from the Taylor Glacier toward the Ross Sea, which explains why most sediment material

Table 5
Results from the permutation test for the effect of habitat (aeolian, lake ice sediment, glacier ice sediment, cryoconite and soil) and location (Fryxell, Hoare and Bonney) on the physical and chemical responses (silt and clays concentration, pH, water content (WC), organic matter content (OM), PC, PN and PP) from Canonical Correspondence Analysis (CCA). df = degrees of freedom.

Effect	df	F	p-value
Habitat	4	2.13	0.051
Localities	2	2.47	0.047
Residual	20		

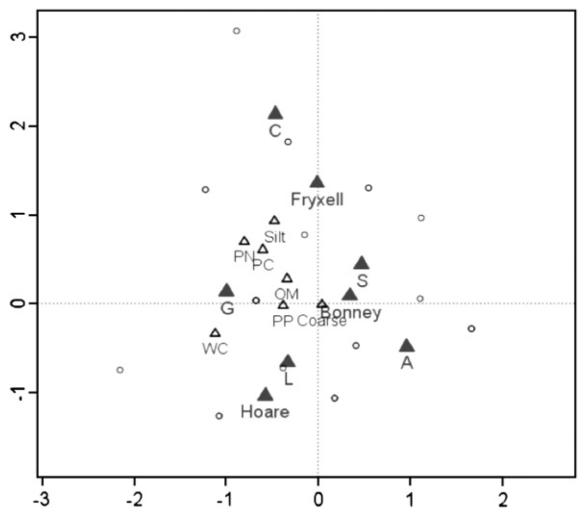

Fig. 9. Plot of the Canonical Correspondence Analysis (CCA) results displaying the linear constraint site scores (circles), response scores (open triangles), and location and habitat centroids (filled triangles). Locations: Fryxell, Hoare and Bonney. Habitats: A = aeolian material, L = lake ice sediment, G = glacial ice sediment, C = cryoconite sediment and S = soils. Response variables: pH, WC (water content), OM (organic matter content), Silt (concentrations of silt and clay fraction <63 μm), PC, PN and PP.

on Canada Glacier is deposited on its western side (Lyons et al., 2003) and provides a viable explanation for why the PC and PN in Taylor Valley soils increases from Lake Bonney to Lake Fryxell (Fritsen et al., 2000).

We observed the highest aeolian flux for the mid-valley area near Lake Hoare and lowest in the upper parts of the valley around Lake Bonney. This is in contrast to a previous study conducted by (Lancaster, 2002), who measured highest aeolian flux around Lake Bonney. Lancaster's measurements of aeolian flux in Hoare and Fryxell area are approximately 2–4 orders of magnitude lower than our data. This discrepancy is presumably the result of differences in the height of trap deployment; our traps were 30 cm above the ground whereas Lancaster's traps were 100 cm above the ground. Data from our wind particle counters clearly showed that aeolian flux is 3- and 5 times higher closer to the ground (at ~20 cm) than at 100 cm. We emphasize that trap locations with respect to local topography may also play a role in modulating sediment fluxes within the Taylor Valley, which could also influence comparisons of our data with those of others.

Of the three Taylor Valley lakes, aeolian transport provides the largest input into the permanent ice of Lake Hoare. Taylor Valley is narrower at the Lake Hoare basin, which might be a factor in explaining the large volumes of aeolian deposits on the lake surface, and small dunes at the eastern end of the lake on the windward side of the Canada Glacier. Also, intrusion of Canada Glacier into Lake Hoare alters the wind pattern and reduces near surface wind speeds, causing the larger particles to fall out. Further down valley, in the Lake Fryxell basin, the valley widens and the aeolian material can be deposited over a much larger area. The aeolian flux varies between lake basins and from year-to-year depending on the frequency of strong föhn winds ($\geq 20\ m\ s^{-1}$). Our data showed that only a few more hours of strong föhn winds per year results in significantly greater volumes of material deposited in our passive soil collectors. This should also be reflected in the deposition onto the surrounding soils and on the lake ice surfaces.

Statistical comparisons of PC, PN and PP showed that the aeolian sediment had the lowest organic matter content within the Taylor Valley soil/sediment habitats. The molar PC:PN ratios of the aeolian sediment, soil and lake and glacier ice sediment range from 10 to 14. These ratios are above the C:N ratio (7:1 by moles) typical of cells in balanced growth, indicating that the organic matter in aeolian sediments is not dominated by actively growing organisms (Sterner and Elser, 2002). The cryoconite sediment had an average PC:PN ratio near 7, implying that the organic matter from these sediments may contain a relatively higher proportion of actively growing cells, a contention supported by biological analysis of cryoconite in this region (Foreman et al., 2007). The PN:PP molar ratios for all samples were less than 4, indicative of nitrogen poor systems with respect to microbial growth (Sterner and Elser, 2002).

Lancaster (2002) suggested that the aeolian material is likely derived from fluvial sediments found around the edges of the lakes or in streambeds, because they are composed of high concentrations of silts and clays similar to the aeolian sediment deposited at traps situated 100 cm above the ground. The material collected in our aeolian traps that were deployed 30 cm above the ground, was, however, composed mostly of coarse sands with <1% of silt and clay particles (<63 μm) showing that fine low-density grains are transported at higher altitudes above ground level than coarser soil particles (Willetts, 1998). This difference may further be related to changes in vertical wind profiles related to local surface roughness. Aeolian transport is also sensitive to small changes in moisture content, due to surface tension that binds the sediment. The critical moisture threshold for aeolian uplift is approximately 4–6% (Wiggs et al., 2004), therefore aeolian transport of fluvial sediments should be enhanced during winter months when the sediments have lower water content. Based on the similarities in the physical and chemical characteristics and PC:PN and PN:PP ratios, we assume that the vast areas of exposed soils are the primary source of aeolian material, rather than microbial mats associated with streams and lake margins. Despite the relatively low amount of cellular matter in the aeolian sediments, this material may provide an important seed for habitats on glacier and lake ice surfaces.

Air temperatures in Antarctica are expected to rise in the next century (IPCC, 2007; Walsh, 2009), which may lead to changes in synoptic scale circulation patterns in the troposphere over the Ross Sea Region (Speirs et al., 2010). Such changes are expected to affect the frequency and intensity of strong föhn winds in the MDV area. Such climate induced wind activity should enhance sediment and particulate organic matter transport through the McMurdo Dry Valleys increasing connectivity among ecosystem components and leading to a more homogeneous landscape.

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