Biotic and abiotic factors influencing soil properties across a latitudinal gradient in Victoria Land, Antarctica

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Abstract

Through the cooperative efforts of the Scientific Committee on Antarctic Research (SCAR) Evolution and Biodiversity in Antarctica (EBA) Project and the Latitudinal Gradient Project (LGP), a monitoring network was established in Victoria Land in 2002 to assess the impacts of climate change on vegetation, soils, active-layer dynamics, and permafrost across a latitudinal gradient. In this study, we report on the key factors influencing soil development across the gradient, including vegetation, parent material characteristics, and climate. Physical and chemical soil properties at depths of 2-8 and 10-20 cm were investigated at 7 sites and on 14 permanent plots from Apostrophe Island in Northern Victoria Land (73°30′S, 167°50′E) to Granite Harbour in Southern Victoria Land (77°00′S, 162°26′E) along the Ross Sea coast. The relationships among vegetation, parent material, and regional climate and soil properties were tested with Principal Component Analyses. There were no significant correlations or relationships in soil properties across the climate gradient. In fact, local microclimatic appears to be more effective than the regional gradient in influencing the properties. Microclimate was also important relative to active-layer depth and vegetation distribution. Lithology was strongly related to several chemical parameters, notably extractable Al, Fe, Ca, K, but was unrelated to grain-size distribution. Vegetation was related to the chemistry of the surface-soil layer, including nitrate, organic carbon, C/N ratio and water content, and also the active-layer depth. Penguins had the greatest influence on soil properties in initiating the development of ornithogenic soils. Further analyses on soil properties, including a greater number of sites, will be required to represent more extensively the lithological variability and to extend the latitudinal extremes of the gradient. The results presented here are an important reference for future monitoring activities in Victoria Land.
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1. Introduction

Polar regions are important for assessing and monitoring climate change impacts on biotic and abiotic components of Antarctic ecosystems (i.e. Convey, 2001; Doran et al., 2002; Geringhausen et al., 2003; Vaughan et al., 2003; Cook et al., 2005; Turner et al., 2005). Changes in climate may affect vegetation, soil properties, active-layer dynamics, and permafrost in different ways and these environmental components may interact through complex mechanisms, activating both positive and negative feedbacks. These topics have been studied only recently in Antarctica (Melick and Seppelt, 1997; Barrett et al., 2006a, 2006b; Beyer et al., 2000; Cannone et al., 2006; Guglielmin et al., 2005, 2008-this issue; Bockheim, 2008-this issue). Moreover, vegetation and active layer dynamics play an important role in the carbon cycle (cf., Oechel et al., 2000; Mack et al., 2004; Chapin et al., 2005), although the carbon content of Antarctic soils is much lower than in the Arctic.

In Antarctica, international panels are addressing the problem of how to detect the effects of climate change on ecosystems. In particular, within the framework of the Scientific Committee on Antarctic Research (SCAR) Evolution and Biodiversity in Antarctica (EBA) program, formerly the Regional Sensitivity to Climate Change in Antarctic terrestrial and limnetic ecosystems (RiSCC) project, specific research protocols have been developed for assessing and monitoring climate change impacts on vegetation, soils, and permafrost. Their main approach is to set

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up networks along latitudinal and environmental gradients (Cannone and Guglielmin, 2003; Cannone, 2004, 2006).

In the frame of the SCAR project EBA and, in cooperation with the Latitudinal Gradient Project (LGP), a monitoring network was established in 2002 and 2003 to assess the impacts of climate change on vegetation, soils, and permafrost in Victoria Land (Continental Antarctica) across a latitudinal gradient (Cannone, 2006). The network includes 7 sites and 14 permanent plots and is located along a latitudinal gradient from Apostrophe Island (73°30′S, 167°50′E) in Northern Victoria Land to Finger Point (Granite Harbour) (77°00′S, 162°26′E) in Southern Victoria Land. Plots are located at key sites along this gradient so as to include a coastal transect and a coast–inland sub-transect in the Terra Nova Bay area. The study sites were selected on the basis of the results of a latitudinal-transect study that investigated 25 sites from Cape Hallett (72°76′S, 169°56′E) to Lake Fryxell (77°35′S, 163°20′E) (Cannone, 2005).

Here we report on work carried out at seven coastal transect sites in Victoria Land to analyze changes in physical and chemical properties of soils in relation to parent material and vegetation conditions along the climatic gradient. The main aims of the paper are to:

1) describe the main physical and chemical parameters of the soils within the monitoring network as a reference for future monitoring activities;

2) assess the relationships between the soil characteristics and a) the latitudinal gradient, b) the lithology, c) the vegetation.

2. Study Sites

The study area is located in Victoria Land, East Antarctica where, within the main latitudinal network, seven sites and 14 permanent plots were investigated from Apostrophe Island (73°30′S, 167°50′E) to Finger Point (Granite Harbour) (77°00′S, 162°26′E) (Fig. 1). The climate of Victoria Land is a frigid Antarctic one, with a gradient of increasing mean annual air temperature (MAAT) from (a) Southern Victoria Land, with MAAT of −19.9 °C at Scott Base (77° 51′ S; 167°46′E) over the period 1957-2005 (Harper, unpublished), to (b) Boulderclay (74°43′ S, 164°05′E), in the vicinity of Mario Zucchelli Station (Terra Nova Bay area), with MAT of -16.4 °C to −15.1 °C in the period 1997-2003 (Guglielmin, 2006), to (c) Cape Hallett, where the MAT is c. −15.3 °C (Duphorn, 1981). Precipitation, always in the form of snow, is very low and ranges between 100 and 200 mm (Grigioni et al., 1992).

All sites are located along the coast, with the exception of Tarn Flat, which is inland on the slope area before the plateau. They have a similar altitudinal range (10 - 250 m a.s.l.) so that comparable data, not influenced by elevation, are obtained for assessing relationships along the latitudinal gradient. The sites represent the most common environmental conditions, and almost all the rock substrates were sampled (i.e. granite, basalts,
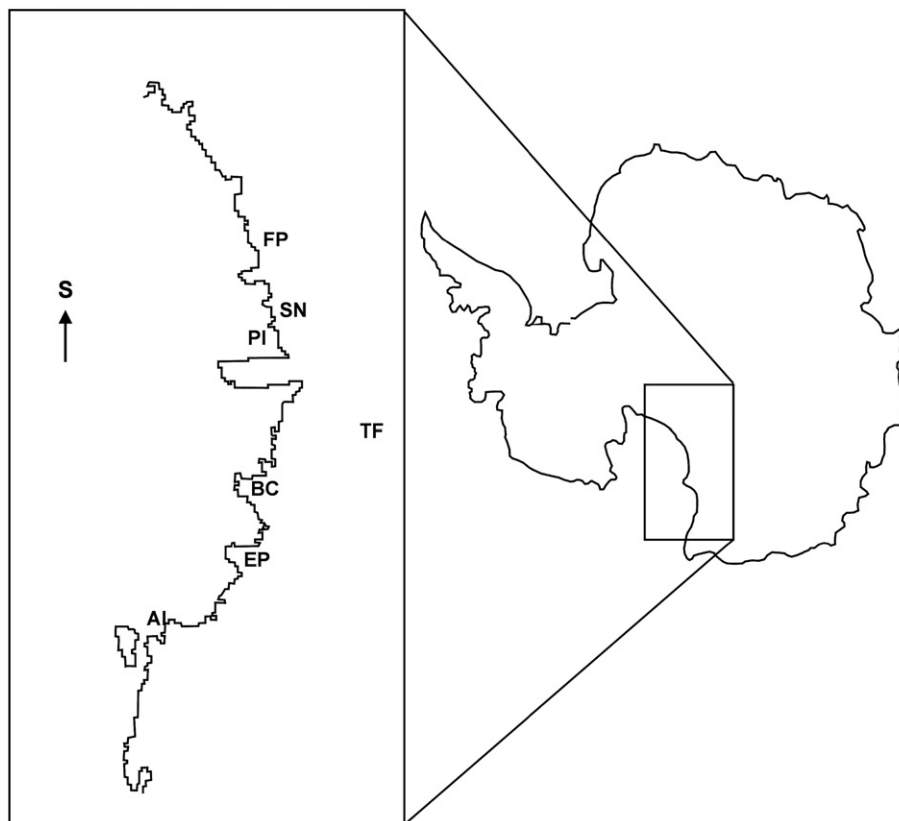

Fig. 1. Location map of the investigated sites in Victoria Land. Legend: AI = Apostrophe Island, BC = Boulder Clay, ED = Edmonson Point, FP = Finger Point, PI = Prior Island, SN = Starr Nunatak, TF = Tarn Flat.

gabbro, metamorphic rocks, morainic and marine deposits). Some sites have ornithogenic soils. All the sites are located in ice-free areas, most of them very close to glacial boundaries, and are characterized by the occurrence of continuous permafrost with an active layer thickness ranging from 20 cm to more than 100 cm (Guglielmin and French, 2004), and, in one case (Apostrophe Island, permanent plot 7), by the occurrence of patterned ground.

The vegetation of Victoria Land is composed exclusively of cryptogams. Previous descriptions of the moss and lichen flora and of the main vegetation communities have been provided (Kappen, 1985; Wynn-Williams, 1985; Schwarz et al., 1992; Castello and Nimis, 1995; Seppelt et al., 1995, 1996; Seppelt and Green, 1998; Smith, 1999; Cannone, 2005). The vegetation of the Victoria Land monitoring network includes four main vegetation types, respectively dominated by a) mosses, b) mosses encrusted by epiphytic lichens, c) macrolichens, and d) scattered epilithic lichens and mosses. Cannone (2006) described the vegetation of the permanent plots of the monitoring network in detail.

The soils of Victoria Land are Gelisols: while in the Dry Valleys of Southern Victoria Land Anhyortels and Anhyturbels are prevalent (Bockheim, 2002), in Northern Victoria Land data on the soil classification are still lacking.

3. Methods

3.1. Field

At each permanent plot, pits were dug for describing and sampling soils. Due to the thin active layer, the very coarse texture, and logistical problems, the maximum depth of the pits was 55 cm. To obtain comparable data from all the investigated sites and plots, soils were sampled at two depths, from 2 to 8 cm and from 10 to 20 cm. Where there was evidence of accumulation of organic matter at the surface, a surface layer (between 1 and 3 cm) was collected. Soil samples were immediately stored at -20 °C and sent in frozen state to the Alfred Wegener Institute (AWI) laboratory for the chemical and physical analyses.

Maximum thawing depth at the moment of the sampling (from mid December to mid January) was estimated by using a frost probe according the CALM (Circumpolar Active Layer Monitoring) protocol (Nelson et al., 1998) at least on 5 different points within the plot and excluding all the measurements hindered by the occurrence of stones in the ground. In some sites also the temperature was measured, according to Guglielmin (2006), to estimate the maximum depth of the permafrost table (0 °C isotherm).

3.2. Laboratory

Soil samples were oven dried at 105 °C for 24 hours. The water content was calculated by taking the difference between the fresh sample weight and that of the dried sample. Particle-size analysis was performed by sieving for gravel and sand, and using a hydrometer for silt and clay (Day, 1965). All chemical analyses were carried out on the <2 mm soil fraction. Water-soluble cations and anions were extracted by a modified method of the Gerasimov and Glazovskaya (1965). A 1:1 soil to distilled water suspension was used for determining pH. Electric conductivity was carried out using a conductivity bridge and cell. Total carbon (TC) and total nitrogen (TN) contents were determined with an automatic element analyser (Elementar VARIO EL III). The total organic carbon (TOC) content was measured on corresponding samples after HCl (10%) acid digestion to remove the carbonate on the same analyser (Elementar VARIO EL III). The C/N ratio was calculated on the basis of TOC and TN values. The dried original sample (2 g) was diluted with 50 ml of distilled water and, after 3 minutes stirring and filtration through a 0.45-µm cellulose acetate filter. Water-extractable cations were analysed with an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Perkins Elmer) and anions with an Ion Chromatograph (DX320, DIONEX Corp., USA). For all chemical analyses analytical precision was checked using international standards (NBS, SRM).

The number of chemo-organotrophic bacteria was determined on agar plates using a 10-fold serial dilution of sediment in growth medium. The agar medium was prepared according to the protocol of Bunt and Rovina (1955) for Antarctic soils. For each sample, three agar plates were inoculated with 0.1 ml from each dilution and incubated for 3 weeks at 18 °C. Cell numbers were determined by counting the colonies and taking into account the individual dilution steps.

3.3. Statistical analyses

Pearson correlation matrices were calculated by means of the software Statistica 6.0 made by StatSoft®, and Principal Component Analyses (PCA) were performed using the software CANOCO for Windows (ter Braak and Šmilauer, 1998). In particular, for all PCA the data were log transformed, the scaling was made through the inter-species correlation, the standardization by species was centered, and the sample standardization was centered and normal. A table with the eigenvalues and the percentage of variance was reported for each analysis.

4. Results

Soil properties were analyzed in relation to different abiotic and biotic environmental factors, including site location, latitudinal (and associated climatic) gradient, lithology, and vegetation.

4.1. Soil properties in relation to site

Seven sites, one inland and six coastal, were investigated (Table 1). No evidence of cryoturbation was observed in the investigated sites, and only in correspondence with AI7 did a frost-fissure polygon occur. Holocene raised beaches were not included in the selected sites. Generally the sites are far both from streams and ponds or lakes, except for Edmonson Point. Ornithogenic soils occur at the PP6 site at Prior Island, although

Table 1
Location and main characteristics of the study sites * active layer thickness obtained by thermal data

Sites	Coordinates	Elevation (m a.s.l.)	Plot Number	Location	Lithology	Slope and Aspect	Active Layer (cm)	Vegetation Coverage (%)	Vegetation Type	Soil sample label	Soil sample depth (cm)	Soil classification (ST)
Apostrophe Island	73°30′ S 167° 50′ E	50	PP7	Coast	Morainic deposits (Gabbro)	2°; S	43	53.4	Macrolichens (*Usnea sphacelata*)	A17_1 A17_2	3-8 12-18	Glacic Haploturbels
Apostrophe Island	73°30′ S 167° 50′ E	50	PP8	Coast	Morainic deposits (Gabbro)	3°; W	45	4.8	Scattered epilithic lichens and mosses (*Bryum argenteum*)	A18_1 A18_2	0-6 6-21	Glacic Haplorthels
Edmonson Point	74° 19′ S 165° 07′ E	40	PP1	Coast	Alluvial sediments (Basalts)	2°; E	41*	83.8	Mosses (*Bryum argenteum, B. pseudotriquetrum, Ceratodon purpureus*)	EP1_1 EP1_1b	3-5 3-5	Aquic Psammorthels
Edmonson Point	74° 19′ S 165° 07′ E	40	PP2	Coast	Alluvial sediments (Basalts)	3°; E	82*	88.1	Mosses (*Syntrichia princeps*)	EP2_1 EP2_2	3-7 12-16	Aquic Haplorthels
Edmonson Point	74° 19′ S 165° 07′ E	50	PP3	Coast	Weathering bedrock (Basalts)	2°; E	48*	0	No vegetation	EP3_1 EP3_2	3-6 12-15	Lithic Haplorthels
Boulder Clay	74°30′ S 164° 05′ E	150	PP10	Coast	Morainic deposits (granite)	2°; E	62	11.2	Scattered mosses (*Bryum subrotundifolium, Schistidium antarctici*) and epilithic lichens	BC10_1 BC10_2	1-3 3-9	Glacic Haplorthels
Tarn Flat	74°59′ S 162° 37′ E	100	PP14	Inland	Morainic deposits (granite)	5°; S	42	0.8	Scattered epilithic crustose lichens	TF14_1 TF14_2	2-4 10-15	Glacic Haplorthels
Tarn Flat	74°59′ S 162° 37′ E	20	PP17	Inland	Morainic deposits (granite)	2°; W	58*	1.3	Scattered epilithic crustose lichens	TF17_1 TF17_2	1-3 10-15	Glacic Psammorthels
Prior Island	75° 41′ S 162° 52′ E	150	PP4	Coast	Morainic deposits (granite)	2°; E	55	46.5	Mosses (*Schistidium antarctici, Sarconeurum glaciale*) encrusted by lichens (*Candelariella, Xanthoria*)	PP4_0	0-3	Glacic Haplorthels
Prior Island	75° 41′ S 162° 52′ E	150	PP6	Coast	Morainic deposits (granite)	3°; SE	47	10.9	Scattered epilithic lichens (*Buellia frigida, Xanthoria*)	PP6_0 PP6_1 PP6_2 PP6_3 PP6_3b	0-3 3-6 6-15 15-30 15-30	Glacic Haplorthels
Starr Nunatak	75° 53′ S 162° 33′ E	150	PP15	Coast	Morainic deposits (granite)	2°; NE	65	60.8	Mosses (*Sarconeurum glaciale*) encrusted by lichens (*Physcia caesia*)	ST15_1 ST15_2	2-7 10-16	Glacic Haplorthels
Starr Nunatak	75° 53′ S 162° 33′ E	150	PP16	Coast	Morainic deposits (granite)	2°; SW	82*	2.8	Scattered epilithic lichens (*Buellia frigida, Lecidella siplei*)	ST16_1 ST16_2 ST16_3	2-4 7-13 22-27	Glacic Haplorthels
Finger Point	77° 00′ S 162° 26′ E	20-50	PP9	Coast	Morainic deposits (granite)	3°; E	62	95.8	Mosses (*Schistidium antarctici, Bryum* spp.) encrusted by lichens (*Lecidella siplei*)	FP9_0 FP9_1 FP9_2	2-4 7-11 20-25	Glacic Haplorthels
Finger Point	77° 00′ S 162° 26′ E	20-50	PP19	Coast	Morainic deposits (granite)	2°; N	73	0.7	Scattered epilithic lichens (*Lecidella siplei*)	FP19_0 FP19_1 FP19_2	0-4 5-9 14-21	Glacic Psammorthels

Table 2
Chemical and physical soil parameters of the investigated sites. Bacteria are calculated as cell number per gram (number/g) divided by 100

| Sample	pH	Cond (µs/cm)	F⁻(mg/l)	Cl⁻(mg/l)	SO_4^- (mg/l)	Br⁻ (mg/l)	NO_3^- (mg/l)	PO_4^- (mg/l)	HCO_3^- (mg/l)	Al (µg/l)	Ca (mg/l)	Fe (µg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	P (mg/l)	Si (mg/l)	BacteriaCell (n)	Corg (%)	N (%)	C/N	Sand (%)	Silt (%)	Clay (%)	Water (%)
AI7_1	5.5	15.2	0.3	1.8	1	<0.1	1.1	0.4	2.3	89.9	<0.1	33.7	0.3	<0.1	2.7	0.1	0.5	798	0.3	0.1	3.2	75,7	22,5	1,8	7
AI7_2	5.6	12	0.2	1.2	0.6	<0.1	0.9	0.5	2.9	35.3	<0.1	<20	0.4	<0.1	2.1	0.1	0.8	953	0.3	0.1	4	80,9	17,3	1,8	7.9
AI8_1	5.5	14.4	0.1	1.2	0.7	<0.1	2.1	0.3	1.7	33.8	0.1	30.1	0.3	<0.1	2.1	0.1	0.5	234	0.2	0.8	0.3	67,5	31,1	1,4	4.4
AI8_2	5.8	8	0.1	0.7	0.5	<0.1	0.4	0.5	1.8	37.5	0.2	23.1	0.2	<0.1	1.3	0.1	0.7	122	0.2	0.7	0.3	69,4	29,2	1,4	4
EP1_1	5.7	25.5	0.2	1	0.9	<0.1	7.5	0.2	3.1	30.3	0.6	24.5	0.9	0.3	3.8	0.2	0.1	17	1.6	0.2	7.4	91,5	7,5	0,9	30.3
EP1_1b	5.5	26.2	0.2	1.5	0.9	<0.1	7.1	0.3	2.6	<20	0.6	<20	1	0.3	3.7	0.1	<0.1	59							
EP2_1	5.9	8.5	0.1	0.5	0.2	<0.1	1.5	0.1	3.2	38.7	<0.1	29.2	0.3	<0.1	1.6	<0.1	0.2	10	0.5	0.1	4.5	67,3	32,5	0,2	27.6
EP2_2	5.9	7	0.2	0.7	0.2	<0.1	0.6	0.2	1.6	73.8	<0.1	35.1	0.2	<0.1	1.3	<0.1	0.2	1553	0.2	0.6	0.3	80,5	17,6	1,9	
EP3_1	5	25.2	0.5	4.5	1.36	<0.1	1.4	0.7	1	42.2	0.2	72.3	0.5	<0.1	4.9	0.2	0.1	5546	0.1	0.1	1.9	95,8	4,2	0,0	16
EP3_2	6	17.3	0.2	3.5	0.8	<0.1	0.6	0.2	1.6	<20	<0.1	<20	0.3	<0.1	3.2	<0.1	<0.1	89	0.2	0.1	3.1	89,7	9,6	0,7	17.5
BC10_1	6	14.9	0.1	1	0.4	<0.1	2.9	0.2	3.2	134.7	<0.1	122.1	0.2	<0.1	3	0.2	0.3	772	0.2	0.6	0.3	89,0	7,9	3,1	0.9
BC10_2	6.2	7.5	0.1	0.4	0.3	<0.1	0.4	0.3	2.7	246.6	0.1	219	<0.2	<0.1	1.7	<0.1	0.5	585	0.2	0.6	0.3	62,5	21,4	16,2	5.1
TF14_1	5.5	6.9	0.1	0.3	0.6	<0.1	1.1	<0.1	0.7	44.7	<0.1	51.2	<0.2	<0.1	1.2	<0.1	0.1	613	0.1	0.1	2	95,6	4,2	0,2	5.9
TF14_2	5.7	4.9	0.1	0.3	0.3	<0.1	<0.2	<0.1	1.7	28.5	<0.1	25.4	<0.2	<0.1	0.9	<0.1	0.2	34	0.1	0.1	1.7	84,1	14,2	1,7	5.3
TF17_1	5.7	20.3	0.5	1.9	0.8	<0.1	0.3	<0.1	7.3	496	0.3	486.9	0.6	0.2	4.4	<0.1	1.4	44	0.2	0.1	2.8	67,9	13,8	18,4	5.4
TF17_2	5.7	16.7	0.5	0.4	0.4	<0.1	<0.2	0.2	8.2	401	0.5	325.6	1	0.2	2.8	<0.1	2.1	4520	0.2	0.1	2.6	67,8	11,6	20,6	2.6
PP4_0	5	70.1	0.1	3	2.4	<0.1	24.6	2.3	1.3	29.1	1.6	25.9	4	1.1	4.3	1.1	<0.1	215	1.2	0.2	5.5	96,1	2,1	1,8	
PP6_0	6.4	418	1.5	100.4	6.4	0.2	<0.2	51	38.4	69	1.2	81.1	11.2	7.2	60.2	17.8	0.2	562	3.2	0.6	4.9	85,8	8,7	5,5	3.8
PP6_1	7.6	649	6.2	62.8	8.4	0.2	22.5	285	154	45.5	0.7	49.9	11.3	33.2	66.8	87.7	0.3	3206	4	1.4	2.9	74,8	22,7	2,5	0.7
PP6_2	7.4	530	4.1	46.9	9.4	0.1	11.4	207	122.6	33.4	0.4	53.9	8.6	18.7	60.5	66.5	0.2	1	3.1	1.2	2.7	85,8	1,0	13,1	0.7
PP6_3	7.6	559	3.1	42.2	22.3	0.1	19.3	206	113.6	155.5	0.6	244.8	14.7	2.32	92.6	73.3	0.4	1046	0.7	0.4	1.7	88,8	7,3	3,9	1.4
PP6_3b	7.5	448	2.3	35.9	18.6	0.1	16.4	156	87.5	113	0.4	172.3	11.3	1.4	76.4	52	0.3	41							
ST15_1	5.2	9.2	0.05	0.5	0.1	<0.1	1.9	1.5	1.5	22.1	0.2	<20	0.4	<0.1	1.1	0.5	<0.1	836	0.9	0.2	4.6	95,8	3,0	1,2	2.9
ST15_2	5.5	3.9	<0.1	0.2	0.1	<0.1	<0.2	1.1	2.2	<20	<0.1	<20	<0.2	<0.1	0.5	0.3	<0.1	109	0.2	0.1	2.9	94,9	4,6	0,5	1.5
ST16_1	5.7	13.6	<0.1	1.38	0.9	<0.1	0.6	2.7	3.2	26.1	<0.1	30.3	0.4	<0.1	2.7	0.9	0.1	7	0.1	0.1	1.7	91,9	7,0	1,1	0.7
ST16_2	5.6	5.5	<0.1	0.4	0.3	<0.1	0.3	1.31	2	21.5	<0.1	<20	<0.2	<0.1	1.1	0.4	<0.1	13	0.2	0.1	2.5	84,0	14,4	1,6	6.1
ST16_3	5.5	3.9	<0.1	0.2	0.2	<0.1	<0.2	0.9	1.3	<20	<0.1	<20	<0.2	<0.1	0.7	0.3	<0.1	36	0.2	0.1	2	85,5	10,7	3,8	4
FP9_0	5.7	20.5	<0.1	1.2	0.6	<0.1	5.5	0.2	3.7	112.2	1.2	106.2	0.9	0.4	1.6	0.1	0.3	5	1.5	0.5	2.9	83,8	11,1	5,1	14.9
FP9_1	5.6	10.1	<0.1	0.9	0.4	<0.1	1.1	0.6	3.2	134.9	0.4	133.3	0.5	0.1	1.1	0.2	0.4	101	0.6	0.1	5.5	46,3	34,2	19,5	12.6
FP9_2	5.5	8.2	<0.1	0.7	0.2	<0.1	0.9	0.6	1.7	99	0.3	95.6	0.4	0.1	0.9	0.2	0.3	0							
FP19_0	9.9	1046	2	182.7	113.7	0.3	2.9	1	186.4	879.4	0.5	1263.8	4.3	0.5	228.4	0.3	2.3	0	0.2	0.1	2.8	77,7	19,1	3,2	23.7
FP19_1	7.2	141.2	0.3	24	13.8	0.05	0.2	0.3	18.8	303.2	0.3	457.4	0.7	0.2	33.8	<0.1	0.8	0	0.3	0.1	3.9	89,5	10,1	0,5	0.7
FP19_2	6.1	22.5	0.3	3.8	0.7	<0.1	<0.2	1.3	4.8	952.1	0.2	729.5	0.7	0.2	4.5	0.4	2.4	134	0.2	0.1	2.8	86,3	12,2	1,5	2.2
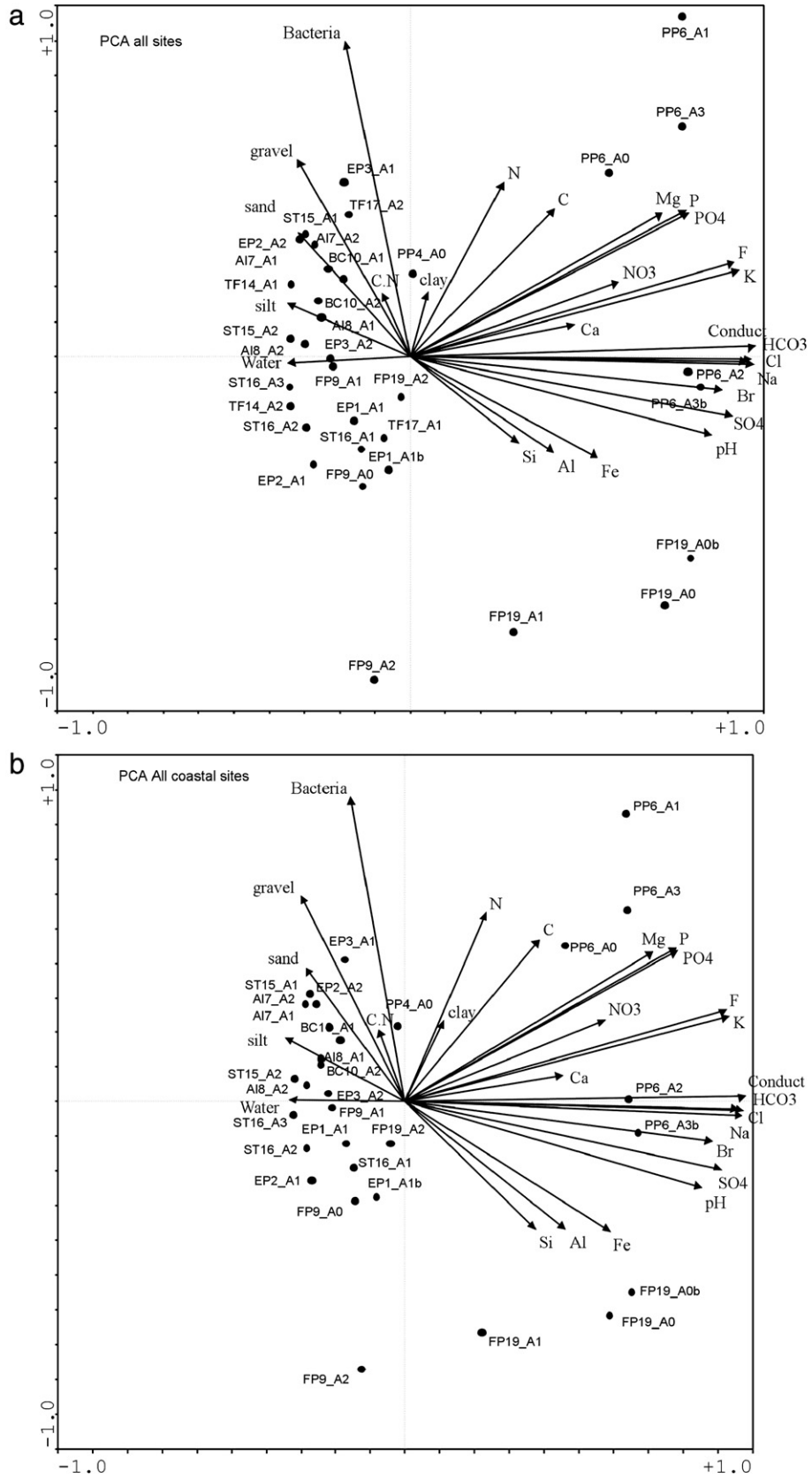
Fig. 2. a. Principal Component Analysis of all the investigated sites. See Table 2 for abbreviations. b. Principal Component Analysis of the coastal sites. See Table 2 for abbreviations.

there is no modern penguin rookery nearby. The active layer is highly variable among as well as within sites. All the investigated soils are Gelisols (Soil Survey Staff, 2006) (Table 1). Most of them are Haplorthels (with one lithic haplorthels, EP3, one Acquic Haplorthels, EP2, and the others being Glacic Haplorthels), three are Psammorthels (EP1, TF17, FP19) and only one soil (AI7) is a Glacic Haploturbels.

The physical and chemical parameters of the soils change within as well as among sites (Table 2). Soil pH (4.99-9.92) ranges from very strongly acid to very strongly alkaline, with conductivity, F, Cl, sulfate, phosphate, Al, and Fe also showing wide ranges of variation. Organic C and total N are generally very low. Grain size is coarse or very coarse in all sites, with the finer material (silt and clay) always less than 30% and mainly below 20%. Water content is highly variable (0.7% – 30.3%).

The northernmost site at Apostrophe Island is on a flat ice-free area close to a glacier boundary and is characterized by gabbro outcrops and morainic till, locally reworked by periglacial features such as unsorted patterned grounds and frost fissures polygons. Here two plots were selected: one (AI7) vegetated with macrolichens (*Usnea sphacelata* with total coverage more than 50%) and one not vegetated (AI8), with active layer thicknesses of 43 and 45 cm, respectively. The soil samples are characterized by acid values of pH, low conductivity, coarse texture, and low water content, and they do not show extremely high or low values of the investigated parameters, which decrease with depth, with the exception of phosphate and HCO_3^-.

Edmonson Point is a wide ice-free area on the eastern slope at the foot of Mount Melbourne, the active volcano close to the Mario Zucchelli Station (MZS). Here we selected three plots, one on bare ground (EP3), one vegetated by mosses in moist conditions (EP1), and one with mosses along a stream (EP2). EP3 is located on a weathered basaltic outcrop, while EP1 and EP2 are on alluvium. The active layer ranges from 41 cm (EP1) to 82 cm (EP2). Bacteria and water content show here the highest values recorded among all the investigated sites. Comparing the soils of this site, EP1 has the highest values of nitrate, organic C and water content, EP2 has the lowest conductivity, but highest Al and silt, while EP3 has the highest values of Cl, sulfate, Fe, and Na (which may be related to the absence of vegetation uptake), and the highest recorded values of bacteria.

Boulder Clay is an ice-free and flat area very close to MZS and the selected plot stands within the CALM grid site on till composed mainly of granitic boulders and pebbles and with scattered mosses and crustose lichens. The chemical and physical parameters of the soil do not show peculiar characteristics at this site, except for the relatively high values of Al and Fe.

Tarn Flat is the only inland site, located on the largest ice-free area close to the MZS. It is characterised by till composed mainly of granitic boulders and pebbles, and the sampling sites are on flat areas with bare ground at different elevations (TF14 at 100 m a.s.l. and TF17 at 20 m a.s.l.). The active layer ranges from 42 cm (TF14) to 58 cm (TF17). Comparing the two soils, TF17 shows a strong enrichment of HCO_3^-, Al, and Fe, and higher values of conductivity and Na than TF14. Both samples

are characterised by very low values of nitrate, phosphate, organic C and total N.

Prior Island in an ice-free island immediately south of the Drygalski ice tongue, which is characterized by till and the occurrence of ornithogenic soils. Here we selected two sampling sites at the top of the island (150 m a.s.l.), one with bare ground (PP6) and one with closed moss vegetation encrusted by lichens (PP4), with active layer thicknesses of 47 and 55 cm, respectively. All the collected soil samples show very high conductivity and very low water content. PP6 is characterised by a very strong enrichment of all the analysed chemical parameters, with the highest values recorded in all the study area for F, phosphate, Mg, P and organic C. The peculiar characteristics of PP6 are linked to its ornithogenic origin.

Starr Nunatak is a small, flat, granitic nunatak along the Harbord glacier and close to the coast where we investigated two plots, one with closed moss vegetation encrusted by lichens (ST15) and one on bare ground (ST16). The active layer thickness is deeper in the bare ground plot (82 cm) than in the vegetated one (65 cm). The soils are enriched in Cl, sulfate,

Table 3
Eigenvalues and cumulative percentage variance of species data for the Principal Component Analysis carried out for all sites, for the coastal sites, for the coastal sites on granite lithology, for the unvegetated coastal sites and for the vegetated coastal sites

PCA all sites

Axes	1	2	3	4	Total variance
Eigenvalues	0.482	0.196	0.111	0.1	1.000
Cumulative percentage variance of species data	48.2	67.7	78.8	88.8	

PCA coastal sites

Axes	1	2	3	4	Total variance
Eigenvalues	0.491	0.2	0.108	0.095	1.000
Cumulative percentage variance of species data	49.1	79.9	89.4		

PCA coastal sites on granite lithology

Axes	1	2	3	4	Total variance
Eigenvalues	0.504	0.219	0,101	0.89	1.000
Cumulative percentage variance of species data	50.4	72.4	82.5	91.4	

PCA unvegetated coastal sites

Axes	1	2	3	4	Total variance
Eigenvalues	0.536	0.211	0.11	0.067	1.000
Cumulative percentage variance of species data	53.6	74.4	85.7	92.4	

PCA vegetated coastal sites

Axes	1	2	3	4	Total variance
Eigenvalues	0.334	0.202	0.147	0.117	1.000
Cumulative percentage variance of species data	33.4	53.5	68.2	79.9	

Table 4
Pearson correlation matrix for all sites

	pH	Conduc.	F⁻	Cl⁻	SO₄⁻	Br⁻	NO₃⁻	PO₄⁻	HCO3⁻	Al	Ca	Fe	K	Mg	Na	P	Si	Bacteria	Corg	N	C/N	gravel	sand	silt	clay	Water
pH	1.00	**0.93**	-0.17	**0.87**	**0.85**	**-0.75**	-0.09	**0.41**	**0.91**	**0.49**	0.34	**0.67**	-0.18	**-0.50**	**0.94**	0.18	-0.25	-0.10	0.32	0.30	-0.01	-0.09	0.06	0.07	0.03	0.07
conductivity	**0.93**	1.00	-0.13	**0.93**	**0.81**	**-0.79**	-0.03	**0.55**	**0.98**	0.33	**-0.38**	**0.52**	-0.18	**-0.48**	**0.95**	0.08	-0.22	0.06	**0.51**	**0.41**	0.04	0.09	-0.08	-0.05	0.00	0.05
F⁻	-0.17	-0.13	1.00	-0.13	-0.09	0.17	0.37	-0.13	-0.12	-0.14	**0.42**	-0.11	**0.66**	0.28	-0.13	-0.27	**0.74**	-0.16	-0.14	-0.19	-0.07	0.14	-0.03	-0.19	-0.15	-0.17
Cl⁻	**0.87**	**0.93**	-0.13	1.00	**0.87**	**-0.71**	0.04	0.28	**0.84**	**0.42**	-0.33	**0.62**	-0.17	**-0.44**	**0.95**	-0.03	-0.19	-0.01	**0.40**	0.24	0.11	0.06	-0.06	0.00	-0.03	0.15
SO₄⁻	**0.85**	**0.81**	-0.09	**0.87**	1.00	**-0.50**	-0.11	0.05	**0.74**	**0.56**	-0.23	**0.79**	-0.13	-0.34	**0.94**	-0.08	-0.13	-0.09	-0.01	-0.05	0.01	-0.16	0.12	0.13	-0.02	0.30
Br⁻	**-0.75**	**-0.79**	0.17	**-0.71**	**-0.50**	1.00	0.02	**-0.53**	**-0.76**	-0.12	**0.46**	-0.27	0.23	**0.62**	**-0.70**	-0.15	0.27	0.02	**-0.65**	**-0.42**	-0.34	-0.03	-0.06	0.19	0.07	-0.07
NO₃⁻	-0.09	-0.03	0.37	0.04	-0.11	0.02	1.00	0.03	-0.07	0.22	0.07	0.07	0.36	-0.14	-0.05	0.01	0.19	0.10	0.08	-0.12	0.01	-0.01	0.06	-0.19	0.11	-0.30
PO₄⁻	**0.41**	**0.55**	-0.13	0.28	0.05	**-0.53**	0.03	1.00	**0.65**	-0.13	-0.20	-0.10	0.05	-0.28	0.33	**0.46**	-0.23	0.16	**0.64**	**0.60**	-0.09	0.20	-0.16	-0.22	0.13	-0.33
HCO3⁻	**0.91**	**0.98**	-0.12	**0.84**	**0.74**	**-0.76**	-0.07	**0.65**	1.00	0.29	-0.36	**0.46**	-0.17	**-0.45**	**0.90**	0.14	-0.21	0.09	**0.53**	**0.48**	-0.01	0.11	-0.10	-0.05	0.04	0.00
Al	**0.49**	0.33	-0.14	**0.42**	**0.56**	-0.12	0.22	-0.13	0.29	1.00	-0.35	**0.93**	-0.18	**-0.53**	**0.47**	0.03	-0.18	-0.05	-0.24	-0.26	-0.03	**-0.51**	0.36	0.20	0.35	0.05
Ca	-0.34	**-0.38**	**0.42**	-0.33	-0.23	**0.46**	0.07	-0.20	-0.36	-0.35	1.00	-0.35	**0.44**	**0.69**	-0.33	-0.01	**0.38**	-0.25	**-0.38**	**-0.40**	-0.13	-0.04	0.13	0.02	-0.37	0.00
Fe	**0.67**	**0.52**	-0.11	**0.62**	**0.79**	-0.27	0.07	-0.10	**0.46**	**0.93**	-0.35	1.00	-0.17	**-0.51**	**0.69**	0.01	-0.14	-0.08	-0.22	-0.26	0.00	**-0.45**	0.34	0.17	0.25	0.13
K	-0.18	-0.18	**0.66**	-0.17	-0.13	0.23	0.36	0.05	-0.17	-0.18	**0.44**	-0.17	1.00	**0.41**	-0.17	0.17	**0.42**	-0.18	-0.21	-0.17	-0.29	0.15	-0.06	-0.19	-0.06	-0.22
Mg	**-0.50**	**-0.48**	0.28	**-0.44**	-0.34	**0.62**	-0.14	-0.28	**-0.45**	**-0.53**	**0.69**	**-0.51**	**0.41**	1.00	**-0.45**	-0.12	**0.39**	-0.01	**-0.41**	-0.13	**-0.43**	0.06	0.01	0.12	**-0.42**	-0.10
Na	**0.94**	**0.95**	-0.13	**0.95**	**0.94**	**-0.70**	-0.05	0.33	**0.90**	**0.47**	-0.33	**0.69**	-0.17	**-0.45**	1.00	0.01	-0.19	-0.02	0.27	0.19	0.03	-0.04	0.03	0.03	-0.01	0.17
P	0.18	0.08	-0.27	-0.03	-0.08	-0.15	0.01	**0.46**	0.14	0.03	-0.01	0.01	0.17	-0.12	0.01	1.00	-0.18	0.11	0.08	0.06	-0.09	-0.28	0.13	0.13	**0.40**	-0.07
Si	-0.25	-0.22	**0.74**	-0.19	-0.13	0.27	0.19	-0.23	-0.21	-0.18	**0.38**	-0.14	**0.42**	**0.39**	-0.19	-0.18	1.00	-0.17	-0.17	-0.27	0.06	0.10	0.06	-0.29	-0.21	-0.07
Bacteria	-0.10	0.06	-0.16	-0.01	-0.09	0.02	0.10	0.16	0.09	-0.05	-0.25	-0.08	-0.18	-0.01	-0.02	0.11	-0.17	1.00	0.12	0.09	-0.11	-0.01	0.03	-0.17	0.19	-0.07
Corg	0.32	**0.51**	-0.14	**0.40**	-0.01	**-0.65**	0.08	**0.64**	**0.53**	-0.24	**-0.38**	-0.22	-0.21	**-0.41**	0.27	0.08	-0.17	0.12	1.00	**0.75**	0.34	**0.49**	**-0.40**	-0.27	-0.02	-0.07
N	0.30	**0.41**	-0.19	0.24	-0.05	**-0.42**	-0.12	**0.60**	**0.48**	-0.26	**-0.40**	-0.26	-0.17	-0.13	0.19	0.06	-0.27	0.09	**0.75**	1.00	-0.25	**0.47**	**-0.48**	-0.05	0.02	-0.30
C/N	-0.01	0.04	-0.07	0.11	0.01	-0.34	0.01	-0.09	-0.01	-0.03	-0.13	0.00	-0.29	**-0.43**	0.03	-0.09	0.06	-0.11	0.34	-0.25	1.00	0.05	0.00	-0.09	-0.08	**0.50**
gravel	-0.09	0.09	0.14	0.06	-0.16	-0.03	-0.01	0.20	0.11	**-0.51**	-0.04	**-0.45**	0.15	0.06	-0.04	-0.28	0.10	-0.01	**0.49**	**0.47**	0.05	1.00	**-0.89**	-0.36	-0.05	-0.14
sand	0.06	-0.08	-0.03	-0.06	0.12	-0.06	0.06	-0.16	-0.10	0.36	0.13	0.34	-0.06	0.01	0.01	0.03	0.13	0.03	**-0.40**	**-0.48**	0.00	**-0.89**	1.00	-0.03	-0.23	0.07
silt	0.07	-0.05	-0.19	0.00	0.13	0.19	-0.19	-0.22	-0.05	0.20	0.02	0.17	-0.19	0.12	0.12	0.03	-0.29	-0.17	-0.27	-0.05	-0.09	-0.36	-0.03	1.00	0.03	0.32
Clay	0.03	0.00	-0.15	-0.03	-0.02	0.07	0.11	0.13	0.04	0.35	-0.37	0.25	-0.06	**-0.42**	-0.01	**0.40**	-0.21	0.19	-0.02	0.02	-0.08	-0.05	-0.23	0.03	1.00	-0.18
Water	0.07	0.05	-0.17	0.15	0.30	-0.07	-0.30	-0.33	0.00	0.05	0.00	0.13	-0.22	-0.10	0.17	-0.07	-0.07	-0.07	-0.07	-0.30	**0.50**	-0.14	0.07	0.32	-0.18	1.00

In bold significant correlations with $p < 0.05$.

phosphate, HCO_3^- and Na in the bare ground plot (ST16) with respect to the vegetated one (ST15), which shows higher nitrate and organic C concentrations in the upper soil layers.

Finger Point is the southernmost location along the latitudinal gradient and is a flat area along the coast characterized by till deposits mainly composed of granitic boulders. Also in this case, we selected two sites close to each other but with different vegetation (FP9 with closed moss cover, and FP19 on bare ground). Also at Finger Point, the bare ground has a thicker active layer than the moss vegetated ground (73 versus 62 cm). The two soils show very different characteristics; moreover, FP19 is totally different from all the other analysed soils with the highest values of most of the investigated parameters (pH, conductivity, Cl, sulfate, HCO_3^-, Al, Fe, Na, Si).

4.2. Patterns of soil characteristics with latitude

To investigate the potential occurrence of broad patterns influencing the soil characteristics, two Principal Component Analyses (PCA) were performed, one considering all the investigated sites (Fig. 2a; Table 3) and the other only the coastal sites (Fig. 2b; Table 3). PCA provides indirect information on the relations between the analysed parameters (represented by vectors/arrows) and the sites (represented by points). The length of the vectors/arrows indicates the importance of the analysed parameters, the distribution of the vectors indicates a positive or negative influence respect to the clusters of sites.

The two analyses clearly indicate that the broad and general patterns of soil characteristics do not exhibit consistent variation with regard to site location (coast versus inland, as shown in Fig. 2a), latitude, lithology and vegetation (Fig. 2b). Both analyses discriminate from all the other samples the ornithogenic soil (PP6) and the samples with very high Fe, Al and Si concentrations (FP19) independently of their depth.

Considering the soil chemical parameters, some relations indicated by PCA were similar to those outlined by the Pearson correlation matrix for all sites (Table 4), which allowed us to identify groups of correlated parameters. In particular, positive correlations were observed for: 1) pH, conductivity, Cl, Na, sulfate and HCO_3^-, 2) Al and Fe, 3) organic carbon and total nitrogen. Sand and gravel are inversely correlated (when the first increases the latter decreases and *vice versa*). Unlike the Pearson correlation matrix, both PCA (Fig. 2a and 2b) indicated relations between K and F and between P and PO4 along the first axis, although along the second axis, all the grain size components were positively related.

To assess the influence of latitude avoiding potential interference linked to the different lithology, a third PCA (Fig. 3; Table 3) was performed considering only the coastal sites with granitic lithology. Unfortunately the latitudinal gradient referring to these sites was more limited (74°-77°S) with respect to the whole investigated transect. Nevertheless, PCA showed there was no appreciable pattern with latitude and that the patterns of soil parameters were very similar to the above-
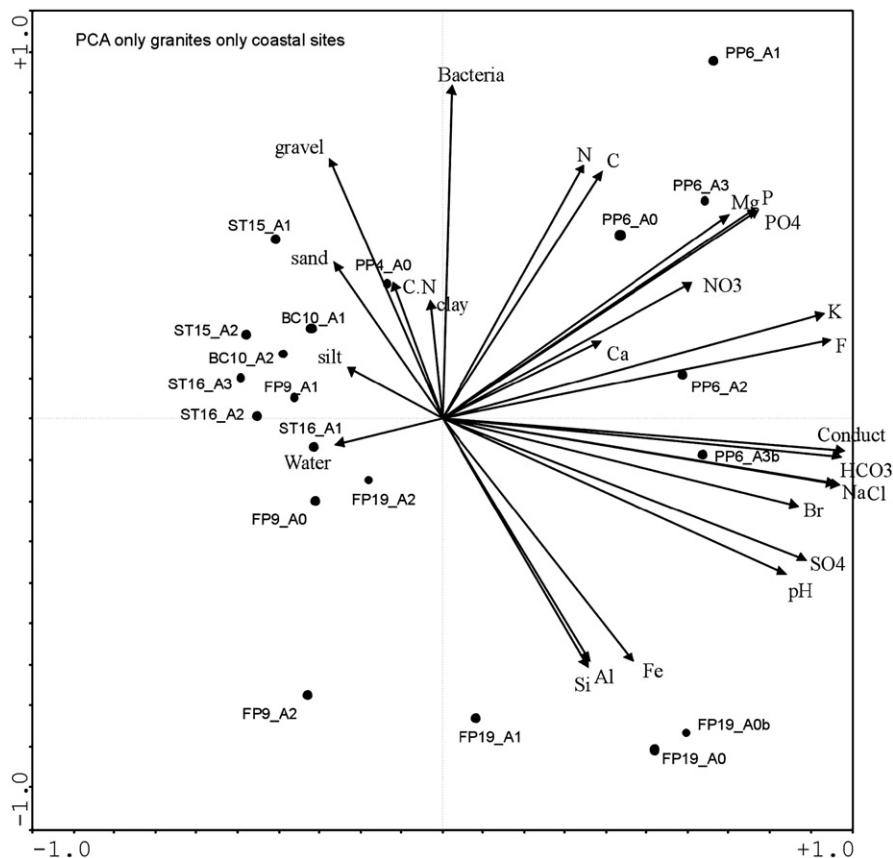

Fig. 3. Principal Component Analysis of the coastal sites with granitic lithology. See Table 2 for abbreviations.

mentioned results. Also by eliminating the samples with peculiar characteristics (PP6 and FP19), the PCA provided similar results (data not shown).

Further, to avoid the potential influence of vegetation, we performed the PCA considering only the unvegetated coastal sites (Fig. 4; Table 3). Also in this case, latitude did not exert any significant influence on soil characteristics and the soil parameters showed the same patterns already outlined in Figs. 2a, b and 3.

The Pearson correlation matrix of the unvegetated sites (Table 5) confirms the general patterns obtained for all sites (Table 4), in particular concerning 1) the link between pH, conductivity, Na, Cl, sulfate, and HCO_3^-, 2) between Al and Fe, and 3) the negative relation between gravel and sand. In addition, the unvegetated sites are characterized by the following positive correlations: 1) F and K (shown also by the PCA); 2) total nitrogen and phosphate; 3) organic carbon and total nitrogen.

4.3. Patterns of soil characteristics with lithology

From qualitative observations of the chemical and physical data, the samples of both Apostrophe Island (gabbro) and Edmonson Point (basalts) (Table 2) are characterized by slightly lower contents of Al, Fe and Ca, and K than the samples collected in the granitic sites. In addition, PCA indicates that lithology does not influence soil properties, when considering

all the investigated sites (Fig. 2a), only the coastal sites (Fig. 2b), and the unvegetated coastal sites as well (Fig. 4).

4.4. Patterns of soil characteristics with vegetation

The influence of vegetation occurrence was assessed by comparing the surface layers of vegetated soils with those of bare ground at each site (i.e. AI7_1 vs AI8_1, EP1_1 vs EP3_1, ST15_1 vs ST16_1, FP9_1 vs FP19_1) (Table 2). In most cases, the vegetated surface layers show lower values of pH, anions (except for Apostrophe Island samples) and cations, but higher values of nitrate, organic C, total N, and water. Moreover, in the vegetated soils the values of the chemical parameters tend mainly to decrease with depth.

The PCA of the vegetated sites (Fig. 5; Table 3) indicates that there are no evident patterns with respect to vegetation type, although there is a sorting which separates the surface from the deeper layers. In fact, most of the surface layers show higher values of organic C, total N, and water, and a higher C/N ratio. The enrichment of organic C, total N and water of the surface layers with respect to the deeper layers is confirmed also by the values reported in Table 2 and is an effect clearly linked to vegetation occurrence, independently of site location and lithology.

The Pearson correlation matrix of the vegetated sites (Table 6) shows different relations between the analyzed parameters and those obtained considering all sites and only
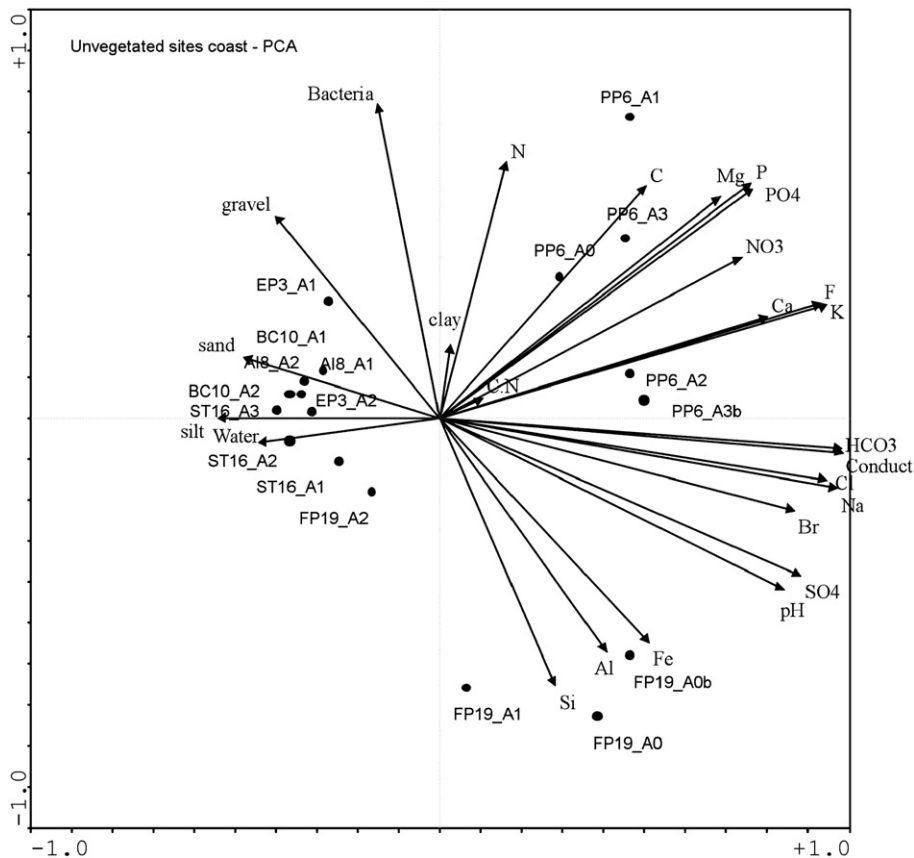

Fig. 4. Principal Component Analysis of the unvegetated coastal sites. See Table 2 for abbreviations.

Table 5
Pearson correlation matrix referred only to the vegetated sites

	pH	Conduc.	F⁻	Cl⁻	SO₄⁻	Br⁻	NO₃⁻	PO₄⁻	HCO3⁻	Al	Ca	Fe	K	Mg	Na	P	Si	Bacteria	Corg	N	C/N	Gravel	Sand	Silt	Clay	Water
PH	1.00	0.08	-0.22	-0.04	-0.09	-0.04	-0.12	-0.13	0.25	0.30	-0.04	0.21	0.06	-0.03	0.26	0.30	**-0.53**	-0.01	-0.14	0.41	-0.36	-0.04	-0.19	0.24	0.29	0.13
Conductivity	0.08	1.00	-0.37	**0.69**	**0.70**	**-0.57**	-0.28	-0.14	**0.53**	0.33	-0.43	0.30	**-0.64**	**-0.70**	**0.83**	-0.21	-0.37	0.13	**0.58**	0.10	0.35	-0.16	0.09	-0.06	0.31	0.40
F⁻	-0.22	-0.37	1.00	-0.32	-0.39	0.07	**0.54**	-0.12	-0.11	-0.04	0.29	-0.03	0.45	0.17	-0.36	-0.20	**0.68**	-0.12	-0.12	-0.19	0.01	-0.06	0.27	-0.26	-0.16	-0.22
Cl⁻	-0.04	**0.69**	-0.32	1.00	**0.80**	-0.10	**-0.51**	-0.01	0.30	0.25	-0.15	0.26	**-0.62**	-0.33	**0.68**	-0.33	-0.36	-0.20	0.16	0.07	0.13	-0.12	-0.05	0.21	0.19	0.10
SO₄⁻	-0.09	**0.70**	-0.39	**0.80**	1.00	-0.41	-0.38	0.11	0.12	0.06	-0.09	-0.01	-0.39	-0.29	**0.66**	-0.21	**-0.54**	-0.08	0.19	0.03	0.14	-0.18	0.10	0.15	0.03	0.23
Br⁻	-0.04	**-0.57**	0.07	-0.10	-0.41	1.00	0.09	0.13	0.00	0.18	0.23	0.20	0.15	0.38	-0.45	0.20	0.10	0.14	**-0.63**	0.06	**-0.59**	0.11	-0.28	0.19	0.15	**-0.66**
NO₃⁻	-0.12	-0.28	**0.54**	**-0.51**	-0.38	0.09	1.00	0.17	0.24	0.17	0.21	0.11	0.45	-0.04	-0.25	0.27	0.31	0.42	-0.25	-0.36	-0.09	-0.19	0.27	-0.24	0.17	-0.28
PO₄⁻	-0.13	-0.14	-0.12	-0.01	0.11	0.13	0.17	1.00	0.04	0.23	0.22	0.27	0.46	-0.02	0.07	**0.62**	-0.17	-0.17	-0.33	-0.39	-0.16	-0.30	0.34	-0.16	0.20	-0.18
HCO3⁻	0.25	**0.53**	-0.11	0.30	0.12	0.00	0.24	0.04	1.00	**0.88**	-0.35	**0.84**	-0.37	**-0.70**	**0.63**	0.36	-0.23	**0.58**	-0.02	-0.23	0.10	-0.30	-0.02	0.04	**0.87**	0.00
Al	0.30	0.33	-0.04	0.25	0.06	0.18	0.17	0.23	**0.88**	1.00	-0.37	**0.97**	-0.08	**-0.55**	**0.55**	0.48	-0.16	0.46	-0.25	-0.16	-0.15	-0.29	-0.04	-0.03	**0.97**	-0.27
Ca	-0.04	-0.43	0.29	-0.15	-0.09	0.23	0.21	0.22	-0.35	-0.37	1.00	-0.38	0.36	**0.59**	-0.24	0.10	0.04	-0.12	-0.39	-0.39	-0.07	-0.28	0.47	0.03	-0.48	-0.06
Fe	0.21	0.30	-0.03	0.26	-0.01	0.20	0.11	0.27	**0.84**	**0.97**	-0.38	1.00	-0.09	**-0.52**	**0.51**	0.44	-0.05	0.39	-0.20	-0.20	-0.08	-0.23	-0.04	-0.12	**0.94**	-0.29
K	0.06	**-0.64**	0.45	**-0.62**	-0.39	0.15	0.45	0.46	-0.37	-0.08	0.36	-0.09	1.00	0.38	**-0.51**	0.45	0.21	-0.15	-0.37	-0.18	-0.32	-0.03	0.21	-0.28	-0.09	-0.28
Mg	-0.03	**-0.70**	0.17	-0.33	-0.29	0.38	-0.04	-0.02	**-0.70**	**-0.55**	**0.59**	**-0.52**	0.38	1.00	-0.48	-0.03	0.25	-0.21	**-0.52**	0.19	-0.48	-0.14	0.26	0.21	**-0.58**	-0.36
Na	0.26	**0.83**	-0.36	**0.68**	**0.66**	-0.45	-0.25	0.07	**0.63**	**0.55**	-0.24	**0.51**	**-0.51**	-0.48	1.00	0.08	-0.43	0.19	0.13	-0.01	0.16	-0.48	0.29	0.09	**0.50**	0.21
P	0.30	-0.21	-0.20	-0.33	-0.21	0.20	0.27	**0.62**	0.36	0.48	0.10	0.44	0.45	-0.03	0.08	1.00	-0.29	0.26	-0.42	-0.35	-0.20	-0.49	0.23	0.21	**0.52**	0.00
Si	**-0.53**	-0.37	**0.68**	-0.36	**-0.54**	0.10	0.31	-0.17	-0.23	-0.16	0.04	-0.05	0.21	0.25	-0.43	-0.29	1.00	-0.04	0.10	-0.19	0.17	0.02	0.29	-0.42	-0.22	-0.29
Bacteria	-0.01	0.13	-0.12	-0.20	-0.08	0.14	0.42	-0.17	**0.58**	0.46	-0.12	0.39	-0.15	-0.21	0.19	0.26	-0.04	1.00	-0.22	-0.19	-0.08	-0.13	0.02	-0.14	**0.51**	-0.32
Corg	-0.14	**0.58**	-0.12	0.16	0.19	**-0.63**	-0.25	-0.33	-0.02	-0.25	-0.39	-0.20	-0.37	**-0.52**	0.13	-0.42	0.10	-0.22	1.00	0.04	**0.66**	0.27	-0.06	-0.29	-0.23	**0.66**
N	0.41	0.10	-0.19	0.07	0.03	0.06	-0.36	-0.39	-0.23	-0.16	-0.39	-0.20	-0.18	0.19	-0.01	-0.35	-0.19	-0.19	0.04	1.00	**-0.61**	0.26	-0.32	0.18	-0.16	-0.18
C/N	-0.36	0.35	0.01	0.13	0.14	**-0.59**	-0.09	-0.16	0.10	-0.15	-0.07	-0.08	-0.32	-0.48	0.16	-0.20	0.17	-0.08	**0.66**	**-0.61**	1.00	0.05	0.06	-0.15	-0.11	**0.70**
Gravel	-0.04	-0.16	-0.06	-0.12	-0.18	0.11	-0.19	-0.30	-0.30	-0.29	-0.28	-0.23	-0.03	-0.14	-0.48	-0.49	0.02	-0.13	0.27	0.26	0.05	1.00	**-0.81**	-0.39	-0.20	-0.11
Sand	-0.19	0.09	0.27	-0.05	0.10	-0.28	0.27	0.34	-0.02	-0.04	0.47	-0.04	0.21	0.26	0.29	0.23	0.29	0.02	-0.06	-0.32	0.06	**-0.81**	1.00	-0.10	-0.16	0.05
Silt	0.24	-0.06	-0.26	0.21	0.15	0.19	-0.24	-0.16	0.04	-0.03	0.03	-0.12	-0.28	0.21	0.09	0.21	-0.42	-0.14	-0.29	0.18	-0.15	-0.39	-0.10	1.00	0.01	0.29
Clay	0.29	0.31	-0.16	0.19	0.03	0.15	0.17	0.20	**0.87**	**0.97**	-0.48	**0.94**	-0.09	**-0.58**	**0.50**	**0.52**	-0.22	**0.51**	-0.23	-0.16	-0.11	-0.20	-0.16	0.01	1.00	-0.23
Water	0.13	0.40	-0.22	0.10	0.23	**-0.66**	-0.28	-0.18	0.00	-0.27	-0.06	-0.29	-0.28	-0.36	0.21	0.00	-0.29	-0.32	**0.66**	-0.18	**0.70**	-0.11	0.05	0.29	-0.23	1.00

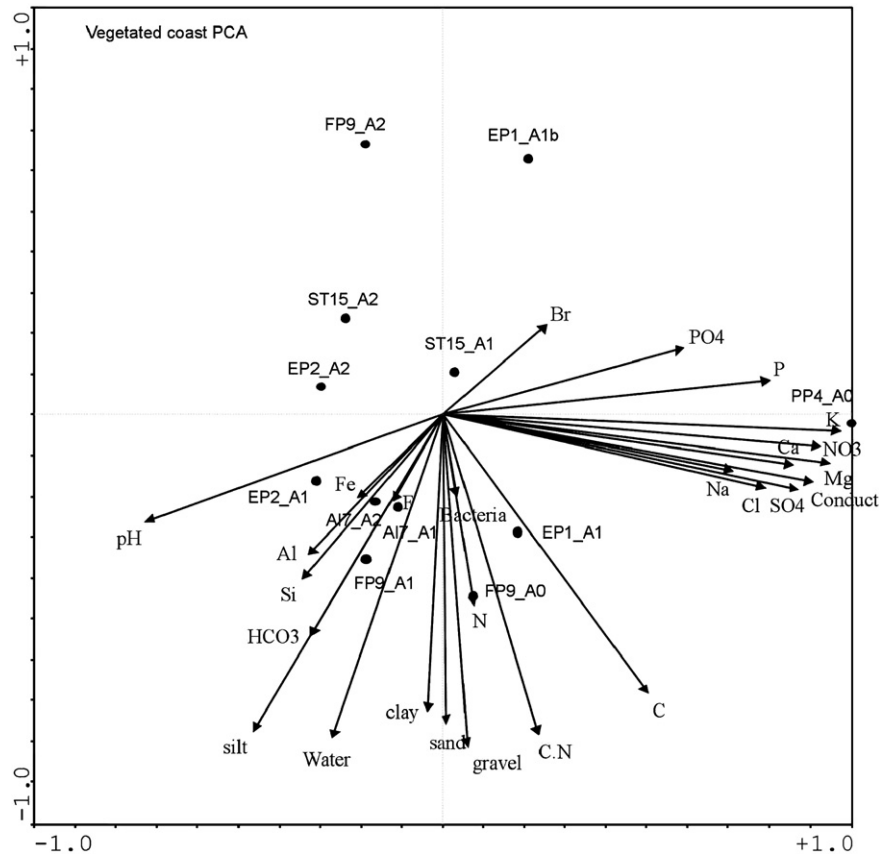In bold significant correlations with p<0.05.

Fig. 5. Principal Component Analysis of the vegetated sites. See Table 2 for abbreviations.

the unvegetated ones, respectively. In particular: 1) there is a positive correlation between conductivity, Na and sulfate, which are all negatively related to Mg; 2) there are positive correlations between HCO_3^-, Al, Fe and clay; 3) organic carbon, the C/N ratio and water are positively linked to each other and all are negatively related to Br; 4) there is an inverse correlation between gravel and sand.

Both PCA and the correlation matrix demonstrate that vegetation occurrence influences the relationship between the chemical and physical properties of the soil. Moreover, the different vegetation types (moss vegetation, lichenized mosses vegetation, macrolichen vegetation, scattered epilithic vegetation with mosses) seem able to produce some differences in the chemical and/or physical characteristics of the investigated soils.

In particular, nitrate, organic carbon, the C/N ratio and water content (Fig. 6) show different patterns depending on the vegetation type. Mosses have the highest water content and organic C, and high values of C/N. Instead, mosses encrusted by lichens have the most xeric conditions, while their C/N is the highest. The scattered vegetation shows the highest N, the lowest C org and C/N, and low values of water. Also the active-layer thickness is influenced by vegetation type: in fact, the active layer is thinner in the moister sites (showing an inverse relation with the water content) and, therefore, it shows its lowest value under the moss vegetation (Fig. 6).

5. Discussion

Although climate along the latitudinal gradient and lithology are not significant sources of variation for soil properties, vegetation seems to influence the soil surface layer. However, the occurrence of ornithogenic soils exerts the highest influence on soil properties. These results are supported by the different PCA, carried out considering all sites, only the coastal sites, only the coastal unvegetated sites and only the coastal vegetated sites, respectively.

These results are compatible with previous studies that show no significant patterns of vegetation distribution (Cannone, 2006) and active layer thickness (Guglielmin, 2006) with latitude along the Ross Sea coast. Local microclimate appears to have a greater influence on site conditions (aspect, slope, altitude, distance from the sea) than regional climate along the environmental gradients. Microclimate influences the active layer, the thermal regime of the soil and water availability through modifying snow accumulation and persistence, wind speed at the ground and radiation balance. The importance of local scale environmental variability is confirmed by the occurrence of "hot spots" of biodiversity, irrespective of the latitudinal gradient, linked to the availability of favourable ecological niches for vegetation colonization and development.

In polar environments of the Northern Hemisphere, vegetation and active-layer and soil properties have for a long time

Table 6
Pearson correlation matrix referred only to the unvegetated sites

|	pH	Conduc.	F⁻	Cl⁻	SO₄⁻	Br⁻	NO₃⁻	PO₄⁻	HCO3⁻	Al	Ca	Fe	K	Mg	Na	P	Si	Bacteria	Corg	N	C/N	Gravel	Sand	Silt	Clay	Water
pH	1.00	**0.92**	-0.36	**0.85**	**0.86**	**-0.78**	-0.22	0.37	**0.90**	0.49	-0.53	**0.68**	-0.33	**-0.72**	**0.94**	0.27	-0.43	-0.22	0.25	0.30	0.18	-0.08	-0.07	0.50	0.41	0.22
conductivity (μs/cm)	**0.92**	1.00	-0.35	**0.91**	**0.79**	**-0.82**	-0.15	0.54	**0.97**	0.29	**-0.59**	0.49	-0.30	**-0.65**	**0.94**	0.17	-0.48	0.00	0.48	0.51	0.16	0.22	-0.34	0.28	0.49	0.22
fluoride	-0.36	-0.35	1.00	-0.31	-0.21	0.42	0.22	-0.23	-0.31	-0.25	**0.62**	-0.22	**0.99**	0.50	-0.31	-0.38	**0.77**	-0.22	-0.24	-0.23	-0.24	0.32	-0.33	-0.01	-0.06	-0.09
chloride	**0.85**	**0.91**	-0.31	1.00	**0.86**	**-0.70**	-0.02	0.19	**0.78**	0.41	-0.51	**0.62**	-0.28	**-0.60**	**0.94**	-0.05	-0.41	-0.09	0.34	0.26	0.38	0.15	-0.28	0.38	0.32	0.40
sulfate	**0.86**	**0.79**	-0.21	**0.86**	1.00	-0.46	-0.24	-0.05	**0.70**	**0.60**	-0.33	**0.83**	-0.20	-0.44	**0.94**	-0.13	-0.26	-0.16	-0.12	-0.10	0.04	-0.19	0.05	**0.58**	0.19	**0.59**
bromide	**-0.78**	**-0.82**	0.42	**-0.70**	-0.46	1.00	0.10	**-0.62**	**-0.77**	-0.06	**0.71**	-0.24	0.35	**0.80**	**-0.69**	-0.48	**0.58**	0.05	**-0.62**	**-0.61**	-0.45	-0.18	0.25	-0.07	-0.49	0.17
nitrate	-0.22	-0.15	0.22	-0.02	-0.24	0.10	1.00	-0.09	-0.22	0.24	-0.08	0.02	0.24	-0.21	-0.18	-0.36	0.06	-0.18	0.17	0.03	0.29	0.19	-0.21	-0.02	0.10	-0.31
phosphate	0.37	0.54	-0.23	0.19	-0.05	**-0.62**	-0.09	1.00	**0.67**	-0.30	-0.43	-0.29	-0.17	-0.38	0.25	0.52	-0.36	0.24	**0.77**	**0.90**	-0.08	0.48	-0.51	-0.25	0.50	-0.44
HCO3-	**0.90**	**0.97**	-0.31	**0.78**	**0.70**	**-0.77**	-0.22	0.67	1.00	0.23	-0.55	0.40	-0.27	**-0.59**	**0.87**	0.25	-0.45	0.05	0.51	**0.60**	0.01	0.24	-0.36	0.25	0.52	0.13
Al	0.49	0.29	-0.25	0.41	**0.60**	-0.06	0.24	-0.30	0.23	1.00	-0.37	**0.93**	-0.27	-0.54	0.47	-0.26	-0.26	-0.27	-0.33	-0.34	0.11	**-0.64**	0.50	**0.77**	0.00	0.31
Ca	-0.53	-0.59	**0.62**	-0.51	-0.33	**0.71**	-0.08	-0.43	-0.55	-0.37	1.00	-0.38	**0.58**	**0.82**	-0.50	-0.20	**0.81**	-0.36	-0.43	-0.42	-0.32	0.22	-0.17	-0.12	-0.31	0.06
Fe	**0.68**	0.49	-0.22	**0.62**	**0.83**	-0.24	0.02	-0.29	0.40	**0.93**	-0.38	1.00	-0.24	-0.55	**0.70**	-0.21	-0.26	-0.27	-0.34	-0.34	0.11	**-0.58**	0.43	**0.81**	0.02	0.47
K	-0.33	-0.30	**0.99**	-0.28	-0.20	0.35	0.24	-0.17	-0.27	-0.27	**0.58**	-0.24	1.00	0.46	-0.27	-0.36	**0.74**	-0.22	-0.18	-0.17	-0.23	0.38	-0.39	-0.04	-0.02	-0.13
Mg	**-0.72**	**-0.65**	0.50	**-0.60**	-0.44	**0.80**	-0.21	-0.38	**-0.59**	-0.54	**0.82**	-0.55	0.46	1.00	**-0.60**	-0.27	**0.66**	0.20	-0.37	-0.35	-0.47	0.23	-0.13	-0.33	-0.43	0.21
Na	**0.94**	**0.94**	-0.31	**0.94**	**0.94**	**-0.69**	-0.18	0.25	**0.87**	0.47	-0.50	**0.70**	-0.27	**-0.60**	1.00	0.02	-0.41	-0.10	0.18	0.19	0.13	0.00	-0.14	0.44	0.35	0.42
P	0.27	0.17	-0.38	-0.05	-0.13	-0.48	-0.36	0.52	0.25	-0.26	-0.20	-0.21	-0.36	-0.27	0.02	1.00	-0.05	-0.02	0.35	0.43	0.25	-0.03	0.03	-0.07	0.10	-0.20
Si	-0.43	-0.48	**0.77**	-0.41	-0.26	**0.58**	0.06	-0.36	-0.45	-0.26	**0.81**	-0.26	**0.74**	**0.66**	-0.41	-0.05	1.00	-0.30	-0.35	-0.35	-0.13	0.20	-0.19	0.00	-0.22	0.21
Bacteria	-0.22	0.00	-0.22	-0.09	-0.16	0.05	-0.18	0.24	0.05	-0.27	-0.36	-0.27	-0.22	0.20	-0.10	-0.02	-0.30	1.00	0.18	0.21	-0.22	0.08	0.00	-0.21	-0.33	0.18
Corg	0.25	0.48	-0.24	0.34	-0.12	**-0.62**	0.17	**0.77**	0.51	-0.33	-0.43	-0.34	-0.18	-0.37	0.18	0.35	-0.35	0.18	1.00	**0.95**	0.44	**0.69**	**-0.70**	-0.30	0.47	-0.38
N	0.30	0.51	-0.23	0.26	-0.10	**-0.61**	0.03	**0.90**	**0.60**	-0.34	-0.42	-0.34	-0.17	-0.35	0.19	0.43	-0.35	0.21	**0.95**	1.00	0.20	**0.63**	**-0.66**	-0.31	0.55	-0.42
C/N	0.18	0.16	-0.24	0.38	0.04	-0.45	0.29	-0.08	0.01	0.11	-0.32	0.11	-0.23	-0.47	0.13	0.25	-0.13	-0.22	0.44	0.20	1.00	0.08	-0.12	0.14	0.01	-0.03
gravel	-0.08	0.22	0.32	0.15	-0.19	-0.18	0.19	0.48	0.24	**-0.64**	0.22	**-0.58**	0.38	0.23	0.00	-0.03	0.20	0.08	**0.69**	**0.63**	0.08	1.00	**-0.98**	-0.48	0.32	-0.21
sand	-0.07	-0.34	-0.33	-0.28	0.05	0.25	-0.21	-0.51	-0.36	0.50	-0.17	0.43	-0.39	-0.13	-0.14	0.03	-0.19	0.00	**-0.70**	**-0.66**	-0.12	**-0.98**	1.00	0.32	-0.36	0.17
silt	0.50	0.28	-0.01	0.38	**0.58**	-0.07	-0.02	-0.25	0.25	**0.77**	-0.12	**0.81**	-0.04	-0.33	0.44	-0.07	0.00	-0.21	-0.30	-0.31	0.14	-0.48	0.32	1.00	-0.36	0.33
clay	0.41	0.49	-0.06	0.32	0.19	-0.49	0.10	0.50	0.52	0.00	-0.31	0.02	-0.02	-0.43	0.35	0.10	-0.22	-0.33	0.47	0.55	0.01	0.32	-0.36	-0.36	1.00	-0.22
Water	0.22	0.22	-0.09	0.40	**0.59**	0.17	-0.31	-0.44	0.13	0.31	0.06	0.47	-0.13	0.21	0.42	-0.20	0.21	0.18	-0.38	-0.42	-0.03	-0.21	0.17	0.33	-0.22	1.00

In bold significant correlations with p<0.05.
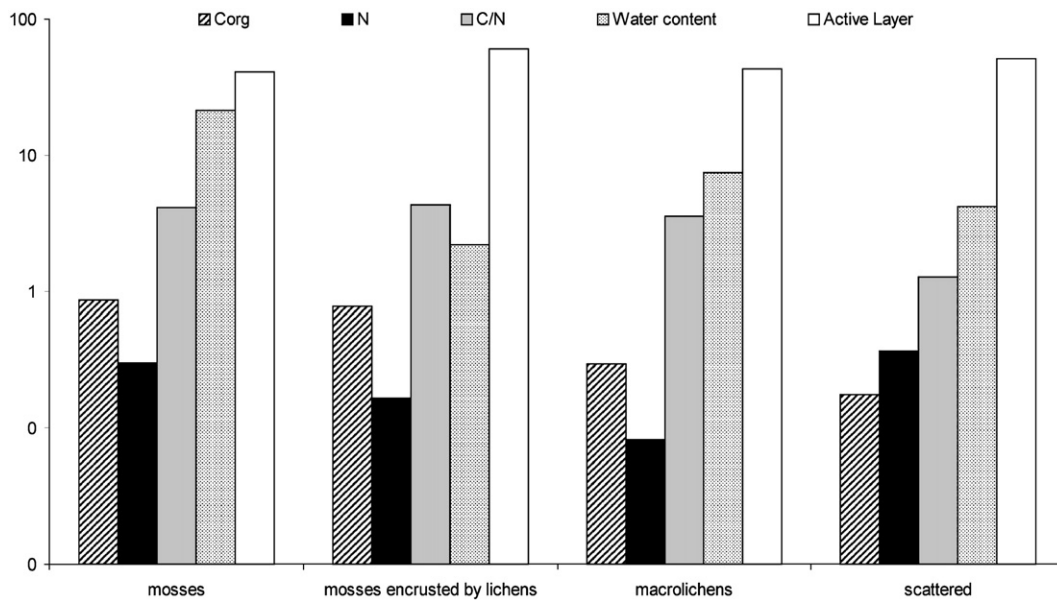
Fig. 6. Average values of Water content (%); Active Layer depth (cm); Corg (%); N (%); C/N for different vegetation types (mosses, mosses encrusted by lichens, macrolichens, scattered crustose lichens).

been recognized to be key components closely interacting with the terrestrial ecosystems (e.g. Shiklomanov and Nelson, 2003; Walker et al., 2003; Chapin et al., 2005). Our results indicate that, even in continental Antarctica, vegetation type is able to influence both soil properties, particularly nitrate, organic carbon, C/N ratio, water content, and active layer depth.

The higher concentrations of organic C, nitrate and total N in the surface layers of the vegetated soils are expected results, as is the lower pH, because of the accumulation of organic matter and its very low decomposition rates. The lower content of anions and cations in the upper layers of most vegetated soils could be related to the macronutrient uptake by cryptogams.

To assess the validity of our results in the Antarctic context, we compared our data with those from the available literature referring to the Victoria Land area, to the Dry Valleys and to other sites of Continental Antarctica. At Edmonson Point, Bargagli et al. (1999) analyzed soil characteristics along a transect from xeric bare ground to the centre of a wet moss stand in a site located very close to our study sites. In particular, the moss site (sample C) and the wet moss site (sample D) of Bargagli et al. (1999) are very similar to our permanent plots 1 (EP1) and 2 (EP2) in their location and vegetation characteristics. With respect to our results, the electric conductivity and, to a lesser extent, pH of those authors showed higher values in all conditions, whereas we recorded similar values of water content and N, indicating that these parameters did not change in the period 1995-2003. Higher pH values, C/N ratio, total organic carbon and similar N were obtained by Bargagli et al. (1996) on vegetated soils on the fumaroles of Mount Rittmann, a site located to the north of Edmonson Point and characterized by basaltic lavas.

Other available data from southern Victoria Land refer to the Dry Valleys, where the soils are generally dramatically more xeric than in our study sites (except for some samples collected at Boulder Clay, Prior Island, and Starr Nunatak) and are much

more basic (except for some peculiar samples collected at Finger Point and Prior Island) (Barrett et al., 2006a). The C/N ratio indicates much lower values in our study sites (ranging between 0.3 and 7.4) with respect to the Dry Valleys (ranging between 9.2 and 87.8) (Hopkins et al., 2006). The lower C/N ratio and the higher water content of our soils show that, along the investigated transect, the decomposition processes of the organic matter seem to be more active than in the Dry Valleys and not so limited by soil moisture, although further analyses are still required to measure the decomposition rates at Victoria Land.

These results indicate that our data may be considered representative of the variability of the chemical and physical properties of Victoria Land soils, covering a wide range of sites, lithology and latitude and then providing a starting point for the large scale assessment of the soil characteristics of the long term monitoring network. In addition, the comparison with the data from the Dry Valleys confirms the appropriateness of considering Victoria Land separately from the Dry Valleys, and confirms that these two contiguous areas are driven by very different environmental forces/factors.

We also tested the significance of our sites within continental Antarctica, selecting the Wilkes Land area as a template, both because of the similar conditions of substrate (mainly acid rocks), latitude, vegetation, and of the availability of a critical mass of data comparable with ours. In particular, the study carried out by Melick and Seppelt (1997) focussing on the relations between soil properties and vegetation types allowed the comparison of pH, conductivity, N% and water content % of similar vegetation types with similar floristic composition, but located in geographically remote areas. At Wilkes Land, the soils are generally more acid and show higher moisture (averages ranging between 4.8% and 27.2%) than at Victoria Land, independently of the vegetation type. The moisture patterns related to vegetation type are slightly different. The highest moisture is recorded under the moss communities, like

at Victoria Land, but the macrolichen vegetation dominated by *Usnea sphacelata* shows the lowest values, unlike in Victoria Land where the lowest water content was measured under the mosses encrusted by lichens. Despite their more northern latitude, it is remarkable that the soils of Victoria Land accumulate higher contents of N, especially in the moss community (averages 0.05 at Wilkes Land and 0.3 at Victoria Land) and also in the mosses encrusted by lichens (average range 0.03-0.06 at Wilkes Land and average 0.17 at Victoria Land).

Measurements carried out by Beyer et al. (2000) at Wilkes Land confirmed the more acid pH of the soils and indicated a higher C/N ratio (ranging from 5.3 to 35.8) than at Victoria Land, despite the greater water availability, northern latitude and milder macroclimatic conditions of Wilkes Land.

6. Conclusions

The description of the main physical and chemical parameters of the soils within the monitoring network here presented may be a suitable reference for future monitoring activities in Victoria Land. Our results demonstrated that, at least for the analyzed samples, the latitudinal gradient does not significantly affect the chemical and physical properties of the soil. In fact, local microclimatic conditions seem to be more effective than the regional gradient, as was demonstrated for active layer depth (Guglielmin, 2006) and vegetation distribution (Cannone, 2006).

Lithology is able to influence some selected chemical parameters (Al, Fe, Ca, K) only to a small extent, while grain size and active layer depth do not show any recognizable impact. The occurrence of ornithogenic soils seems to be more effective than all the other factors in influencing the soil properties. On the other hand, the vegetation types are able to influence the properties of the surface layers of the soil (nitrate, organic carbon, C/N ratio and water content) and are related to active layer depth.

Further analyses on soil properties including a greater number of sites, which would represent lithological variability more extensively, are still required, as is an extension of the latitudinal extremes of the gradient.

Acknowledgements

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