

Soil microalgal communities on an antarctic active volcano (Deception Island, South Shetlands)

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Abstract Contemporary eruptive episodes and present volcanic activity at Deception Island have created a mosaic of different environmental conditions. In this study, the microalgal communities inhabiting 18 sites differing in geology, degree of disturbance and physico-chemical features (texture, water, organic matter and nutrient contents) were characterized in terms of composition, species richness and biomass. One hundred and forty taxa were recorded, with richest communities associated with stable sites and some of the poorest ones in locations affected by recent eruptions. In accordance, a canonical correspondence analysis ordinated species and sites along the first axis according to the percentage of coarse particles, and degree of disturbance (eigenvalues 0.79 and 0.65, $P = 0.04$). Results of a cluster analysis grouped firstly those algal taxa with high fidelity to one set of environmental conditions, while “ubiquitous” ones had the lowest similarity values. These taxa, mainly filamentous Cyanobacteria and diatoms, are the only colonizers of harsher or recently formed environments.

Keywords Antarctica · Soil algae · Community · Colonization · Disturbance

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Introduction

Deception Island (62° 57'S, 60° 38'W) is an active volcano located on a rift along the Bransfield Strait, which actively separates the South Shetland Islands from the NW coast of the Antarctic Peninsula (González-Ferrán 1991). It has a typical maritime climate, with mean monthly air temperatures of -9°C in winter and 1.1°C in summer (Igarzábal 1974). Annual precipitation is around 900 mm, mainly in the form of snow (Smith 2005). Topographically, Deception is a mountainous incomplete ring about 15 km in diameter, enclosing a flooded caldera (Port Foster) formed around 10,000 years ago (Olsacher 1956). Explosive volcanic events occurred in 1842 and more recently in 1967, 1969 and 1970 (Fourcade 1972). Present-day activities are reflected by geothermal activity, thermal springs and fumaroles. Glaciers cover approximately 57% of the island, and ice has interacted with volcanic activity, reshaping the original volcanic landforms (López Martínez and Serrano 2002).

In spite of its volcanic character, Deception Island has long hosted human activity. During the 20th century, a Norwegian whaling station and a number of scientific stations operated on the shores of Port Foster. The former was abandoned in 1931 and the Chilean and British stations were destroyed during the 1967 and 1969 eruptions (Smith 2005). Thus, present research activity is carried out only at the Argentinean and Spanish stations. The unusual landscape, thermal ground and historical sites attract a very large number of tourists (Izaguirre and Mataloni 2000) posing a possible threat to the integrity of fragile terrestrial habitats of Deception Island. Some areas of the Island have been grouped by the XXV Antarctic Treaty Consultative Meeting within ASPA (Antarctic Specially Protected Area) No. 140 (<http://www.scar.org/publications/bulletins/148>).

The structure and ecology of Antarctic soils have been the focus of many studies during the past 20 years, and a thorough account of these advances is provided by Beyer and Bölter (2002). In maritime Antarctica, Broady (1979) pioneered the floristic survey of terrestrial algae on Signy Island (South Orkney Islands). The ecology of soil microalgal communities was then studied by Davey (1988, 1991) and Davey and Rothery (1992, 1993) while Wynn-Williams (1990, 1993) focused on the processes of primary colonization. Mataloni et al. (2000) and Mataloni and Tell (2002) investigated the biodiversity of microalgal communities from mineral and ornithogenic soils respectively from Cierva Point, Danco Coast (Antarctic Peninsula) at a distance of about 100 km from Deception Island. These sites share overall climatic features with Deception, yet they are much more stable in geo-ecological terms, as volcanic activity at Deception Island creates a mosaic of environmental conditions and opportunities for colonization.

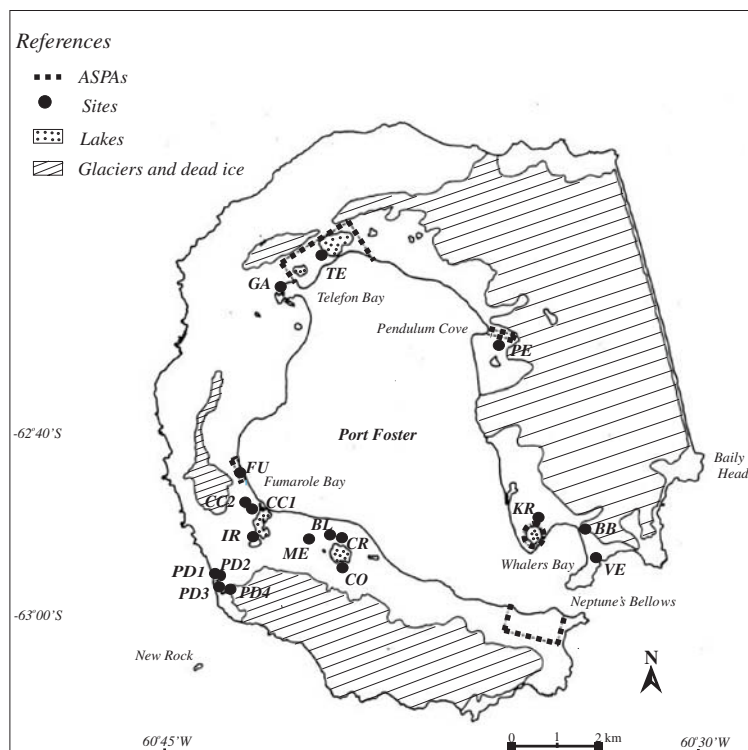
The present study has two main objectives: (1) to characterize the soil microalgal communities from sites representing different stages of soil development and of environmental conditions, and (2) to establish which conditions drive algal growth and community structure. This baseline data will facilitate future studies on colonization and biotic interactions regulating these soil microalgal communities.

Study sites

Sampling sites (Fig. 1) differ widely in their geology and physico-chemical features. Site VE is located on the Foster Formation, where topography has not been modified by eruptions since the Holocene period (Birkenmajer 1992). The sites located at the SW of the island (BL, CR and CO) belong to the Casco and Kirkwood Formations, and were last altered by eruptions in 1842. All these sites show a low degree of historical disturbance. In 1967, two cinder cones arose during an eruption at Telefon Bay, but were destroyed 3 years later, when a new event deeply modified the topography around that area. Site TE is located beside one of the two new lakes created during this event. Sites PE (Pendulum Cove) and BB (Whalers Bay) were mainly affected by the 1969 eruption (Fourcade and Viramonte 1972). Viramonte et al. (1974) found fumarolic activity in both of these areas. These three sites show a high degree of historical disturbance. Coastal areas with present volcanic activity are located at Fumarole Bay (FU), Telefon Bay (TE), Pendulum Cove (PE) and Whalers Bay (BB) (López Martínez and Serrano 2002). Warm soils also occur at the top of Cerro Caliente (CC1 and CC2).

Other sources of disturbance include hydrologic changes at site ME, located on the bed of a temporary river, and local faunal activity: Sites PD1–PD4 are located inside or near from a chinstrap penguin (*Pygoscelis antarctica*)

Fig. 1 Map of Deception Island showing the location of all 18 sampling sites (circles) and the parts of the ASPA No. 140 (dotted lines). Dashed areas indicate permanent snow or ice cover, and dotted ones show lakes



rookery at the Punta de la Descubierta area, while site GA is located at a kelp gull (*Larus dominicanus*) nesting area. Site KR, near Kroner lagoon, is a fur seal wallow. All these sites are subjected to a high degree of disturbance.

Materials and methods

Sampling and preparation

During the Antarctic summer of 2001–2002, all eighteen sites were sampled. At each site, soil temperature was measured at 1 cm below surface using an electronic thermometer, and slope was visually estimated and assigned into one of the following categories: non detectable (1), slight (2) and steep (around 30°) (3). The degree of disturbance was subjectively estimated on a scale ranging between 1 (low disturbance) and 3 (high disturbance). For this, two disturbance sources were considered: a high scale disturbance due to local volcanic eruption having lead to primary colonization—thus related to the substrate age—and a low-scale disturbance mainly due to animal activity (seal wallows, bird colonies and transit areas, etc.) affecting present-day communities in a given site.

Samples for quantitative analyses were taken with 16 mm- diameter sterile plastic corers and used to measure pH, conductivity, water and organic matter contents, nutrient concentrations ($\text{PO}_4\text{-P}$, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) and chlorophyll-a.

For the measurement of pH, conductivity and nutrient concentrations at each site, a composite sample of three cores was placed in a clean Erlenmeyer flask, and 50 ml of distilled-deionized water was added. The flask was continuously shaken in cool, dark conditions for 24 h followed by filtration through pre-weighed Whatman GF/C filters. Conductivity and pH of filtered water was then measured with Hanna HI 8033 and Hanna HI 9025 electronic meters, respectively. Concentrations of ammonia ($\text{NH}_4\text{-N}$) were determined according to the phenate method (APHA 1975) while concentrations of dissolved reactive phosphorus ($\text{PO}_4\text{-P}$) and nitrate ($\text{NO}_3\text{-N}$) were measured using a Hach DR/890 colorimeter (Hach, USA), with the appropriate Hach reactivities for each analysis. Material retained in the filters was dried at 65°C to constant weight in order to obtain the concentrations of nutrients per unit dry weight of soil.

Wet-, dry- and ash-free dry weights were measured using three pooled replicate cores from each site. Water and organic matter contents were calculated as percentages of dry weight (Frenot 2002).

Three pooled replicate cores per site were used for spectrophotometric determination of Chlorophyll-a per unit volume corrected for phaeopigments. Extraction was in

DMSO and absorbance was measured at 665 and 750 nm before and after acidification with 1 N HCl (Hawkes and Fletcher 2002).

For taxonomic identification of algae, qualitative samples were taken in sterile Petri dishes. Algae other than diatoms were first observed by wetting samples with sterile physiological saline solution and placing sterile cover slips on their surfaces. These were removed after 24–36 h, by which time algae had become attached to their undersurfaces, and observed with an Olympus CX31 transmitted light microscope fitted with a digital photcamera and a *camera lucida* device. Small portions of soil were inoculated into both liquid and agarised culture media and cultured under controlled conditions (50 $\mu\text{mol photons.cm}^{-1}$, 16:8 light:dark cycles, 15°C). BBM (Bold's basal medium) was used for eukaryotic algae (Chantanachat and Bold 1962) and BG-11 for cyanobacteria (Stanier and Cohen-Bazire 1977). Cultures were observed 1 and 4 weeks after being initiated, and some rare species identified only following isolation and observation of their life cycles. Authoritative references used for algal identification included Ettl and Gärtner (1995) and Komárek and Anagnostidis (1999, 2005) among many others.

Diatom samples were prepared following the method of Van der Werff (1955). Small parts of the samples were cleaned by adding 37% H_2O_2 and heating to 80°C for about 1 h. The reaction was completed by addition of KMnO_4 . Following digestion and centrifugation, the resulting clean material was diluted with distilled water to avoid excessive concentrations of diatom valves that may hinder reliable observations. Cleaned diatom valves were mounted in Naphrax[®]. Samples and slides are stored at the National Botanic Garden of Belgium. Light microscope observations were conducted using an Olympus BX51 microscope equipped with Nomarski optics. Identifications of Antarctic species were based on Bourrelly and Manguin (1954), Le Cohu and Maillard (1983, 1986), Schmidt et al. (1990), Oppenheim (1994) and Van de Vijver et al. (2002, 2004). Nomenclature follows the latest taxonomical tendencies for the genera separated from *Achnanthes* s.l., *Navicula* s.l. and *Cymbella* s.l., based on Lange-Bertalot (2001), Krammer (2002), Bukhtiyarova and Round (1996) and Round and Bukhtiyarova (1996).

To analyse particle size, the percentage of coarse fragments was calculated by weighing samples before and after passing them through a 2 mm sieve. Texture was evaluated by a gravimetric method (Lamotte Chemical Products Company, USA; Richardson and Vepraskas 2001).

Data analysis

Pearson's correlation coefficients among all abiotic parameters were calculated prior to the CCA in order to eliminate

those variables that, due to their association, (significant correlations at $P < 0.05$) would distort results. A CCA (canonical correspondence analysis) was then performed on standardized values of abiotic parameters, sites and relative frequency of species data in order to check for collinearity. Variables characterized by high inflation factors were then dismissed. Site PD3 was excluded from such analysis as an outlier on account of its extreme values for nutrient concentrations and conductivity. Finally, a CCA was run using a forward selection of remaining variables, and the significance of the results was tested by MonteCarlo permutations (no. of permutations = 199).

Species were clustered based on their relative frequencies at the 18 sites using the UPGMA linking method and Euclidean distance (STATISTICA). For non-diatom taxa, three categories were established which reflected the relative frequencies of algal species in each sample: present in direct observation (2), present only in cultures (1), and absent (0). As the standard preparation methodology used for the study of diatoms prevented us from distinguishing living and dead individuals, relative abundances at each site were estimated by identifying 500 randomly selected valves. Each species was then classified into one of the following categories: dominant (more than 10% of total diatom count), occasional (1–10%), rare (less than 1%) and absent (0%).

Results

Physico-chemical data

The selected sites cover a wide range of abiotic conditions along Deception Island, showing different slopes and degrees of disturbance (Table 1). In spite of weather conditions influencing soil temperature to a certain extent (minimum temperature was recorded during the coldest day of the season, and sites CO and TE were sampled on sunny, calm days), geothermal activity accounted for higher temperatures at sites CC1, CC2 and PE. While the coarse fraction accounted for 0–60% of the total soil weight, texture was less variable, with mostly sandy (eight sites) and loamy sand (seven sites) soils. Only three sites showed a sandy loam texture.

Soil pH ranged from very acid to slightly basic (3.70–8.02). Lowest values were recorded at geothermally active sites (CC1, BB), and highest in the midst of a penguin rookery (site PD3). Conductivity values spanned across two orders of magnitude (10.9–1,148 $\mu\text{S cm}^{-1}$). They can be divided into two groups with values clearly below or above 100 $\mu\text{S cm}^{-1}$ (Fig. 2).

Nutrient concentrations ($\text{PO}_4\text{-P}$, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) were consistently low at the sites located in the SW section

of the island (ME, BL, CR and CO), and showed the highest values at PD3, located in an active chinstrap rookery. The latter were 1–2 orders of magnitude higher than the corresponding average of those values at all other sites. Organic matter accounted for less than 1% of the dry weight at half of the sampling sites, and was highest at PD1, an abandoned penguin-nesting site in which feathers, guano and dead moss were observed. Water content was generally high, with maximum values being recorded at VE, where the soil was saturated with water, and at CC2 during a snowfall. The correlation matrix among all abiotic features showed that conductivity, organic matter, concentrations of $\text{PO}_4\text{-P}$, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, were significantly correlated ($r \geq 0.65$, $P < 0.05$) with at least one other parameter from this group, even after removing site PD3.

Species composition

Soils from Deception Island hosted 140 algal taxa, most of them identified at least at generic level. All non-diatoms found through direct observation and/or cultures are listed in Table 2. Cyanobacteria ranged from 0 to 10 species per site (total = 25 spp). Seventy six percent of them had a filamentous habit and dominated the communities in direct observations.

Chlorophyta accounted for 0–9 species per site (total = 26 spp), 65% of them coccoid unicells. Tribophyceae represented only 0–3 species per site (total = 12 spp), most of them (75%) filaments. Culturing methods were necessary to reveal and identify most taxa from the two latter groups. Figure 3 shows the number of algal taxa from each site. Five sites did not show any algal species by direct observation, while site CR had the highest species richness for these groups (18). Most Chlorophyta and Tribophyceae were observed here, both through direct observation and cultures. Site VE followed in species richness, yet with a very different taxonomic composition: it was the one with the most cyanobacteria.

Among all taxa presented here, only three chlorophytes are new records for Antarctica: *Chlamydomonas reinhardtii* Dangeard, *Chlorococcum tatrense* Archibald and *Neosporiococcum vacuolatum* Deason & Cox. The species *Phormidium autumnale* (Agardh.) Gom., *Leptolyngbya frigida* (Fritsch) Anagn. & Kom. *Chlorococcum tatrense* and *Xanthonema montanum* (Vischer) Silva were found at 8–11 sites out of the 18 studied, while all the rest were present at only 1–5 of them.

Regarding diatoms, the spatial distribution of species richness in Fig. 4 follows a similar trend than the one observed for all other groups together with sites CR, BL and VE presenting some of the higher values. Out of the 74 diatoms recorded (Table 3), *Luticola mutica* (Kützing) Mann, *Luticola muticopsis* (Van Heurck) Mann and *Psam-*

Table 1 Topographic, physical and chemical features measured at each sampling site

Site	Soil temp. (°C)	Slope	Disturbance	% Coarse fraction	Texture	pH	Conductivity ($\mu\text{S}/\text{cm}$)	% H ₂ O	% Organic matter	NH ₄ -N ($\mu\text{g}/\text{g DW}$)	NO ₃ -N ($\mu\text{g}/\text{g DW}$)	PO ₄ -P ($\mu\text{g}/\text{g DW}$)	Chl <i>a</i> ($\mu\text{g}/\text{m}^2$)
ME	4.2	2	3	0	S	7.9	25	23.23	0.21	1.06	0.24	8.95	N.D.
BL	4.7	1	1	1.24	S	7.6	16	16.5	0.13	1.77	0.33	3.97	64
CR	5	3	1	5.26	LS	6.7	16	10.26	0.44	2.56	1.39	7.7	5
CO	11.2	2	1	11.67	LS	7.6	26	22.98	1.85	0.57	0.87	1.3	689
PD1	6.3	3	2	19.29	LS	5.8	195	12.55	9.27	20.58	15.5	31	48
PD2	3.6	3	2	22.15	S	6.6	330	18	0.42	0	9.5	136.5	11
PD3	3.8	1	3	60.78	S	8.02	1148	12.91	4.89	699.62	618.7	3781.2	240
PD4	2.8	2	2	11.31	S	6.28	134	14.73	1.48	0.36	4.85	69.5	75
IR	2.9	1	2	8.65	LS	6.95	30.3	15.88	0.76	0.26	0.07	7.47	N.D.
VE	4.5	2	1	8.17	SL	6.69	19.7	42.73	3.68	1.05	2.13	21.61	107
BB	3.6	1	2	1.84	LS	4.14	232	20.23	1.19	8.36	7.5	134.6	5
KR	6.5	1	3	41.32	S	6.44	33.4	5.14	0.19	3.46	6.8	33.3	N.D.
CC1	8.9	1	1	6.36	S	3.7	70	20.5	2.13	3.02	0.87	2.96	11
CC2	19.1	1	1	32.53	LS	6.31	50	39.05	6.47	0.2	8.84	0.95	43
FU	1.2	3	1	19.31	S	5.3	239	10.26	0.86	1.22	0.6	2.3	91
GA	7.2	2	3	27.65	SL	5.37	276	11.31	0.48	1.06	4	45.2	N.D.
TE	12.3	1	3	4.79	SL	5.4	34	15.51	0.37	2.06	0.38	4.31	16
PE	11.7	2	2	18.50	LS	6.46	10.9	19.76	2.88	1.69	2.29	3.44	32

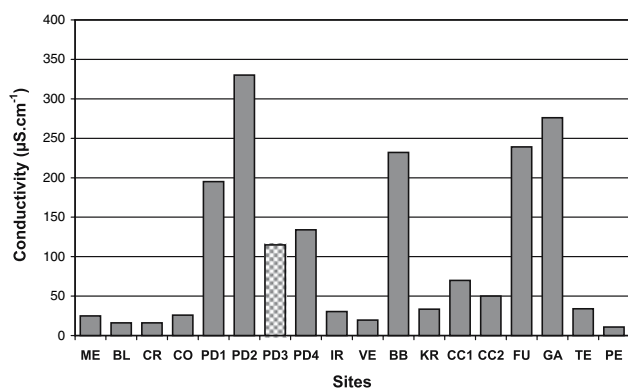


Fig. 2 Conductivity values at the sampling sites. Value at site PD3 is divided by 10

mothidium germanii (Manguin) Sabbe are present in almost all sites. Seven other taxa have been recorded in at least eight sites. On the other hand, 33 (44.6%) diatom species were recorded only at a single site, 13 of them at site CR. Only for this taxonomic group, we observed a significant correlation ($r = 0,72$, $P < 0.05$) between the ratio of rare/total species and species richness.

Community structure

The dendrogram resulting from the cluster analysis performed on all algal species (Fig. 5) revealed a gradient of exclusivity from left to right, placing the most “ubiquitous” species in Group E, and species typical from the richest sites CR and VE in Group A, on the right side of the dendrogram. Group B represents a large number of species closely related to sites KR, CO and BL (subgroups B1–B3, respectively), and a series of taxa that are exclusive or almost exclusive from a single site on account of their common absence from other samples (subgroup B4). Most species characteristic from ornithogenic soils (sites located at Punta Descubierta), mainly represented by cyanobacteria, are gathered in Group C. Group D is composed of fewer taxa, present in groups of three or four sites, which do not seem to respond to any common environmental features. Lastly, Group E includes all diatoms present in at least eight sites, plus the filamentous cyanobacteria *Phormidium autumnale*, a non-diatom taxon present in most of the sites.

Chlorophyll-a varied widely among sites (undetectable to 0.69 mg m^{-2}) and had no significant correlation with any of the abiotic features studied. The highest value was recorded at site CO, characterized by high temperature, low nutrient concentrations and intermediate values for organic matter.

Since significant correlations were found between conductivity, organic matter, concentrations of $\text{PO}_4\text{-P}$, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, all but one of these features were eliminated from the canonical correspondence analysis in order to

avoid colinearity. We decided to preserve phosphorus concentration due to its significance as an inorganic nutrient and for being more stable than nitrogen forms ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$). Soil temperature was also removed from the analysis on account of its high inflation factor.

Slope, coarse fraction and disturbance were expected to influence soil colonization through affecting the mechanical stability of the superficial soil layer. These features showed no significant correlation with the species richness, yet the interaction among two of them (disturbance \times % coarse fraction) significantly contributed to explain the relation species–environment.

Results of the CCA ordinated species and sites along the first axes according to the percentage of the coarse fraction (%CF) (eigenvalue = 0.79) and disturbance (0.65). The interaction between these two parameters showed a strong influence on the second axis (-0.78), while slope had the main weight on the third axis (-0.63). These three axes together explained 52.8% of the cumulative variance of the species–environment relation. Both the first canonical axis and the sum of all canonical axes were significant according to the Monte Carlo permutation test ($P = 0.04$ and 0.02 , respectively).

Figure 6 shows the spatial ordination of species and sites in the space delimited by the two first canonical axes. Species found exclusively at one site were listed beside it. Sites located in the old and stable SW area of the island (CR-CO-IR-BL) are placed together in the lower left quadrant, while site ME, with 0% CF and high disturbance, is placed at the other extreme of the diagram. Sites with high species richness such as CR and VE also show a high number of exclusive species. Sites VE and PD1 are close together, coincidentally with the grouping of their exclusive species together in group A of the dendrogram. Species group B from the dendrogram, in turn, is listed at the lower left quadrant of the CCA ordination. The most “ubiquitous” taxa from group J are not associated to the particular environmental features of any given site. They are thus located mostly on the center of the diagram.

Discussion

Mineral soils from sites located at the SW section of the island showed low conductivity and nutrient concentration values in a comparable range to those recorded by Mataloni et al. (2000) for mineral soils from Cierva Point (Antarctic Peninsula). Sites TE and PE, highly affected by recent eruptions (1967–1970) are also located on mineral soils, but these substrata are much younger and therefore only poorly colonized. Coincidentally, Mataloni et al. (unpublished data) observed that both the planktonic and epilithic communities from the new lakes located at Telefon Bay had considerably

Table 2 Non-diatom taxa recorded at each site

SAMPLING SITE	ME	BL	CR	CO	PD1	PD2	PD3	PD4	IR	VE	BB	KR	CC1	CC2	FU	GA	TE	PE
Cyanobacteria																		
<i>Ammatoidea normanii</i> W. & G.S.West										●								
<i>Aphanocapsa</i> aff. <i>elachista</i> W. & G. S. West					○													
<i>Aphanocapsa</i> sp.							○											
cf. <i>Isocystis pallida</i> Voronichin			●															
<i>Leptolyngbya foveolarum</i> (Rab. ex Gom.) Anagn. & Kom.			○															
<i>Leptolyngbya fragilis</i> (Menegh.) Anagn. & Kom.								○		●							●	
<i>Leptolyngbya frigida</i> (Fritsch) Anagn. & Kom		○	●	○				○	○	●	○		○				●	
<i>Leptolyngbya</i> aff. <i>glacialis</i> (W. & G.S.West) Anagn. & Kom				○					○	○			○					
<i>Leptolyngbya</i> sp. 1	○				○			○							●			
<i>Leptolyngbya</i> sp. 2	●																	
<i>Nodularia harveyana</i> Thuret									○	●	○		○				●	
<i>Nostoc</i> sp.				●														
<i>Oscillatoria amphibia</i> Ag.										●								
<i>Phormidium autumnale</i> (Agardh.) Gom.		●	●	●	●		●	○	●	○			○		●	●		
<i>Phormidium murrayi</i> (W. & G.S.West) Anagn. & Kom					●					●								
<i>Phormidium priestleyi</i> Fritsch		○	○				●										○	
<i>Phormidium</i> sp. 1			●															
<i>Phormidium</i> sp. 2	●																	
<i>Pseudanabaena catenata</i> Lauteb.									○									
<i>Synechococcus elongatus</i> (Naegeli) Naegeli												○						
filamentous Cyanobacteria sp. 1										●								
filamentous Cyanobacteria sp. 2										○								
sarcinoid Cyanobacteria sp. 1							●											
sarcinoid Cyanobacteria sp. 2							●											
sarcinoid Cyanobacteria sp. 3							●											
TOTAL	3	3	6	4	4	0	6	4	5	10	2	1	3	1	2	4	1	0
Chlorophyta																		
<i>Actinotaenium cucurbita</i> (Brebisson) Teiling			●															
<i>Chlamydomonas moewusii</i> Gerloff		○																
<i>Chlamydomonas reinhardtii</i> Dangeard					●													
<i>Chlorella</i> aff. <i>homosphaera</i> Skuja			●															
cf. <i>Chlorella kessleri</i> Fott & Novakova		○																
<i>Chlorella vulgaris</i> Beijerinck				○		○												
<i>Chlorella</i> sp1			○		○		○											
Chlorellaceae aff. <i>Chorycistis</i> (Skuja) Fott																		○
<i>Chlorococcum lobatum</i> (Korschikoff) Fritsch & John				○								○		○				
<i>Chlorococcum tatrense</i> Archibald	○		○			○			○	○			●		○	○	○	○
Chlorococcal sp. 1							○											
Chlorococcal sp. 2										○								
Chlorococcal sp. 3		○	●															
cf. <i>Fasciculochloris boldii</i> Mc Lean & Trainor										○								
<i>Klebsormidium dissectum</i> (Gay) Ettl & Gaertner				○								○						
<i>Muriella</i> cf. <i>zoofingiensis</i> (Doenz) Hindak					○							○						○
<i>Neosporangiococcum</i> cf. <i>alabamense</i> (Deason) Deason			○									○						
<i>Neosporangiococcum</i> sp. Deason						○												
<i>Neosporangiococcum vacuolatum</i> Deason & Cox			○										○					
<i>Prasiola crispa</i> (Lightfoot) Meneghini					●	○												
<i>Pseudococcomyxa simplex</i> (Mainx) Fott				○	●													
<i>Raphidonema nivale</i> Lagerheim			○	○														
<i>Raphidonema pyrenoidifera</i> Korschikoff		○				○							○					
<i>Stichococcus bacillaris</i> Naegeli													○					
<i>Tetracystis</i> cf. <i>tetraspora</i> (Arce & Bold) Brown & Bold					○					○								
<i>Tetracystis</i> sp.			●			○												○
TOTAL	1	4	9	5	5	7	2	0	1	4	3	4	2	1	1	1	1	4
Tribophyta																		
cf. <i>Chlorellidiopsis separabilis</i> Pascher	○																	
<i>Ellipsoidion</i> cf. <i>stichococcoides</i> Pascher												○						
<i>Heterococcus</i> sp. Chodat						○												
<i>Heterotrichella gracilis</i> Reising									○		○							
<i>Tribonema monochloron</i> Pascher et Geitler			○															
<i>Xanthonema debile</i> (Vischer) Silva			●															
<i>Xanthonema montanum</i> (Vischer) Silva		○				○			○	●	○	○			○		○	
<i>Xanthonema</i> cf. <i>solidum</i> (Vischer) Silva					○													
<i>Xanthonema stichococcoides</i> (Pascher) Silva				○									○					
<i>Xanthonema</i> sp. 1										○								
<i>Xanthonema</i> sp. 2			●															
Pleurochloridaceae sp 1				●														
TOTAL	1	1	3	2	1	2	0	0	2	2	2	2	1	0	1	0	1	0

Filled circles: taxa recorded through direct observation. Empty circles: taxa recorded only in cultures

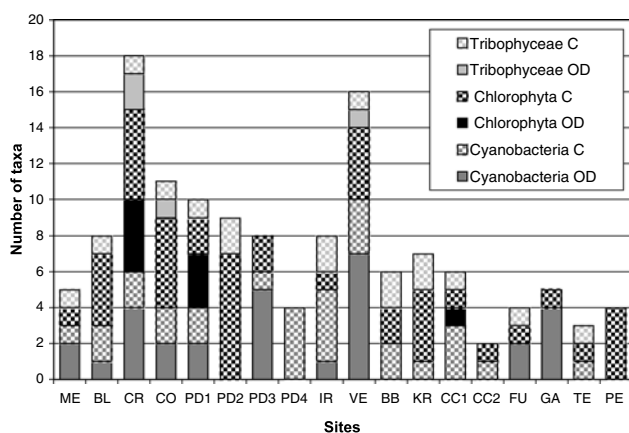


Fig. 3 Number of non-diatom taxa at each sampling site. *OD* Direct observation, *C* Grown only in cultures

lower species richness than those of Crater Lake and other waterbodies at the SW section of the island.

Sites PD1 to PD4 represent different degrees of use by a penguin rookery, while GA is located in a kelp gull nesting area. These sites show generally high values for conductivity and nutrient concentrations due to manuring and trampling by the birds. PD3, located in the active colony, also shows the highest pH value possibly provoked by the abundantly released ammonia from fresh guano decomposition (Tatur and Myrcha 1984). Conversely, at border sites PD2 and PD4 the guano layer is subjected to weathering and dissolution resulting in nitrate as the dominant N form and low pH values (Myrcha and Tatur 1988). On the other hand, pH values at the sites affected by XXth century seismic events are still as low as those recorded by Cameron and Benoit (1970), and could be due to H₂S-releasing fumarolic activity (Fourcade and Viramonte, 1972).

According to Lawley et al. (2004), maritime Antarctic soils are typically poorly developed with low organic content (organic matter percentages between 0.42 and 5.94 for

mineral soils from different Antarctic locations along a latitudinal gradient). At Deception Island, most mineral soils showed even smaller amounts of organic matter, suggesting that they are indeed poorly developed. Nevertheless, organic matter values of ornithogenic soils at sites PD1 and PD3 are similar to those reported by Mataloni and Tell (2002) from similar environments at Cierva Point.

Davey (1988) attributed variations in the development of soil microalgae mainly to water availability. Deception Island has an annual mean precipitation of 500 mm (Igarzabal 1974) and frequent freeze–thaw cycles allow for a superficial soil layer saturated with water (López-Martínez and Serrano 2002). Indeed, in our study, soil water content varied between 10 and 42% of the dry weight with the exception of site KR (5%). Soils from Deception Island are classified as andosols with volcanic glasses (Bölter et al. 1999), characterized by a weak meteorization and large particle size. Wynn-Williams (1997), found a coarse volcanic soil to have a rapid water percolation and air circulation which resulted in the soil being severely water-limited for most of the growing season. This author demonstrated a significant correlation of algal colonization with soil moisture and capability for water retention. Yet, moisture and temperature can change widely over short periods of time (Bölter 2001) thus selecting taxa able to respond quickly to these changes. Although sampling took place at a single time, such changes are likely to occur in the dark coarse soils of Deception. If particle size influences water availability through the mechanisms explained by Wynn-Williams (1997), it would be possible that this factor drives colonization by microorganisms through strong variations in time not detected in this study. Future research at a smaller scale must be done in order to test this hypothesis.

According to Elster (2002), physical disruption of the unstable environment is a crucial stress factor for Antarctic soil algae. Thus, slope is also supposed to negatively affect

Fig. 4 Number of diatom taxa at each sampling site. *White bars* Rare (less than 1% of individuals counted). *Grey bars* Occasional (1–10%). *Black bars* Dominant (more than 10%)

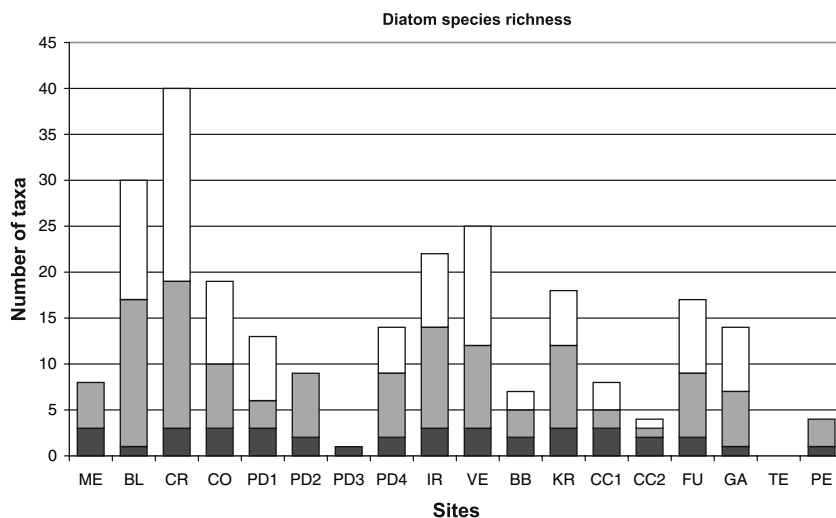


Table 3 Diatom taxa recorded at each sampling site

SAMPLING SITE	ME	BL	CR	CO	PD1	PD2	PD3	PD4	IR	VE	BB	KR	CC1	CC2	FU	GA	TE	PE
Bacillariophyceae																		
<i>Brachysira minor</i> (Krasske) Lange-Bertalot			■							■								
<i>Chamaepinnularia australomediocris</i> (Lange-Bertalot & Schmidt) Van de Vijver			■							■								
<i>Chamaepinnularia evanida</i> (Hustedt) Lange-Bertalot			■							■								
<i>Chamaepinnularia krookii</i> (Grunow) Lange-Bertalot & Krammer	■																	
<i>Chamaepinnularia krookiiformis</i> (Krammer) Lange-Bertalot & Krammer			■		■	■		■		■					■			
<i>Chamaepinnularia</i> sp.					■	■				■						■		
<i>Chamaepinnularia</i> sp.2			■															
<i>Cocconeis californica</i> var. <i>kerquelensis</i> Heiden					■													
<i>Diadesmis</i> aff. <i>comperei</i> Le Cohu & Van de Vijver		■		■				■	■	■							■	
<i>Diadesmis ingeae</i> Van de Vijver		■	■	■	■				■	■					■	■		
<i>Diadesmis</i> sp.		■	■						■									
<i>Diadesmis</i> sp.2																	■	
<i>Fragilaria capucina</i> Desmazières			■															
<i>Fragilariopsis kerquelensis</i> (O'Meara) Hustedt					■							■						
<i>Fragilariopsis nana</i> (Steehan Nielsen) Paasche		■									■							
<i>Geissleria</i> sp.		■	■															
<i>Gomphonema parvulum</i> (Kützing) Kützing var. <i>parvulum</i>			■															
<i>Gomphonemopsis littoralis</i> (Hendey) Medlin					■													
<i>Hantzschia amphioxys</i> (Ehrenberg) Grunow	■	■	■	■					■	■		■			■	■		
<i>Hantzschia</i> sp.		■	■															
<i>Hantzschia</i> sp.2																	■	
<i>Luticola</i> aff. <i>dismutica</i> (Hustedt) Mann		■	■		■				■	■	■						■	
<i>Luticola</i> aff. <i>muticopsis</i> ssp. (Van Heurck) Mann									■									
<i>Luticola mutica</i> (Kützing) Mann	■	■	■	■	■	■	■		■	■	■	■			■	■		■
<i>Luticola muticopsis</i> (Van Heurck) Mann	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■
<i>Luticola nivalis</i> (Ehrenberg) Mann		■							■	■	■	■					■	
<i>Mayamaea</i> aff. <i>exceisa</i> (Krasske) Lange-Bertalot				■					■	■					■			■
<i>Mayamaea atomus</i> (Kützing) Lange-Bertalot var. <i>atomus</i>	■	■	■		■				■	■	■	■			■			■
<i>Mayamaea atomus</i> var. <i>permitis</i> (Hustedt) Lange-Bertalot		■	■	■		■			■	■	■	■	■	■	■	■		■
<i>Mayamaea</i> sp.		■							■									
<i>Melosira charcotii</i> Peragallo												■						
<i>Microcostatus naumanii</i> (Hustedt) Lange-Bertalot			■															
<i>Muelleria algida</i> Spaulding & Kociolek		■																
<i>Muelleria luculenta</i> Spaulding & Kociolek		■	■	■						■								
<i>Muelleria</i> sp.		■	■	■					■									
<i>Muelleria</i> sp. 2			■															
<i>Muelleria</i> sp. 3									■									
<i>Muelleria varipunctata</i> Spaulding & Kociolek		■	■						■	■					■			
<i>Navicula cincta</i> (Ehrenberg) Ralfs												■						
<i>Navicula directa</i> (W. Smith) Ralfs		■																
<i>Navicula gregaria</i> Donkin			■															
<i>Navicula perminuta</i> Grunow															■	■		
<i>Navicula</i> sp.		■							■									
<i>Navicula</i> sp.2											■							
<i>Navicula subminusculea</i> Krasske			■															
<i>Navicula veneta</i> Kützing		■																
<i>Naviculadicta</i> sp.	■	■	■	■					■	■					■	■		
<i>Nitzschia acidoclinata</i> Lange-Bertalot			■							■								
<i>Nitzschia debilis</i> Amott			■															
<i>Nitzschia gracilis</i> Hantzsch			■															
<i>Nitzschia hamburgiensis</i> Lange-Bertalot		■	■															
<i>Nitzschia llebetruthii</i> Rabenhorst		■																■
<i>Nitzschia</i> sp.												■						
<i>Parlibellus</i> sp.																		
<i>Pinnularia acorica</i> Hustedt				■					■									
<i>Pinnularia</i> aff. <i>intermedia</i> (Lagerstedt) Cleve		■		■					■		■							
<i>Pinnularia</i> aff. <i>microstauron</i> (Ehrenberg) Cleve		■	■															
<i>Pinnularia</i> aff. <i>obscura</i> Krasske	■	■		■					■						■			■
<i>Pinnularia</i> aff. <i>schoenfelderi</i> Krammer			■															
<i>Pinnularia borealis</i> var. <i>anceolata</i> Hustedt		■	■	■	■				■	■	■	■	■	■	■	■		■
<i>Pinnularia borealis</i> var. <i>scalaris</i> (Ehrenberg) Ralfs	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■
<i>Pinnularia borealis</i> <i>rabenhorstii</i>					■													
<i>Pinnularia rabenhorstii</i> (Grunow) Krammer		■																
<i>Pinnularia</i> sp.					■					■								
<i>Pinnularia subantarctica</i> var. <i>elongata</i> (Manguin) Van de Vijver & Le Cohu		■		■						■								
<i>Planothidium lanceolatum</i> (Brébisson) Lange-Bertalot			■															
<i>Psammothidium germainii</i> (Manguin) Sabbe	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
<i>Psammothidium manguinii</i> (Germain) Van de Vijver			■	■														
<i>Psammothidium metakryophilum</i> (Lange-Bertalot & Schmidt) Sabbe			■							■								
<i>Stauroneis husvikensis</i> Van de Vijver & Lange-Bertalot		■	■	■					■	■								
<i>Stauroneis kriegeri</i> Patrick																		
<i>Stauroneis latistauros</i> Van de Vijver & Lange-Bertalot			■															
<i>Stauroneis</i> sp.										■								
<i>Stausira alpestris</i> (Krasske) Van de Vijver			■															
<i>Tabularia fasciculata</i> (Kützing) William & Round							■											
<i>Thalassiosira gracilis</i> var. <i>expecta</i> (Van Landingham) Fryxell & Hasle				■														
<i>Tropidoneis laevissima</i> West & West																		
TOTAL	8	30	41	19	13	9	1	14	23	25	7	18	8	4	17	14	0	4

Empty squares: Rare (less than 1%). Half-filled squares: Occasional (1–10%). Filled squares: Dominant (more than 10%)

soil colonization, since soils on steep slopes are generally shallow and have low capability of retaining water and nutrients (Smith and Smith 2001), and sliding of particles

would bury algal propagules. In spite of this, at Deception Island, the richest site was located on a steep slope, as well as PD1 and PD2, showing signs of successful algal coloni-

Fig. 5 Dendrogram showing the clustering of all taxa based on relative abundance categories

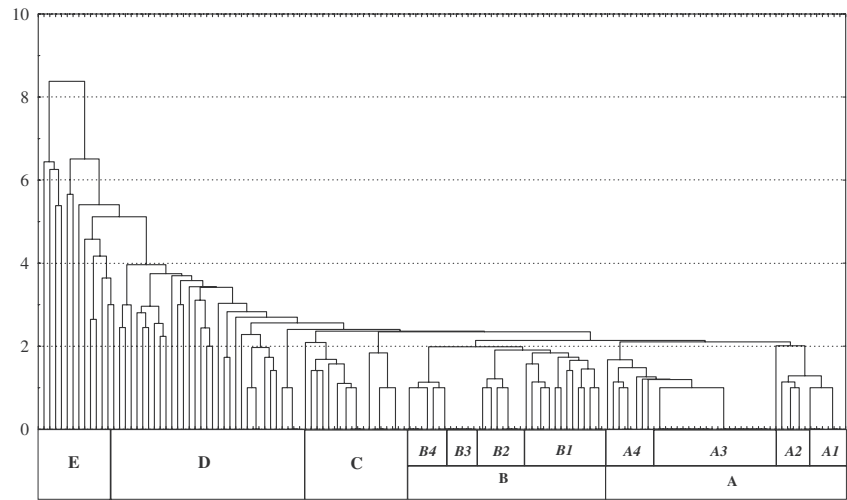
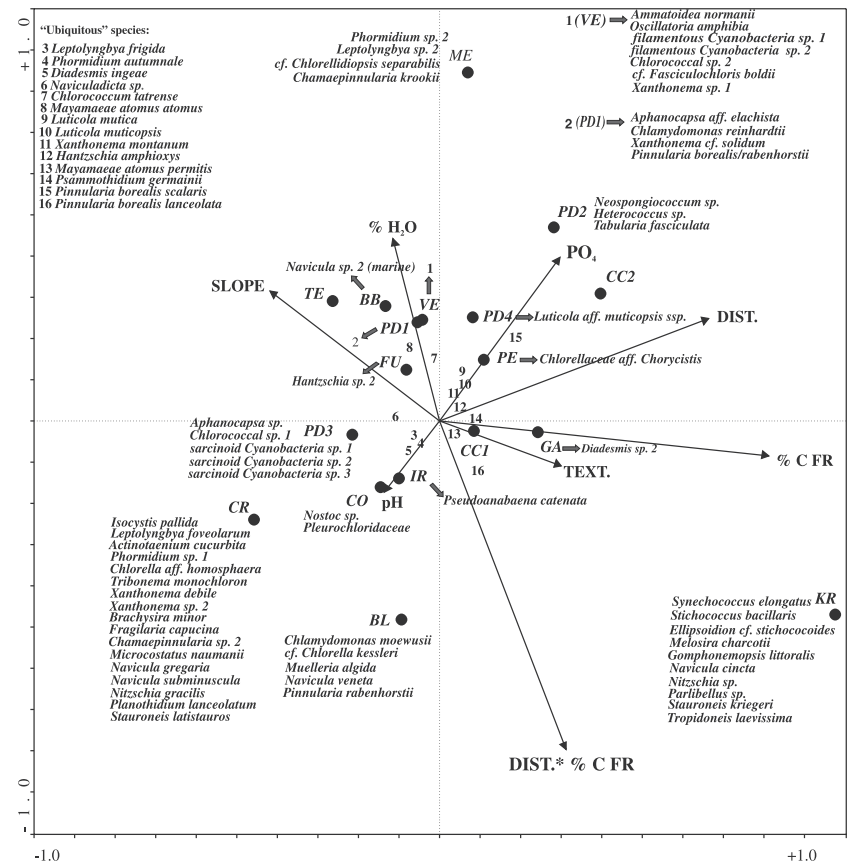


Fig. 6 CCA distribution along the first two axes determined by environmental features



zation, both in biomass and species richness. The effect of moisture continuously running down the slope avoiding drought might be a crucial factor here.

Chlorophyll-a concentrations were much lower than those recorded by Davey and Rothery (1993) and Arnold et al. (2003) for Signy Island, also located in maritime Antarctica. Like the first authors, we did not find any significant correlation between this parameter and any single environmental feature. Furthermore, species were ordinated

along the two first axes of the CCA according to the percentage of the coarse fraction, disturbance and the interaction between these two parameters. Our results thus seem to reflect the importance of long-term disturbance and short-term physical stability on creating “spots” of favorable conditions for algal colonization and growth.

At most sites, algal communities were dominated by cyanobacteria and diatoms, as described by Mataloni et al. (2000) and Mataloni and Tell (2002) for Cierva Point.

Among them, most widespread cyanobacteria were *Phormidium autumnale* and *Leptolyngbya* spp., which in most sites formed a mucilaginous mesh providing shadow and moisture to other microalgae. This facilitation mechanism has been first analyzed by Wynn-Williams (1990) and documented by many authors.

The large number of diatom taxa identified up to only the genus level is not surprising. Actual detailed morphological and taxonomical studies of the islands in the southern Atlantic Ocean are scarce and usually based on northern hemisphere literature. As has been stated already by Sabbe et al. (2003) and Van de Vijver et al. (2005), force-fitting has led in the past to incorrect estimations of species richness, diversity and biogeography. Spaulding et al. (1998) published a revision of the species belonging to the genus *Muelleria*. Several new species from Signy Island (South Orkney Islands) were described, that were previously identified as European species (i.e. *Navicula linearis* Müller or *N. gibbula* Cleve). All new species found in the soils of Deception Island will be subject of a future publication.

Although only sparsely studied and reported, diatoms are a rather common constituent of (sub-)Antarctic soils (Bunt 1954, Van de Vijver and Beyens 1998, Van de Vijver et al. 2002a) and present quite typical communities usually based on the same set of species. Bare soil communities on Ile de la Possession, sometimes also referred to as fellfield-soil communities, are always composed of *Pinnularia borealis* var. *scalaris* (Ehrenberg) Rabenhorst, *Diademesma ingeae* Van de Vijver, *Psammothidium germainii* and various species of *Luticola* (Van de Vijver et al. 2002b). Our results indicate that this community is also present on Deception Island—despite its more southern position—and might therefore be considered as a typical maritime Antarctic diatom community.

The influence of the fur seals on site KR is quite obvious and resulted in the finding of a lot of marine (predominantly benthic) species. On South Georgia, a similar observation was made in an elephant seal wallow (Van de Vijver and Beyens 1996). The relatively high degree of stability in the southwestern part of the island (sites CR-CO-IR-BL) resulted in the rather stabilized diatom flora lacking typical pioneer species. Both the number of species and the number of individuals per species indicate the presence of well established, rather old communities.

Most Chlorophytes and Tribophyceae, in turn, were present in very low abundances. As they required culturing under warmer, wetter conditions in order to show sufficiently detectable growth allowing for taxonomical identification, it is evident that the soil propagule bank is composed mainly of species that had encountered suboptimal conditions allowing them only to survive but not to establish viable communities. As for thermophilic bryophytes (Smith 2005), a large proportion of the recorded

species (almost 50%) was found only at a single site, revealing a high patchiness of favorable conditions as well as a low rate of local dispersal even among ecologically similar sites. This would also explain the low similarity in composition between the two richest sites CR and VE. Davey (1988) and Mataloni et al. (2000) had already described strong differences in the microalgal flora among patches of mineral soils at Signy Island and Cierva Point, respectively.

Although site BB (Whalers Bay) was located in the area of the abandoned Norwegian whaling station, one of the spots most visited by tourists in Antarctica (Smith 2005), the species richness at this site was lower than at other nearby locations (VE, KR). So, contrary to expectations, there was no evidence that tourists arriving from other places in Antarctica acted as a propagule source for this site.

The positive correlation between the ratio of rare/total species and species richness found for diatoms is also not easy to explain. Due to the very good preservation of silica frustules, empty (=dead) diatom valves are able to sustain severe erosion and degradation within the soil. Since we did not make a differentiation between dead and living frustules, it is impossible to say whether these diverse communities as found in the samples are actually present in a viable form. More research will be necessary to evaluate the capabilities of these rich sites in forming optimal dispersal traps for non-established propagules. Chalmers et al. (1996) published the results of some trapping experiments in the maritime antarctic region showing that a large number of freshwater and terrestrial diatoms is dispersed without forming established viable communities at their landing sites.

The dendrogram performed on algal taxa at each site firstly clustered together species exclusive from the same site. At a higher linkage distance, those taxa present in a same group of sites joined in these clusters, forming one large group of species with higher fidelity to sets of ecological conditions. Finally, “ubiquitous” species showed the lowest similarity values. Due to this plasticity, taxa within this group would be more likely to colonize new environments created by volcanic activity. Indeed, the few species present at the youngest, more disturbed sites belong almost exclusively to this group.

Our results therefore provide baseline information for further investigations aiming to elucidate to what extent more stable, old and species-rich areas would act as local propagule sources for the colonization of new environments arisen from volcanic activity and the mechanisms implied in this process. Directing future research at Deception Island to follow-up long-term studies on the succession of young soil communities described in this paper would be desirable.

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