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Soil–landform–plant communities relationships of a periglacial landscape at Potter Peninsula, Maritime Antarctica

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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 monitoring 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 in 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 subformations were identified and classified, and we also determined the total elemental composition of lichens, mosses and grasses. Plant communities at 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 with greater moisture or poorly drained, and acid to neutral pH, are favourable for mosses subformations. Saline, organic-matter rich ornithogenic soils of former penguin rookeries have greater biomass and diversity, with mixed associations of mosses and grasses, while stable felseenmeers and flat rocky cryoplanation surfaces are the preferred sites for *Usnea* and *Himantormia lugubris* lichens, at the highest surface. Lichens subformations cover the largest vegetated area, showing varying associations with mosses.

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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 taluses algae, (*Prasiola crispa* and *P. cladophylla*) and approximately 360 known species of lichens. Only two native phanerogams occur (Antarctica hairgrass *Deschampsia antarctica* Desv., and Antarctica pearlwort, *Colombathus 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 smal isolated patches, adapted to cold climate, relatively low light, high UV radiation and winter snow coverage (Bargagli, 1998).

Abandoned rookeries are characterized by dense vegetation in nitrogen and phosphate rich ornithogenic soils, 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 a.s.l. during the Holocene period as a consequence of the glaciostatic movement following glacial retread (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* contribute to higher organic C levels, and is positively related with soil depth (Simas et al., 2007). Organic matter in such soils is richer in Nitrogen (N) and easily thermo-degradable 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 in both active and abandoned rookeries high nutrient status appears to determine the vegetation distribution and zonation. *D. antarctica* is relatively abundant in ornithogenic soils of abandoned rookeries and in marginal areas of active rookeries. Schaefer et al. (2004a) 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* spp. 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 thalose 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 et al., 2004b). Hence, vegetation can serve as 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 et al., 2004a), are key issues for Antarctic Ecology. Understanding the factors affecting the distribution of vegetation in Antarctica ice-free areas can help studies on climate and landscape change at greater scales. To detect changes in community structure and extent, there is need improved instrumental monitoring of the physico-chemical 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 in 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

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based on habitats and growth forms of the most abundant species. The Tundra Subformation 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 are 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 helped with GPS, (Kim et al., 2007; Schaefer et al., 2004a; 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, the traditional vegetation mapping is more difficult at large scales. In this concern, satellite images with high resolution 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 against which 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 landforms, is relevant for the understanting of the ecological evolution of Antarctic landscapes (Francelino et al., 2011) and how they respond to environmental changes. Environmental monitoring include remote sensing and insitu 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 mapping the vegetations communities with high resolutions satellite image and investigated the relationships between vegetations communities in ice-free areas at 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 in King George island, part of South Shetland archipelago, Maritime Antarctica, in the flowing coordinates: 62°13.5′ and 62°16′ S, 58°42′ and 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 climatic classification of Köppen is ET regime for the King George island, minimum air temperatures from −2.8 °C, with summer −1.3 to 2.7 °C and winter −15.5 to −1.0 °C (Ferron et al., 2004). In terms of geology, Potter Peninsula belongs to Warszawa tectonic block dominated by a volcanic rock sequence formed between 50.6 to 49.1 Ma (Kraus and del Valle, 2008). The geology comprises mainly basalt and basalt-andesitic, frontal and basal moraines and different levels of marine terraces. The peninsula has been shaped by glacial action, moraines formed with classic rock outcrops and different levels of terraces (Birkenmajer, 1998; Kraus and del Valle, 2008). More details can see in Birkenmajer (1998). The soils of Potter are typical from periglacial environment, poorly developed soils, coarse sand, gravel and sandy texture, and ornithogenics soils in marine beaches, permafrost was found at about 90 to 100 cm depth (Poelking, 2011).

Potter Peninsula encompasses the ASPA 132 along the coastal area, where concentration of Antarctica fauna is greater, including penguins 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 by accumulating guano excreta and dead remains.

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3 Material and methods

3.1 Vegetation communities classification

Plant samples were collected and identified during fieldwork in 2008, at each soil sampling point. The vegetation communities 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 the discrimination of vegetation class with following Eq. (1):

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

where NDVI is the Normalized Difference Vegetation Index; NIR is the Near Infrared Band; R is the Red Band.

The image was georeferenced and orthorectified using control points obtained in the field with a Leica DGPS, 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 conference was made with revisits on field with checkpoints taken by GPS. 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, is a measure of

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how the classification is according to the reference data calculated using Eq. (2):

$$K = \frac{n \sum_{i=1}^{c} x_{ii} - \sum_{i=1}^{c} x_{i+} x_{+i}}{n^2 - \sum_{i=1}^{c} x_{i+} x_{+i}} \tag{2}$$

where K is the Kappa coefficient estimate; x_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 "c" the total number of classes. According to Cogalton and Green (1999) values above 0.8 are 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 to 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 nitropercloric digestion of 0.5 g of sample in 10 mL of HNO_3 at 200 °C. P was determined using a colorimetric assay, assessing the phosphomolybdate reduction by C vitamin (Braga and Deffelipo, 1974). Potassium was measured by flame emission photometry, and Ca, Mg, Fe, Zn, Cu and Mn by atomic absorption spectrophotometry (Tedesco et al., 1995).

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4 Results

4.1 Vegetation mapping

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

Figure 2 shows a supervised classified 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.

At 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 developed after the Holocene deglaciation, as well as in ornithogenic landscapes. Recently exposed grounds, such as stable moraines, are being progressively occupied by patchy of lichens and mosses 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. Lichens and Mosses 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,

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P17 and P18). Mat patches of the algae *Prasiola crispa* were found on stable, homogeneous areas around bird nests, which contained high concentrations of ammonia. (P12 and 16). They form limited N rich habitats, close to active roockeries 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 specifics habitats (Longton, 1988; Smith and Girmingham, 1976).

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

Old exposed grounds at 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 mosses 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* sp. and nitrophilous mosses. Upland, exposed shallow and rocky soils are covered by dense fields of *Usnea* sp. and *Himantormia lugubris*. Recently exposed nearby soils showed a sparse development of *D. antarctica* tuffs.

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, *Polytricales* and *Sanionia* formed thick uniform carpets (P14) (Fig. 4a) or cushions, establishing occasional limited associations with tuffs of *D. antarctica* (P15) and cianobacteria mats, the latter in permanently water-saturared soils of marine terraces (P5). Soils in these areas are

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relatively fertile, due to high inputs 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 in Potter, and most soils are well-drained and quite developed. The sparseness of *D. antarctica* tuffs within *Polytrichales* moss carpets indicate a more advanced stage of succession, as suggested by Schaefer et al. (2004a) 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 grasses and mosses in shallow soil developed on the surface of basalt dyke, strongly influenced by *Larus 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

Macrolichens 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).

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They account for the initial stages of rock and soil weathering, and some organic matter arising from decomposing lichens were found in subsurface, especially on the surface of large rock fragments. Soils under almost pure stands of *Usnea* sp. or mixed with *Himantormia lugubris* and *Umbilicaria* sp. were observed in Potter Peninsula, probably forming the most extensive communities of all King George Island according to the authors account (P3, P1, P7 and P8). They covered more than 0.5 km^2 of ice free area.

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, marine terraces and mostly at elevated areas with stable, well drained soils (P4, P7, P8) (Fig. 4d). They represent the larger subformation mapped in the present work, characterized by mixed fruticulose lichens, short moss turf and small cushion subformation. They range from driest soils to rather moist habitats with acid substrata (Longton, 1988), and associated basically with *D. antarctica*, mosses (*Sanionia*) and *Prasiola crispa*. Rock outcrops, and coarse fragments on moraine, talus and protalus deposits (Victoria et al., 2013).

4.2.5 Macroscopic algae sub-formation

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

4.3 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, being the mineral substrate 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 at Potter Peninsula showed variable values of bioavailable macro and micro nutrients (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 et al., 2004a; Poblet et al., 1997). *D. antarctica* showed the highest values of all elements, possibly because they are 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 et al., 2004; Poblet et al., 1997; Allen et al., 1967; Tatur et al., 1997). In general, most 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 Marítime 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 to the contrary.

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 patch, occupying different landscape positions, 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* 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 are poor relationship to soil chemical, due to absorption of nutrients by directly contacting 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 et al. (2004b) 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 is the dominant source of nutrient supply to moss carpets growing on deep peat. However, in Potter peninsula the nutrient content of precipitation is not high and their 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 micro elements 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 roockeries 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 and relationships and distributions of plant communities in ice-free areas in Potter Peninsula have a close relationship with geomorphological and pedological attributes, which also influence the chemical composition of plants. The main points are:

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1. Plant communities at Potter Peninsula cover 23 % of the ice-free area, occupying different landscape positions, 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 mosses subformations. Saline, organic-matter rich ornithogenic soils of former penguin rookeries have greater biomass and diversity, with associations of mosses and grasses, while stable felseenmeers and flat rocky cryoplanation surfaces are the preferred sites for *Usnea* and *Himantormia lugubris* lichens, at the highest level.

3. Lichen subformations cover the largest vegetated area, showing varying associations with mosses.

This survey will allow the accuracy 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 at ice free areas.

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

Vegetation communities	Landforms and soils	Dominant plant species	Sociations 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., Polytricum, Bryum	*Cyanobacteria*; *D. antarctica*; Without lichens
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., Tipe 3
Fruticulose and Foliose Lichen Sub-Formation	Homogeneous lichens fields in well drained rocky, skeletal soils (P1, P2, P3, P7) of stables cryoplanation surfaces.	*Usnea* sp., *Ochrolechia* cf. *frigida*, *Cladonia* sp., *Neuropogum*, *Himantormia*	*Polytrichu*, *Bryum*, *Sanionia* Tipe 1
Fruticulose Lichens/ Short Moss Turf and Cushion Sub-Formation	Mosses and foliose/crustose lichens communities in ornithogenic soils on marine terraces (P13, P6) and weakly ornithogenic soils (P4, P10, P15). Occur 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*; *Polytricales* Tipe 2
Macroscopic alga Sub-Formation	*Prasiola crispa* in the vicinity of penguin's and giant-petrels 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. Tipe 2

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Table 2. Plant communities classes and their relative areas in 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

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Table 3. 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

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Table 4. Range and mean values of macro and micro nutrients in lichens, mosses and *D. antarctica* of ice-free areas at 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

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Table 5. Mean values of macro and micro nutrients 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[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[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 6. Correlation between soil macro and micronutrients available and total plant amounts in the dry matter of mosses at 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**

Marked correlations are significant at $p < 0.05$, $N = 12$.
(m) Mosses; (s) Soil.

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Table 7. Correlation between soil macro and micronutrients availables and total plant amounts in *D. antarctica* growing at 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

Marked correlations are significant at $p < 0.10$, $N = 4$.
(g): Grass (*D. antarctica*); (s) Soil.

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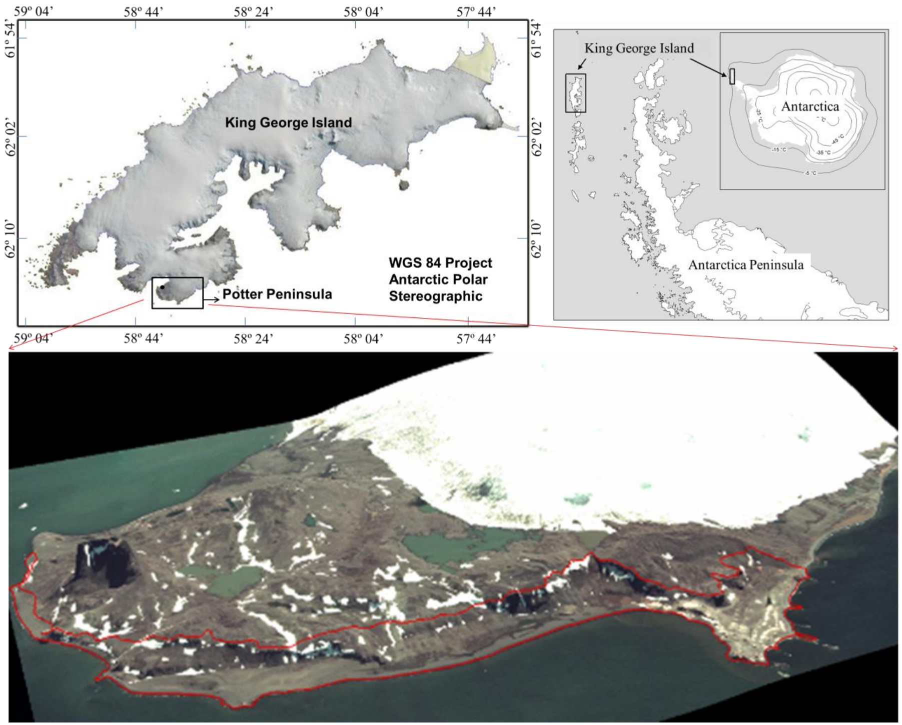

Figure 1. Potter Peninsula localization map at Maritime Antarctica. Quickbird 2 image in perspective view. The red line shows the limit of ASPA 132.

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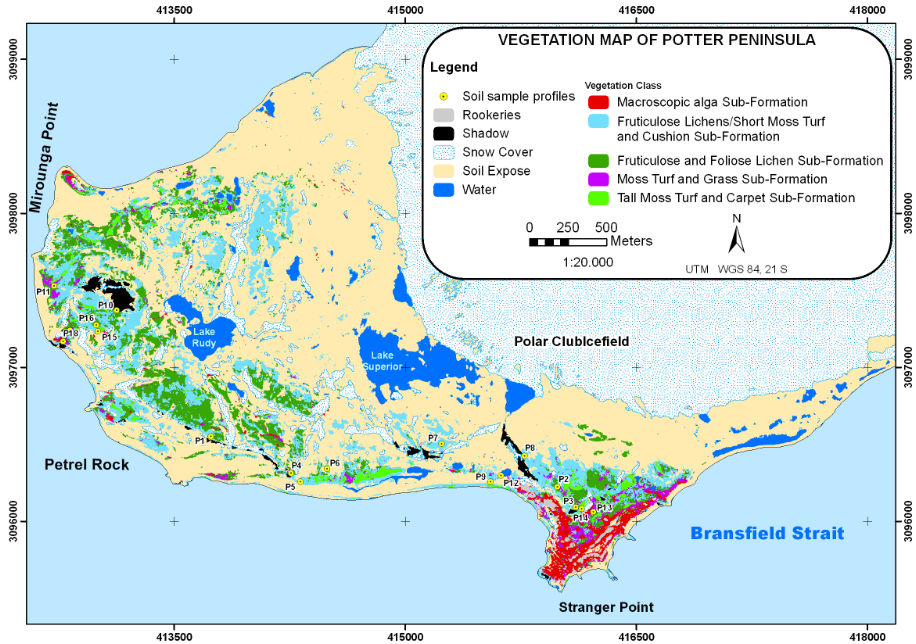

Figure 2. Vegetation map of Potter Peninsula, Maritime Antarctica.

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Soil–landform–plant communities relationships of a periglacial landscape at Potter Peninsula

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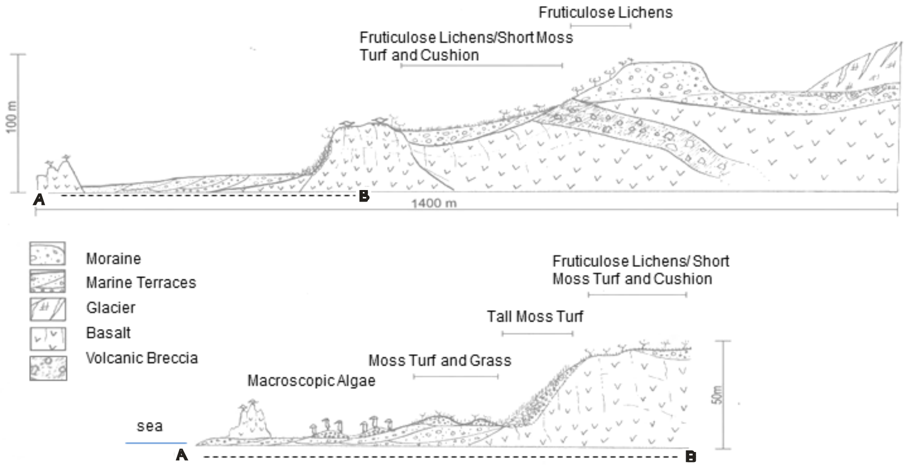

Figure 3. Topographic sequence and distribution of vegetation at Stranger Point, Potter Peninsula.

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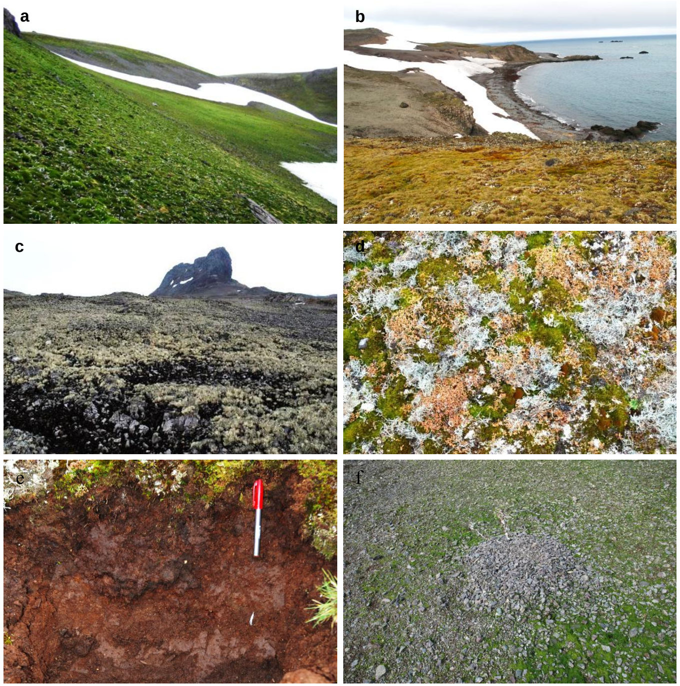

Figure 4. (a) Moss Turf Carpet in Stranger Point talus slope, covered by *Sanionia and Polytricales*. **(b)** *D. antarctica* grass tuff around Giant Petrel nests in Petrel Rock. **(c)** Crioplanation surface covered by Fruticulose Lichens *Usnea* sp. and *Himantormia* on skeletic soils. **(d)** Plant communities of Mixed Fruticulose Lichens and *Sanionia* Moss tuffs in ornitogenic soils (P15). **(e)** P17 (Histic Leptic Cryosols (Ornithic, Arenic)) formed by humus cummulation around Giant Petrel nest. **(f)** *Prasiola crispa* mat around bird nest (P16).

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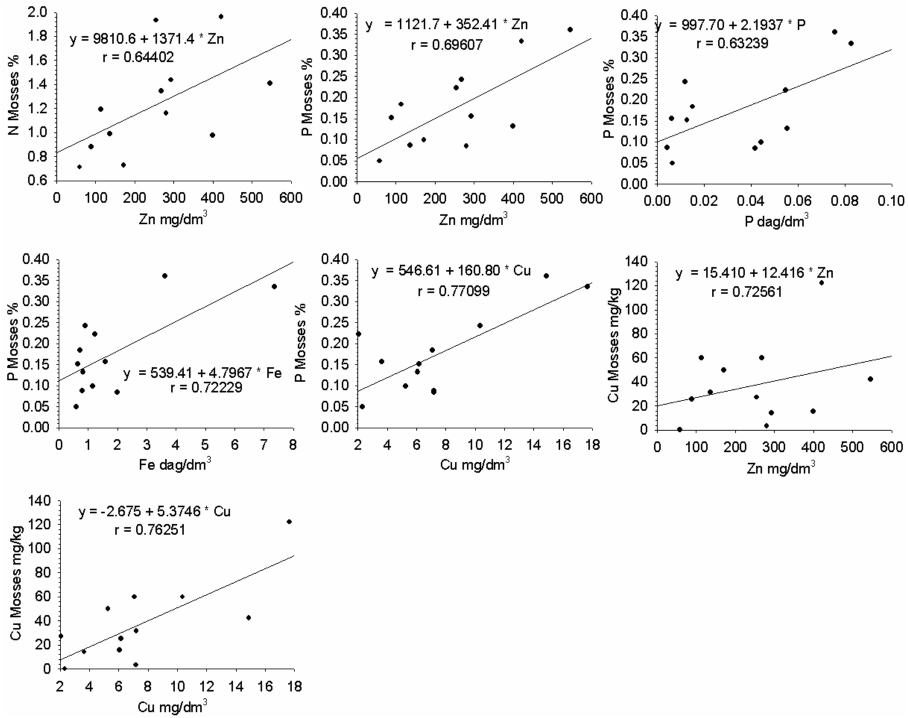

Figure 5. Graphs illustrating the Correlation between soil macro and micronutrients availables and total plant amounts in mosses.

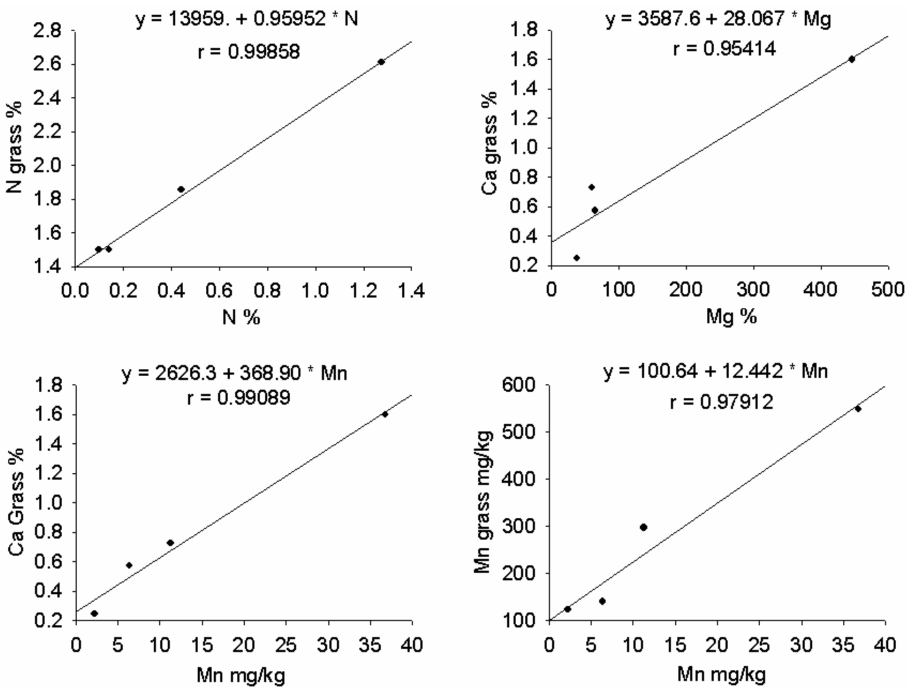

Figure 6. Correlation between soil macro and micronutrients availables and total plant amounts in *D. antarctica*.