Solid Earth, 6, 583–594, 2015
www.solid-earth.net/6/583/2015/
doi:10.5194/se-6-583-2015

Soil–landform–plant-community relationships of a periglacial landscape on Potter Peninsula, maritime Antarctica

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Received: 30 March 2014 – Published in Solid Earth Discuss.: 6 August 2014
Revised: 26 October 2014 – Accepted: 27 October 2014 – Published: 27 May 2015

Abstract. Integrated studies on the interplay between soils, periglacial geomorphology and plant communities are crucial for the understanding of climate change effects on terrestrial ecosystems of maritime Antarctica, one of the most sensitive areas to global warming. Knowledge on physical environmental factors that influence plant communities can greatly benefit studies on the monitoring of climate change in maritime Antarctica, where new ice-free areas are being constantly exposed, allowing plant growth and organic carbon inputs. The relationship between topography, plant communities and soils was investigated on Potter Peninsula, King George Island, maritime Antarctica. We mapped the occurrence and distribution of plant communities and identified soil–landform–vegetation relationships. The vegetation map was obtained by classification of a QuickBird image, coupled with detailed landform and characterization of 18 soil profiles. The sub-formations were identified and classified, and we also determined the total elemental composition of lichens, mosses and grasses. Plant communities on Potter Peninsula occupy 23 % of the ice-free area, at different landscape positions, showing decreasing diversity and biomass from the coastal zone to inland areas where sub-desert conditions prevail. There is a clear dependency between landform and vegetated soils. Soils that have greater moisture or are poorly drained, and with acid to neutral pH, are favourable for moss sub-formations. Saline, organic-matter-rich ornithogenic soils of former penguin rookeries have greater biomass and diversity, with mixed associations of mosses and grasses, while stable felsenmeers and flat rocky cryoplanation surfaces are the preferred sites for *Usnea* and *Himantormia lugubris* lichens at the highest surface. Lichens sub-formations cover the largest vegetated area, showing varying associations with mosses.

1 Introduction

Ice-free areas in maritime Antarctica have a peculiar flora dominated by a "fellfield" physiognomy, cryptogams with dominance of bryophytes (including mosses and liverworts), two species of talus algae (*Prasiola crispa* and *Prasiola cladophylla*) and approximately 360 known species of lichens. Only two native phanerogams occur (Antarctic hair grass, *Deschampsia antarctica* Desv., and Antarctic pearlwort, *Colonbanthus quitensis* (Kunth) Bartl.; Øvstedal and Smith, 2001).

The poorly diverse maritime Antarctic tundra ecosystems are best developed on ice-free areas under strong faunal influence during the summer period. The most important sites are coastal penguin rookeries, which provide suitable conditions for plant diversity in their marginal areas (Allen et al., 1967; Tatur and Myrcha, 1989; Tatur et al., 1997; Michel et al., 2006; Smykla et al., 2007; Simas et al., 2007; Victoria et al., 2013). As one moves inland, the vegetation becomes progressively sparse and less structured. Most biotic communities occur as small isolated patches, adapted to cold climate, relatively low light, high UV radiation and winter snow coverage (Bargagli et al., 1995).

Abandoned rookeries are characterized by dense vegetation in nitrogen- and phosphate-rich ornithogenic soils,

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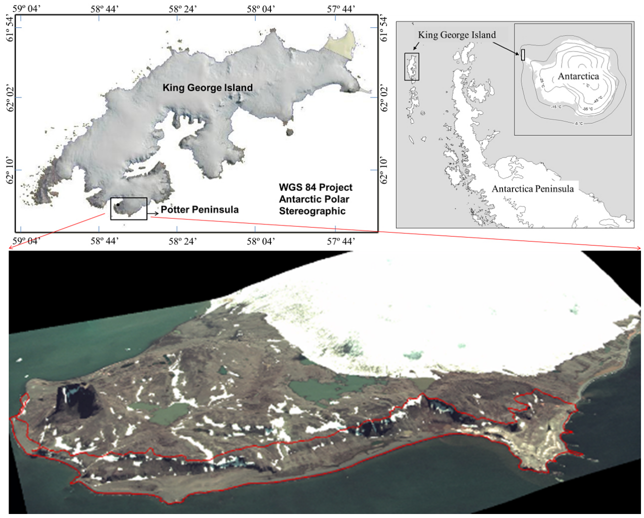

Figure 1. Top left: localization map of Potter Peninsula in the maritime Antarctica. Top right: location in relation to Antarctic Peninsula. Bottom: Quickbird 2 image in perspective view. The red line shows the limit of ASPA 132.

which maintain high levels of available nutrients centuries or millenniums after abandonment (Myrcha and Tatur, 1991). The South Shetland Islands uplift of 18–20 m above sea level during the Holocene period as a consequence of the glaciostatic movement following glacial retreat (Fretwell et al., 2010). During the last 500 years the environment are progressively stabling and occupied by plants (Birkenmajer, 1998). Throughout this period, the penguin rookery of Stranger Point progressively moved down from the highest cliff to the recent beaches (Tatur and Myrcha, 1989).

Ornithogenic soils are the most important compartment of immobilized carbon (C) in Antarctic ice-free areas. The presence of two flowering plants – *D. antarctica* and *C. quitensis* – contributes to higher organic C levels, and is positively related to soil depth (Simas et al., 2007). Organic matter in such soils is richer in nitrogen (N) and easily thermodegradable compounds, representing a considerable pool of easily degradable C in the maritime Antarctic environment (Michel et al., 2006). Consequently, these soils may be vulnerable to C losses to the atmosphere in response to global warming and permafrost degradation (Michel et al., 2006; Simas et al., 2007).

At Stranger Point, in the eastern part of Potter Peninsula, Tatur et al. (1997) observed that high nutrient status appears to determine the vegetation distribution and zonation in both active and abandoned rookeries. *D. antarctica* is relatively abundant in ornithogenic soils of abandoned rookeries and in marginal areas of active rookeries. Schaefer, C. E. G. R. et al. (2004) and Francelino et al. (2011) found colonies of *D. antarctica* and *C. quitensis* in stable and shallow soils at nearby Keller Peninsula, close to bird nests. Large vegetated uplands and slopes are occupied by *Usnea* sp. lichen mainly in well-drained moraines, felsenmeer and rocky slopes (Francelino et al., 2011). Mosses are locally extensive in hydromorphic, waterlogged soils. Plant succession begins with talus algae and cyanobacteria mats, and culminates with a mixed formation of lichens, bryophytes and eventually higher plants. Vegetation development is particularly sensitive to the nutrient transfer from marine to terrestrial ecosystems by faunal action (Schaefer, C. N. et al., 2004). Hence, vegetation can serve as a proxy of environmental changes and human-mediated pollution (Bargagli et al., 1995; Poblet et al., 1997).

The assessment of plant communities' temporal dynamics and ecological relationships with physical attributes, such as soil parent material, slope, and climate (Schaefer, C. E. G. R. et al., 2004), are key issues for Antarctic ecology. Understanding the factors affecting the distribution of vegetation in Antarctica ice-free areas can help in studying climate and landscape change at greater scales. To detect changes in community structure and extent, there is a need for improved instrumental monitoring of the physicochemical and biological characteristics of periglacial areas in order to understand and model the effects of global change on water, permafrost, soil and primary ecosystem processes (Bargagli, 2005). Longton (1988), based on many previous works, adapted a vegetation classification system to maritime Antarctica, where the grouping of different species was based on growing forms and habitats. The criteria for separating formations were based on habitats and growth forms of the most abundant species. The tundra sub-formation units are based on growth form, and the predominant association refers to the floristic similarity between the components (Smith and Gimingham, 1976).

Systematic vegetation mapping at large scale in Antarctica is very limited. At regional scales and low resolution, the application of NOAA AVHRR for vegetation analysis in Antarctica has failed to detect the highly fragmented and dispersed nature of local vegetation (Fretwell et al., 2011). At greater scales, most previous studies have focused on field floristic surveys aided by GPS (Kim et al., 2007; Schaefer, C. E. G. R. et al., 2004; Victoria et al., 2013), and the identification of aerial photograph mosaics (Francelino et al., 2011) resulting in vegetation maps of large scales in small ice-free areas, or large areas with remote sensing images at low resolution (Fretwell et al., 2011). On the other hand, in isolated areas with heterogeneous distribution of vegetation in maritime Antarctica, traditional vegetation mapping is more difficult at large scales. In this regard, high-resolution satellite images are excellent alternatives. Satellite images obtained through remote sensing can help the monitoring of climate change impacts on ice-free areas with greater efficiency and higher resolution. A baseline survey of the amount and distribution of vegetation is required for comparison against in order to monitor future changes (Fretwell et al., 2011).

It is widely recognized that the relationship between Antarctic vegetation and abiotic factors, such as soils and

Table 1. Vegetation community classification of Potter Peninsula (adapted from Longton, 1988).

Vegetation communities	Landforms and soils	Dominant plant species	Sociation plants
Tall moss turf and carpet sub-formation	Mosses in wet, hydromorphic areas (partially associated with cyanobacteria mats) in wet marine terrace soils (with < 10 % slope) (P5) (P14). At Stranger Point, very dense moss carpets occur in old stable talus (P14) (30 % slope).	*Sanionia uncinata, Andreaea, Phormidium* sp., *Polytrichum, Bryum*	*Cyanobacteria; D. antarctica;* without lichens, Fig. 5a
Moss turf and grass sub-formation	Mosses and *D. antarctica* on well-drained marine terraces and ornithogenic soils of abandoned rookeries and petrel nests (P11, P13, P17, P18).	*Sanionia* sp., *D. antarctica, Polytrichum*	*Umbilicaria*; *Cladonia* sp., *Himmantormia* sp.; *Neurophogum* sp., Fig. 5b
Fruticulose and foliose lichen sub-formation	Homogeneous lichen fields in well-drained rocky, skeletal soils (P1, P2, P3, P7) of stables cryoplanation surfaces.	*Usnea* sp., *Ochrolechia* cf. *frigida, Cladonia* sp., *Neurophogum, Himantormia*	*Polytrichum, Bryum, Sanionia* , Fig. 5c
Fruticulose lichens/short moss turf and cushion sub-formation	Mosses and foliose/crustose lichen communities in ornithogenic soils on marine terraces (P13, P6) and weakly ornithogenic soils (P4, P10, P15). Occurrence on dry to moist habitats, acid and cryoturbic soils derived from moraines and uplifted marine terraces.	*Polytrichum* sp., *Usnea* sp., *Sanionia uncinata,*	*D. antarctica; Sanionia* sp.; *Prasiola; Polytrichales,* Fig. 5d
Macroscopic alga sub-formation	*Prasiola crispa* in the vicinity of penguin and giant petrel rookeries (recent guano). Habitats with high ammonia in Stranger Point occur in widespread marine terraces (flat slopes < 5 %).	*P. crispa,*	*Cyanobacteria. D, antarctica*; *Umbilicaria and Ramalina* sp. , Fig. 5e

Table 2. Spectral characteristics of QuickBird satellite image.

Spectral band	Wavelength (nm)	Spatial resolution (m)
Panchromatic	405 to 1053	0.60
Blue	430 to 545	
Green	466 to 620	
Red	590 to 710	2.44
NIR	715 to 918	

landforms, is relevant for the understanding of the ecological evolution of Antarctic landscapes (Francelino et al., 2011) and how they respond to environmental changes. Environmental monitoring including remote sensing and in situ measurements, mapping the extent of vegetation, and biological characterization at community and population levels (both floristically and faunistically) can help to detect changes in community structure and extent (Bargagli, 2005). The present work aims to map the vegetation communities with high-resolution satellite images and investigated the relationships between vegetation communities in ice-free areas on Potter Peninsula and selected geomorphological and pedological features. In addition, we evaluated some basic plant chemical composition to compare with the amounts of available nutrients in soils.

2 Study area

Potter Peninsula is located on King George Island (Fig. 1), part of the South Shetland archipelago, maritime Antarctica, at the following coordinates: 62°13.5′–62°16′ S, 58°42′–58°33′ W. Potter Peninsula stretches over a 6 km long east–west extension, and 3.5 km long north–south axis, with a total of approximately 7.13 km^2 ice-free area during the summer (Fig. 1). The Köppen climate classification for King George Island is ET. Average annual air temperature is −2.8 °C, with summer temperature ranging from −1.3 to 2.7 °C and winter from −15.5 to −1.0 °C (Ferron et al., 2004). In terms of geology, Potter Peninsula belongs to the Warszawa tectonic block, which is dominated by a volcanic rock sequence formed between 50.6 and 49.1 Ma (Kraus and del Valle, 2008). The geology mainly comprises basalt and basaltic andesite, frontal and basal moraines, and different levels of marine terraces. The peninsula has been shaped by glacial action, moraines formed with typical rock outcrops, and different levels of terraces (Birkenmajer, 1998; Kraus and del Valle, 2008). More details can be found in Birkenmajer (1998). The soils of Potter Peninsula are typical for a periglacial environment, with poorly developed soils, coarse sand and gravel, sandy texture, and ornithogenic soils in marine beaches; permafrost was found at about 90 to 100 cm depth (Poelking, 2011).

Potter Peninsula encompasses Antarctic Specially Protected Area no. 132 (ASPA 132) along the coastal area, where concentration of Antarctica fauna is greater, including penguin rookeries (*Pygocelis* sp.) and populations of marine mammals, such as Weddell seals (*Leptonychotes weddellii*), elephant seals (*Mirounga leonina*) and fur seals (*Arctocephalus gazella*). In the elevated areas, skuas (*Catharacta* sp.) and giant petrel (*Macronectes giganteus*) nests are concentrated. This fauna accounts for sea–land nutrient transfer, fertilizing soil environments through accumulation of guano excreta and dead remains.

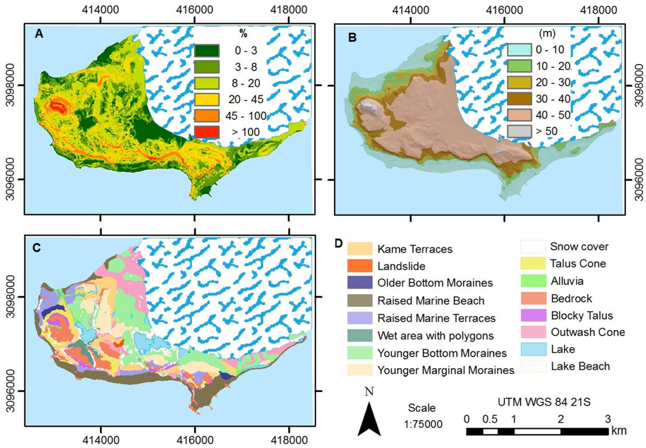

Figure 2. Map of hypsometry **(a)**, altimetry **(b)** and geomorphology (Birkenmajer, 1988) **(c)**. Legend is shown in **(d)** (Poelking, 2011).

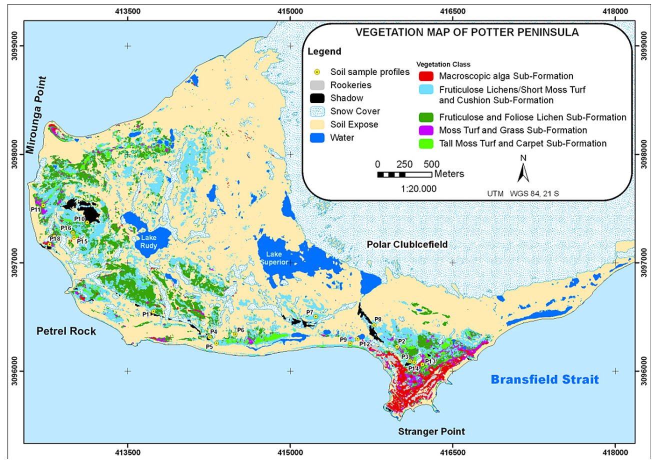

Figure 3. Vegetation map of Potter Peninsula, maritime Antarctica.

3 Material and methods

3.1 Vegetation community classification

Plant samples were collected and identified during fieldwork in 2008 at each soil sampling point. The vegetation community classification was adapted from Longton (1988) based on local variations and main dominant species. Thematic classes and descriptions are presented in Table 1.

3.2 Vegetation mapping

For vegetation mapping we used a QuickBird image (January 2007) with four separate multispectral bands and a spatial resolution of 2.4 m. We used the NDVI (normalized difference vegetation index) to help in the discrimination of vegetation class following Eq. 1:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - R)}{(\mathrm{NIR} + R)}, \tag{1}$$

where NIR is the near-infrared band and R is the red band.

The image was georeferenced and orthorectified using control points obtained in the field with a Leica DGPS and coupled with a digital elevation model (Lusky et al., 2001) following ArcGIS 9.3 routine procedures. For the supervised image classification, we adopted the Maxver classifier (maximum-likelihood estimation) using Idrisi Andes software, in which the training samples were demarcated based on field observations and intensive plant collection in the summer of 2008 using precise DGPS location. The classification check was done through revisits on field, with checkpoints taken by GPS. The kappa index was adopted to verify the classified accuracy for different vegetation cover classes (Cogalton and Green, 1999). The kappa coefficient (K) is a measure of the real agreement minus the agreement by chance; in other words, it is a measure of how much the classification is in agreement with the reference data calculated using Eq. 2:

$$\hat{k} = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i})}, \tag{2}$$

where K is the kappa coefficient estimate; x_i is the value in row i and column i, $x_i i$ is the value in row i and column i, x_i+ is the sum of row i, $x_+ i$ is the sum of column i of the confusion matrix, N is the total number of samples, and r is the total number of classes. According to Cogalton and Green (1999), values above 0.8 are considered excellent.

3.3 Soil sampling, analytical procedures and plant chemical analysis

In total, 18 soil pits were described. Soil classification followed the World Reference Base for Soil Resources (WRB) classification system (IUSS Working Group WRB, 2006). Soil samples were collected, air-dried, passed through a 2 mm sieve, and submitted to chemical and physical analyses. Soil pH, exchangeable nutrients and texture were determined according to Embrapa (1997).

Collected plant samples were washed to remove soil, dried at 70 °C for 72 h and milled into particles smaller than 0.5 mm. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), manganese (Mn) and iron (Fe) were measured by means of nitropercloric digestion of 0.5 g of sample in 10 mL of HNO3 at 200 °C. P was determined using a colorimetric assay, assessing the phosphomolybdate reduction with vitamin C (Braga and Deffelipo, 1974). Potassium was measured via flame emission photometry, and Ca, Mg, Fe, Zn, Cu and Mn via atomic absorption spectrophotometry (Tedesco et al., 1995).

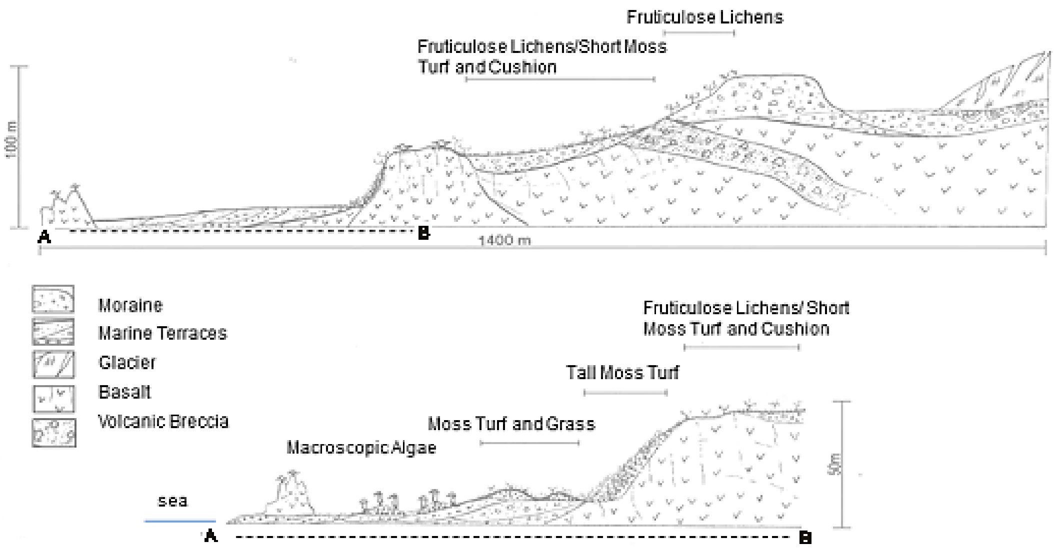

Figure 4. Topographic sequence and distribution of vegetation at Stranger Point, Potter Peninsula.

Table 3. Plant community classes and their relative areas on Potter Peninsula.

Thematic class	Areas (ha)	%
Tall moss turf and carpet sub-formation	9.46	1.31
Moss turf and grass sub-formation	9.23	1.28
Fruticulose and foliose lichen sub-formation	52.11	7.24
Fruticulose lichens/short moss turf and cushion sub-formation	81.26	11.29
Macroscopic alga sub-formation	12.17	1.69
Rookeries	4.4	0.61
Bare soil	461.57	64.11
Water bodies	43.94	6.1
Snow cover	39.05	5.42
Shadow	6.77	0.94
Total	719.96	100

4 Results

4.1 Vegetation mapping

The infrared wave band (0.76 to 0.90 mm) allowed for distinguishing between vegetated areas under different photosynthetic activities compared with other types of surfaces (e.g. snow, exposed soil, water bodies). The NDVI offers a clear distinction between the surfaces according to different spectral responses of the infrared and red bands (Fretwell et al., 2011).

Figure 3 shows a supervised classification map which produced a very satisfactory kappa index (0.90) according to Cogalton and Green (1999). Although we used a high-resolution image, a reliable automated classification of the vegetation was constrained by local microhabitats and the high heterogeneity of Antarctic plant communities, whose composition and distribution are controlled by the interaction of a wide range of factors and processes.

On Potter Peninsula, about 23 % of ice-free areas are vegetated (Table 2) and widely distributed across the landscape. The most rich and diverse flora is found in the oldest exposed areas that developed after the Holocene deglaciation, as well as in ornithogenic landscapes. Recently exposed grounds, such as stable moraines, are being progressively occupied by patches of lichen and moss communities.

4.2 Classification of plant communities

Lichens showed the greatest diversity in most landscapes. They occurred in mixed forms associated with mosses and grasses in specific habitats. Extensive fields dominated by *Usnea* sp. and *Himantormia lugubris* occupy upland areas of stony soils or rock outcrops. Lichen and moss sub-formations are distributed in soils under little ornithogenic influence.

D. antarctica is widespread in well-drained ornithogenic soils, especially near penguin (P12, P13) or giant petrel rookeries and associated pedoenvironments (P15, P 16, P17 and P18). Mat patches of the algae *Prasiola* were found on stable, homogeneous areas around bird nests, which contained high concentrations of ammonia. (P12 and 16). These patches form limited N-rich habitats close to active rookeries on marine terraces at Stranger Point (Fig. 3).

Longton (1988) adapted a subjective hierarchical classification where major units were defined by the growth form of the community dominant species, while minor units reflected the floristic composition. The associations are characterized by codominant species or by restricted occurrence in more

Table 4. Exchangeable nutrient concentration at surface horizons (0–10 cm) for the studied soils.

Profile	N	P	K	Ca	Mg	Fe	Zn	Mn	Cu	pH	> 2 mm
	$dag\,kg^{-1}$					$mg\,dm^{-3}$				H_2O	%
P1	0.31	66.1	95	496	264	58.89	0.58	6.77	2.32	5.58	55
P2	0.48	158.2	187	988	724.8	548.84	5	13.3	10.87	5.19	44
P3	1.09	443.1	298	384	307.2	171.4	1.17	24.27	5.28	4.51	93
P4	0.48	554.8	154	246	196.8	399.01	0.82	2.77	6.07	4.99	42
P5	0.04	150.9	111	2240	1026	114.11	0.71	38.18	7.08	6.13	64
P6	0.72	419.2	125	220	102	280.46	1.99	3.79	7.19	4.33	80
P7	0.42	68.5	117	510	373.2	256.22	5.32	18.93	11.78	5.67	74
P8	0.17	705	157	876	619.2	176.58	0.91	21.67	10.27	5.98	52
P10	0.37	44.3	161	1614	526.8	135.95	0.81	82.31	7.21	6.26	49
P11	0.08	127.7	124	1716	385.2	88.71	0.64	14.27	6.17	6.14	46
P12	0.14	218.5	232	2384	446.4	67.5	0.95	36.80	7.37	5.06	41
P13	0.44	757	213	268	64.8	546.2	3.6	6.4	14.9	4.7	66
P14	0.56	829.1	193	516	106.8	421.5	7.35	16.82	17.65	4.42	81
P15	1.29	62.4	103	458	260.4	292.79	1.59	6.05	3.65	5.01	59
P16	0.76	617.8	248	436	214.8	357.4	4.48	3.9	2.14	4.52	91
P17	1.28	549	43	150	38.4	255.08	1.23	2.29	2.06	4.42	0
P18	0.01	118.9	82	140	60	267.83	0.91	11.31	10.35	5.18	1

P, K, Ca, Mg Fe, Zn, Mn and Cu: Melich 1 exchangeable; N: Kjendal method

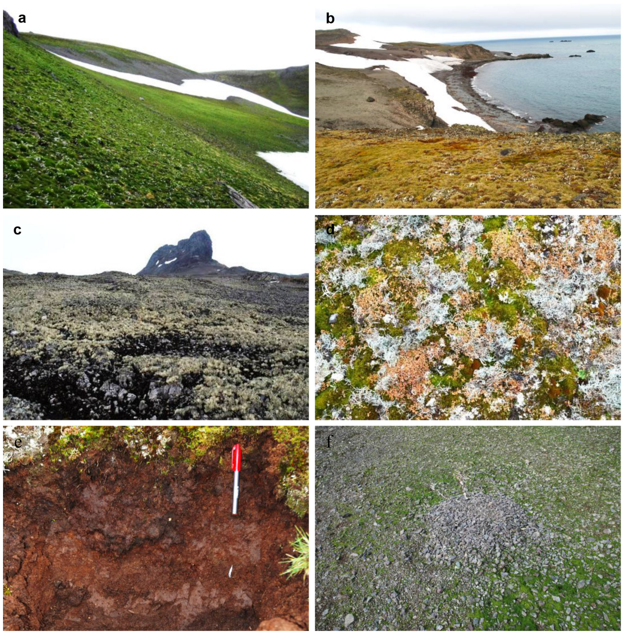

Figure 5. (a) Moss turf carpet on Stranger Point talus slope, covered with *Sanionia* and *Polytrichales*. **(b)** *D. antarctica* grass tuft around giant petrel nests in Petrel Rock. **(c)** Cryoplanation surface covered with fruticulose lichens *Usnea* sp. and *Himantormia* on skeletic soils. **(d)** Plant communities of mixed fruticulose lichens and *Sanionia* moss tufts in ornithogenic soils (P15). **(e)** P17 (Histic Leptic Cryosols (Ornithic, Arenic)) formed by humus cumulation around giant petrel nest. **(f)** *Prasiola crispa* mat around bird nest (P16).

specifics habitats (Longton, 1988; Smith and Girmingham, 1976).

The proportion of ice-free ground surface on Potter Peninsula clearly reduces with increasing altitude and distance from the coastal zone, although upland areas are not lifeless. Recently exposed bare ground adjacent to Polar Club Glacier appears devoid of plants, apart from dense cyanobacteria mats growing in oligotrophic lakes and temporary shallow pools.

Old exposed grounds on Potter Peninsula have a wide variety of plant communities. Lower terrace levels are occupied by dense stands of mosses and *D. antarctica* replacing areas formerly occupied by pure moss stands, thus revealing an advanced stage of succession following uplift. Poorly drained areas close to pools and depressions rich in leachates coming from nearby penguin rookeries are associated with *Prasiola* and nitrophilous mosses. Upland, exposed shallow and rocky soils are covered with dense fields of *Usnea* sp. and *H. lugubris*. Recently exposed nearby soils showed a sparse development of *D. antarctica* tufts.

4.2.1 Tall moss turf and carpet sub-formation

Bryophytes are typically associated with moist, hydromorphic soils or humid slopes and wet microhabitats protected from strong winds. There, *Polytrichales* and *Sanionia* formed thick, uniform carpets (P14) (Fig. 4a) or cushions, establishing occasional limited associations with tufts of *D. antarctica* (P15) and cyanobacteria mats, the latter in permanently water-saturated soils of marine terraces (P5). Soils in these areas are relatively fertile due to high inputs

Table 5. Range and mean values of macro- and micronutrients in lichens, mosses and *D. antarctica* of ice-free areas on Potter Peninsula.

	N	P	K	Ca	Mg	Fe	Zn	Mn	Cu
	%						mg kg^{-1}		
	Lichens								
Minimum	0.59	0.04	0.09	0.05	0.04	0.11	6.4	13.5	0.1
Maximum	1.5	0.22	0.26	0.86	0.32	1.86	40.1	277.7	90.1
Mean $n = 7$	099	0.1	0.17	0.53	0.13	0.54	19.8	84	25.3
Standard deviation	0.31	0.07	0.05	0.28	0.09	0.6	11.1	91.6	32.8
CV %	31	68.4	30.7	53.4	76.5	112.7	56.3	109.0	129.3
	Mosses								
Minimum	0.71	0.05	0.11	0.4	0.04	0.04	6.8	17.4	0.1
Maximum	1.96	0.36	0.34	1.41	0.39	2.38	53.7	464.4	122.1
Mean $n = 12$	1.22	0.17	0.19	0.85	0.26	1.26	33.9	209.7	37.6
Standard deviation	0.41	0.09	0.06	0.32	0.11	0.8	14.8	119.6	33.3
CV %	33.8	56.3	33.9	37.0	42.1	63.2	43.7	57.0	88.7
	Grass								
Minimum	1.5	0.22	0.15	0.25	0.17	0.78	35.8	123.4	12.2
Maximum	2.6	0.3	0.77	1.6	0.40	2.59	69.2	548.8	71.1
Mean $n = 4$	1.87	0.27	0.37	0.79	0.28	1.64	49.3	277.3	44.2
Standard deviation	0.52	0.03	0.29	0.58	0.09	0.79	14.1	197.1	29.8
CV %	28.1	13.2	77.0	73.4	34.2	48.2	28.7	71.1	67.4

Table 6. Mean values of macro- and micronutrients reported in the literature for maritime Antarctica.

Reference	N	P	K	Ca	Mg	Fe	Zn	Mn	Cu
	%						mg kg^{-1}		
	Lichens								
Admiralty Bay[a]		0.05	0.12	0.87	0.05	0.09	8.4	10.1	9.1
Admiralty Bay[b]		0.07	–	1.41	0.22	1	23.9	138.8	19.3
Potter Peninsula[c]		–	–	–	–	0.07	10.3	30.2	4.5
	Mosses								
Admiralty Bay[a]		0.22	0.33	0.75	0.57	1.58	43.7	301.4	58.1
Admiralty Bay[b]		0.17	–	0.67	0.53	1.8	32.8	315.9	40.7
Potter Peninsula[c]		0.68	0.61	0.39	0.3	–	–		
Signy[d]		0.23	0.38	0.47	0.5				
	Grass								
Admiralty Bay[a]		0.21	0.32	0.52	0.43	0.8	42.8	265.9	45.6
Admiralty Bay[b]		0.42	–	0.49	0.27	0.65	38.4	254	13.8
Signy[d]		0.25	0.4	0.36	0.44	–	–	–	–
Stranger Point[e]	2.5	0.4	1.5	0.2	0.2	0.05	30	60	10

[a] Simas (2006), [b] Schaefer et al. (2004c), [c] Poblet et al. (1997), [d] Allen et al. (1967), [e] Tatur et al. (1997).

Table 7. Correlation between soil macro- and micronutrients available and total plant amounts in the dry matter of mosses on Potter peninsula.

	N (*m*)	P (*m*)	K (*m*)	Ca (*m*)	Mg (*m*)	Zn (*m*)	Fe (*m*)	Mn (*m*)	Cu (*m*)
N (*s*)	0.34	−0.06	−0.49	−0.06	0.06	0.09	−0.22	0.05	−0.17
P (*s*)	0.52	**0.63**	0.17	0.26	0.12	0.49	−0.03	−0.05	0.45
K (*s*)	−0.28	0.09	0.16	0.47	0.33	0.47	0.52	0.52	0.35
Ca (*s*)	−0.28	−0.19	0.09	0.25	0.28	0.06	0.31	0.39	0.11
Mg (*s*)	−0.36	−0.30	0.14	0.38	0.32	0.09	0.37	0.45	0.05
Zn (*s*)	**0.64**	**0.70**	−0.04	0.04	−0.05	0.44	0.10	−0.11	**0.73**
Fe (*s*)	0.56	**0.72**	0.41	0.03	0.10	0.33	0.08	−0.18	0.31
Mn (*s*)	−0.24	−0.24	−0.24	0.04	0.13	0.06	0.29	0.48	0.19
Cu (*s*)	0.43	**0.77**	0.35	0.15	0.12	0.52	0.42	0.07	**0.76**

Note: marked correlations are significant at $p < 0.05$ N = 12; (*m*): mosses; (*s*): soil

Table 8. Correlation between soil macro- and micronutrients availables and total plant amounts in *D. antarctica* growing on Potter Peninsula.

	N (*g*)	P (*g*)	K (*g*)	Ca (*g*)	Mg (*g*)	Zn (*g*)	Fe (*g*)	Mn (*g*)	Cu (*g*)
N(*s*)	**0.998**	−0.058	0.851	−0.713	−0.844	−0.363	0.203	−0.671	−0.881
P (*s*)	0.596	0.632	0.173	−0.563	−0.714	−0.667	−0.035	−0.726	−0.884
K (*s*)	−0.578	0.833	−0.478	0.705	0.598	0.342	0.353	0.517	0.282
Ca (*s*)	−0.472	0.398	0.030	**0.939**	0.817	**0.918**	0.795	**0.907**	0.515
Mg (*s*)	−0.511	0.369	−0.005	**0.954**	0.845	**0.925**	0.766	**0.926**	0.558
Zn (*s*)	0.094	0.713	−0.376	−0.320	−0.388	−0.672	−0.300	−0.532	−0.514
Fe (*s*)	0.196	0.334	−0.388	−0.631	−0.605	**−0.920**	−0.646	−0.777	−0.542
Mn (*s*)	−0.657	0.254	−0.151	**0.991**	**0.934**	**0.925**	0.633	**0.979**	0.712
Cu (*s*)	−0.607	0.412	**−0.925**	0.116	0.206	−0.386	−0.557	−0.048	0.228

Note: narked correlations are significant at $p < 0.10$ N = 4; (*g*): grass (*D. antarctica*); (*s*): soil

of leachates from nearby rookeries (P14, P15, P17) (Fig. 4e) or to nutrient concentration by melting water channels (P5, P11). These moss carpets afford high thermal insulation, leading to shallow, ice-cemented permafrost occurrence and a thin active layer of 40–50 cm deep (P14, P15 and P17).

4.2.2 Moss turf and grass sub-formation

The two higher plants *D. antarctica* and *C. quitensis*, which form cushions closely interspersed with moss *Sanionia*, are concentrated in more stable areas near large *Larus dominicanus* (Gull) nests (P17 and P18) and around penguin rookeries (Stranger Point, marine terraces P6, P11) (Fig. 4b).

These are the oldest exposed areas on Potter Peninsula, and most soils are well drained and quite developed. The sparseness of *D. antarctica* tufts within *Polytrichales* moss carpets indicates a more advanced stage of succession, as suggested by Schaefer, C. E. G. R. et al. (2004) and Francelino et al. (2011) for the same region. Regarding the ecological relationships of *D. antarctica*, Smykla et al. (2007) pointed out that, although it is widely distributed in maritime Antarctica landscapes, it shows a preference for old rookeries and their vicinities, gradually reducing its frequency away from these rich nutrient spots. Victoria et al. (2013) found that grasses and mosses in shallow soil developed on the surface of basalt dyke, strongly influenced by *L. dominicanus* colonies. Overall, mixed plant communities are preferably associated with ornithogenic sites (Simas et al., 2008), and are probably dependent on high nutrient status, as observed in P13, P16 and P12.

4.2.3 Fruticulose and foliose lichen sub-formation

Macrolichen communities are widespread in extensive areas from sea level to high inland on dry stables or exposed soils (Longton, 1988). Lichens have a low biomass but were widely distributed across Potter Peninsula landscapes, where they formed dense stands on rocky cryoplanation surfaces, felsenmeer and stables slopes (Fig. 4c). They account for the initial stages of rock and soil weathering, and some organic matter arising from decomposing lichens was found in the subsurface, especially on the surface of large rock fragments. Soils under almost pure stands of *Usnea* sp. or mixed with *H. lugubris* and *Umbilicaria* sp. were observed on Potter Peninsula, probably forming the most extensive communities of all King George Island (P3, P1, P7 and P8). They covered more than 0.5 km^2 of ice-free area.

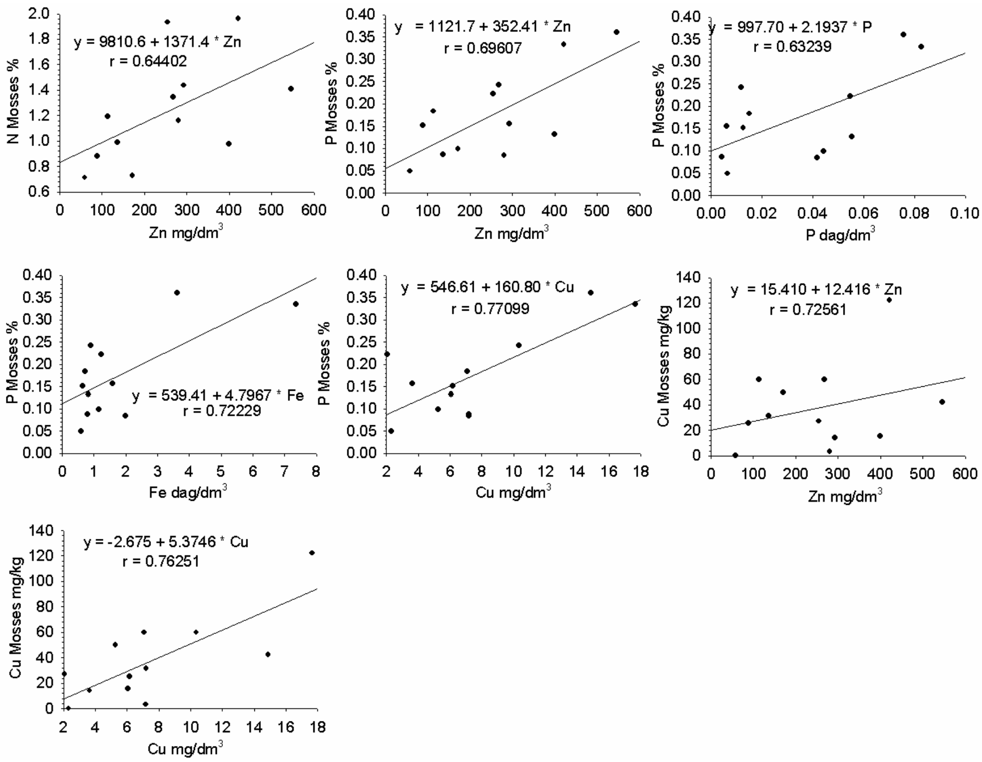

Figure 6. Graphs illustrating the correlation between soil macro- and micronutrients available and total plant amounts in mosses.

4.2.4 Fruticulose lichens/short moss turf and cushion sub-formation

These communities occurred on soils with some degree of ornithogenic influence from abandoned rookeries at Stranger Point, and on marine terraces and mostly at elevated areas with stable, well-drained soils (P4, P7, P8) (Fig. 4d). They represent the larger sub-formation mapped in the present work, characterized by mixed fruticulose lichens, short moss turf and small cushion sub-formation. They range from driest soils to rather moist habitats with acid substrata (Longton, 1988), and are associated basically with *D. antarctica*, mosses *(Sanionia)* and *Prasiola*. Furthermore, they also occur on rock outcrops, and coarse fragments on moraine, talus and protalus deposits (Victoria et al., 2013).

4.2.5 Macroscopic alga sub-formation

The green alga *Prasiola* is conspicuous in pebbly soils adjacent to Stranger Point penguin rookeries and bird nests (Fig. 4f) since it tolerates local trampling and occasional manuring, as well as low pH and high N availability (Longton, 1988). It also forms assemblages with ornithocoprofilous lichen *Mastodia tesselata*, a lichenized form of *P. crispa*, which occurs preferably on large rock surfaces found within the same area. The typical pedoenvironments are P12 and P16.

4.2.6 Soil–plant and landscape relationships

In maritime Antarctica, soils are formed predominantly from basaltic and andesitic volcanic rocks. There, although physical weathering dominates, chemical alteration of parent material also occurs, the mineral substrate being an important source of K and Ca (Simas et al., 2008). Waterlogged areas normally show higher contents of soluble nutrients due to their accumulation via melting water channels during summer. Ornithogenic influence results in high inputs of N and P mainly due to guano deposition, as described by Simas et al. (2008). Soils developed from volcanic rocks on Potter Peninsula showed variable values of bioavailable macro- and micronutrients (Table 3).

As expected for a higher plant, *D. antarctica* showed the highest mean values for Ca, Zn, Fe and Mn (Table 4), whereas P, K, Mg and Cu were comparable to reference values from elsewhere in the same region (Simas, 2006; Schaefer, C. E. G. R. et al., 2004; Poblet et al., 1997). *D. antarctica* showed the highest values of all elements, possibly because it is closely associated with ornithogenic soils. The mean total values of Ca, Mg, Fe, Zn and Mn were similar to those reported in previous works in maritime Antarctica (Table 5). However, the values of P, K, Cu obtained in the present study were higher than those reported in the literature (Simas, 2006; Schaefer, C. N. et al., 2004; Poblet et al., 1997; Allen et al., 1967; Tatur et al., 1997). In general, most

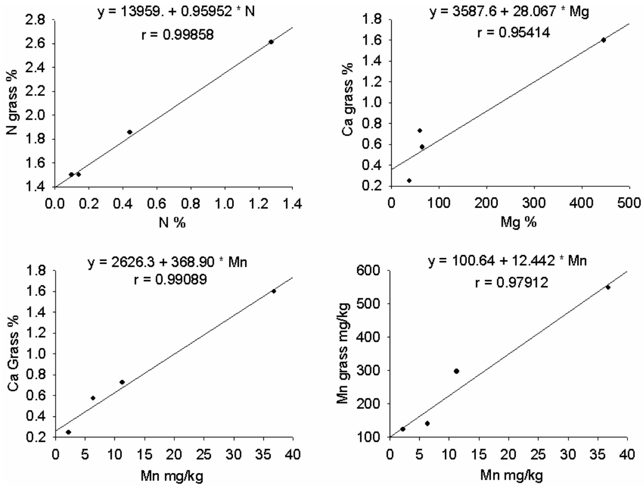

Figure 7. Correlation between soil macro- and micronutrients available and total plant amounts in *D. antarctica*.

elements had a wide range of values depending on the site characteristics and the age of plant communities.

Table 6 shows the correlation between soil available nutrients and total amounts in the dry matter. We observed a trend of increasing magnification of P in Mosses. Similarly, the same was observed for Cu in all plants and soils (Fig. 5). Due to its distribution associated with seasonal or permanent water accumulation, higher concentration of Fe was detected in the dry matter, with lower values of K, Mg, Fe, Mn and Cu compared to places studied elsewhere in maritime Antarctica. Only Ca had greater values in mosses.

In lichens, little correlation with soil was observed since they develop on rock fragments that are not conditioned by soil underneath. However, the biomass can influence the deposition of elements in the soil. On the other hand, lichens can interfere in soil, but not vice versa.

Mosses showed little correlation between the available and the total plant concentration. Mosses increased P concentration correlated with improved availability of P, Zn, Cu and Fe in the soil.

Grasses showed a tight relationship with soil nutrient availability (Table 7). *D. antarctica* is best developed on nutrient-rich soils under a more advanced weathering stage. These plants have an apparent tolerance to high Fe availability, with high amounts of Fe in their biomass. The total amounts of P, Ca, Mg and Mn in the plant biomass of *D. antarctica* showed to be positively correlated with bioavailable levels in soils, although Fe and Zn showed an opposite trend (Fig. 6).

5 Discussions

The vegetation mapping shows widespread areas with vegetation cover in small patches, occupying different landscape positions and showing decreasing diversity and biomass from the coastal zone to inland areas, where sub-desert conditions prevail. In areas protected from winds and exposed to solar radiation, bryophytes, grasses and algae receive moisture and warmth and grow in close stands (Bargagli, 2005). *D. antarctica* is usually associated with abandoned bird nest sites with higher biodiversity. Lichens predominate in drier and wind-exposed habitats in inland (Bargagli, 2005; Francelino et al, 2011). Consistent with our observations, Kim et al. (2007) observed similar widespread development of such lichen communities on rocky surfaces distant from ornithogenic spots at the nearby Barton Peninsula. Eventually, lichens form associations with mosses at both sites. Lichens have a poor relationship to soil chemical, due to absorption of nutrients by directly contacting with their structures with air and water. Also, lichens are good bioindicators of air pollutants such as heavy metals (Bargagli et al., 1995; Poblet et al., 1997; Simas, 2006) because of their uptake of the elements dissolved in rain water or melting snow.

According to Schaefer, C. N. et al. (2004) bryophytes are adapted to environments with higher humidity, which can be either saline or eutrophic. The humic horizons, formed by the cycling of the biomass of mosses, serve as reservoirs of nutrients in organic colloids (Allen et al., 1967), which depend on the contribution of the elements via precipitation and snow melt channels. The concentrations of elements in moss samples often reflect the biogeochemical nature of soils and rocks rather than atmospheric input of elements (Bargagli, 2005). According to Allen et al. (1967), rainfall inputs are the dominant source of nutrient supply to moss carpets growing on deep peat. However, on Potter Peninsula the nutrient content of precipitation is not high and survival depends on the capacity of living mosses and organic matter in colloidal forms to retain nutrients. In this area, as elsewhere in Antarctica, climate and landscape-soil stability play a dominant role in controlling both the establishment of vegetation and soil development.

Our data suggest that higher concentrations of Fe, Zn, N and P in soils are inversely correlated with the concentrations of K, Ca, Mg, Zn, Fe, Mn and Cu in grasses. On the other hand, high bioavailable concentrations of Ca, Mg, Mn and K in soils contribute to a high uptake of microelements by *D. antarctica*. These data confirm a previous work at Stranger Point by Tatur et al. (1997), in which the chemical composition of *D. antarctica* growing in the marginal zones of active rookeries showed the highest concentrations of N, P, Ca, Zn and Cu derived from decomposing guano. Higher P levels from guano appear to be an important determinant of vegetation patterns (Michel et al., 2006). Bioaccumulation of metals in mosses and *D. antarctica* is greatly determined by substrate geochemistry (Simas, 2006).

6 Conclusions

The distribution of plant communities in ice-free areas in Potter Peninsula has a close relationship with geomorphological and pedological attributes, which also influence the chemical composition of plants. The main points are as follows:

1. Plant communities on Potter Peninsula cover 23 % of the ice-free area, occupying different landscape positions and showing decreasing diversity and biomass from the coastal zone to inland areas, where sub-desert conditions prevail.

2. There is a clear dependency between landform and soils with vegetation. Soils with greater moisture or poorly drained and acid to neutral pH are favourable for moss sub-formations. Saline, organic-matter-rich ornithogenic soils of former penguin rookeries have greater biomass and diversity, with associations of mosses and grasses, while stable felsenmeers and flat rocky cryoplanation surfaces are the preferred sites for *Usnea* and *H. lugubris* lichens, at the highest level.

3. Lichen sub-formations cover the largest vegetated area, showing varying associations with mosses.

This survey will allow for accurate monitoring of plant communities in ice-free areas from Potter Peninsula. It may be possible to verify, with further map surveys, the dynamics of vegetation cover in ice-free areas.

Edited by: M. Oliva

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