

Spatial Variation in Soil Chemistry on a Sub-Antarctic Island

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ABSTRACT

On both west and east sides of sub-Antarctic Marion Island (47°S, 38°E), total Na and exchangeable Na, Mg and K concentrations in the soil decline with increasing distance inland and altitude, related to a decrease in the intensity of seaspray deposition. On the east side, the coastal plain is wide and slopes gently up to the mountainous interior and total C, total N and soil moisture content all decrease significantly, whereas bulk density increases significantly, as one moves away from the sea, reflecting a gradual change from organic, wet, low bulk density peats characteristic of lowland coastal regions to mineral, dry, high bulk density volcanic soils characteristic of inland areas. On the west side, the narrow coastal plain is bounded by an escarpment that rises up very steeply to the highland interior. There, sampling was largely restricted to the coastal plain (soils are rare on the escarpment and interior) and did not cover the same transition from organic to mineral soils as on the east side. Hence, total C, total N and bulk density did not change significantly with increasing distance inland on the west side. Most total Mg is in the mineral fraction of the soil, with a lesser contribution by organic, exchangeable and soil solution forms of Mg. On the east side the gradual transition from highly organic peats to very mineral soils results in an increase in total Mg going inland, but on the west, where there was not this change in soil minerality, total Mg decreased with increasing distance inland, reflecting the decreasing intensity of seaspray. Once the between-side differences in the influence of altitude and distance from the sea are accounted for, there are significant differences in soil chemical composition between the two sides of the island. Overall, west side soils are more influenced by both seaspray and the parent volcanic basalts than are east side soils.

Keywords: Sub-Antarctic; Soil nutrients; Altitudinal Variation; Seaspray; Mineral-Organic Gradient; Soil Organic Matter

1. Introduction

Marion Island (47°S, 38°E, 2100 km southeast of Cape Town) has a hyperoceanic climate typical of the sub-Antarctic region [1]. It is cool (annual mean air temperature is 6°C, the mean temperatures of the coldest and the warmest month differ by only 4°C), wet (mean annual rainfall is 2200 mm·y⁻¹, mean relative humidity 80%) and windy (mean wind velocity is 25 km·h⁻¹, gales occur on 110 days per year). The island is volcanic, 290 km² in area and consists of a central highland (highest peak 1230 m above sea level) that on the eastern and northern sides slopes down gently to a coastal plain 3 to 5 km wide. On the island's western and southern sides the coastal plain is narrow (400 to 900 m wide) and meets an escarpment rising up very steeply to the mountainous interior. The most prevalent (and strongest) winds are from the west [2] so that haline plant communities resistant to saltspray extend much further inland (hundreds of meters) on the west side of the island than they do on its east side

(rarely more than a few score meters). The island's ecosystem is classified as sub-Antarctic tundra [3].

An early aim of the ecological research program on the island was to draw up a nutrient budget for the whole terrestrial ecosystem [4], which involved quantifying nutrient inputs to, and losses from, the island and assessing the spatial patterns of nutrient concentrations in its soils and plants. This reflected the influence of the Tundra Biome Project of the International Biological Programme (1967-1974), a major objective of which was to elucidate patterns of distribution of nutrients within tundra ecosystems [5]. Research at the island has subsequently provided much information on the magnitudes of nutrient transfers from the ocean to the island through saltspray, precipitation and dryfallout [6] and also by seabirds and seals that feed in the ocean and deposit excreta, shells, moulted feathers and fur on the island [7]. In contrast, soil nutrient concentrations have been measured only at a few localities, and detailed nutrient budgets have been drawn up for only eight of the island's 41 plant com-

munities [8,9], all within a 1.5 ha area about 35 m a.s.l. and 600 m from the coast on the island's eastern side. Some soil nutrient information exists for other areas on the east side but there is none for other parts of the island. In fact, prior to this study there was no information on the spatial variation in soil chemical composition at the island.

One component of a nutrient budget is the *soil nutrient standing stock*, which is the mass of a particular nutrient per square meter of soil down to a specified depth. This depends on the concentration of that nutrient in, and the bulk density (mass per volume) of, the soil. Hence, to construct a nutrient budget on a whole-island basis it is important to know how soil nutrient concentration and soil bulk density change with increasing distance inland and elevation, and if the changes are different on the various sides of the island. Here, we report the results of an investigation aimed at providing such information for the island's eastern and western sides.

2. Material and Methods

2.1. Sampling Localities and Protocol

In April/May 2010, soils were sampled from 77 localities on the east side, and 55 localities on the west side, of the island (**Figure 1**). Each locality's latitude and longitude were recorded using a GPS and used with a digital elevation model in ArcGIS 8 (ESRI, California) to estimate its altitude and distance to the sea, and also to construct **Figure 1**. A 5 cm diameter core, 25 cm deep where the soil was deep enough to allow it, was taken from the soil and the surface vegetation, litter and conspicuous roots removed. If the core contained conspicuous horizons, these were separated. The volume of the whole core or horizon section was calculated from its diameter and length.

2.2. Soil Moisture and Chemical Analyses

The fresh core or horizon section was weighed, air dried and weighed again. A weighed subsample of the air-dried soil was dried in an oven at 105°C for 12 hours and re-weighed. From the fresh, air-dried and oven-dried masses, moisture content was calculated on an oven-dried basis. From the oven-dried mass and volume of the soil core or horizon section, bulk density was calculated.

All chemical analyses were performed on the air-dried subsamples and the concentrations expressed on an oven-dried mass basis using the air-dry:oven-dry mass ratios. For total P, Ca, Mg, K and Na, a soil subsample was extracted with boiling HCl:HNO₃ mixture (3:1) and the concentrations of P and the cations in the extract determined by Inductively Coupled Plasma—Optical Emission Spectrometry (Varian Vista-MPX; Varian, Inc. California). Total N was measured with a Leco FP-528

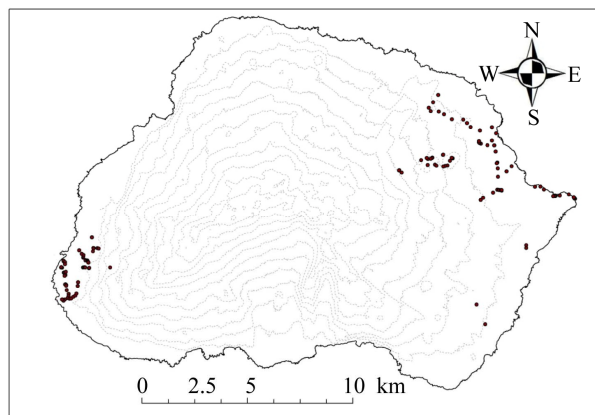


Figure 1. Map of Marion island with 100 m contour lines and showing localities where soils were sampled.

nitrogen analyser (LECO Corporation, Michigan). Total carbon was determined by the Walkley-Black method [10]. Exchangeable cations were determined by extracting soil subsamples with 1 M ammonium acetate solution and measuring the concentrations of Ca, Mg, Na and K in the extract by ICP-OES.

2.3. Data Analyses

Linear regression analysis was used to test if the magnitudes of the soil chemistry variables were significantly ($P \leq 0.05$) related to altitude or distance to the sea. For total Na and exchangeable Na and Mg, the relationships were approximately negative exponential ones, so the data were log-transformed. Two regression analyses were carried out, one on the east side data and the other on the west side data. If one or both of the regressions were significant, a homogeneity-of-slopes analysis was used to test if the slopes differed significantly between east and west sides. If they did not, the between-sides difference in concentrations was tested by analysis of covariance; if they did, a separate-slopes test was used (in both instances altitude or distance to the sea was the covariate). Where the values of a chemical variable were unrelated to altitude or distance to sea, the east-west difference in its mean values was tested by analysis of variance. The statistical analyses were done using Statistica 9 software [11].

3. Results and Discussion

Table 1 compares the relationships (slopes) of the soil chemistry values with altitude and with increasing distance from the sea between the eastern and western sides of the island, and also gives the mean values for each side (or the means adjusted for the effect of altitude and distance from the sea).

On both the eastern and the western sides of the island, concentrations of exchangeable Na, Mg and K declined

Table 1. Relationships between soil chemistry variables and altitude or nearest distance to sea. Only slopes of significant regressions are reported. Where slopes or means differed significantly ($P \leq 0.05$) between the east and west side of the island, one of the pair is marked with an asterisk*. Where a variable was significantly influenced by altitude or distance to sea, the mean value is the mean (\pm standard error) adjusted for that influence and is given in italics. Otherwise, actual means (\pm standard error) are reported. For total Na and exchangeable Na and Mg, the influence of altitude or distance to sea was approximately a negative exponential one so the data were log-transformed for the analysis. In that case the logs of the adjusted means and standard errors are reported and the exponential value of the (log) mean given in brackets. The reported slope values for total C, total N, CEC, exch. K and exch. Ca are the actual slope values $\times 10^4$. N is the number of samples.

	N	Altitude				Distance to the Sea			
		Slope		Means \pm S.E. (Adj. Mean \pm S.E.)		Slope		Means \pm S.E. (Adj. Mean \pm S.E.)	
		(East/West)	East	West	East	West	East	West	East
Range (m)		7 - 409	27 - 130			20 - 4958	200 - 1268		
Moisture content (%)	77/55	-1.69	-8.59	834 \pm 73.7	640 \pm 79.1	-0.101		829 \pm 77.9	641 \pm 80.1
Bulk density (g/cm ³)	77/55	12.18		0.17 \pm 0.025	0.25 \pm 0.026	0.771		0.18 \pm 0.027	0.25 \pm 0.028
Total C (g/kg)	76/55	-417.43		205 \pm 11.4	155 \pm 12.1*	-29.89		207 \pm 12.1	155 \pm 12.3*
Total N (g/kg)	77/55	-28.54		13.6 \pm 0.66	9.9 \pm 0.71*	-2.13		12.8 \pm 0.63	9.0 \pm 0.75*
Total P (mg/kg)	74/54			667 \pm 35.2	654 \pm 68.5			667 \pm 35.2	654 \pm 68.5
Total Na (mg/kg)	74/54		-1.05	6.5 \pm 0.07 (644)	7.5 \pm 0.09* (1778)	-0.14	-1.01*	6.46 \pm 0.066 (636)	7.46 \pm 0.0775* (1745)
Total K (mg/kg)	74/54			262 \pm 14.8	679 \pm 87.4*		-0.995	255 \pm 51.8	682 \pm 52.6*
Total Ca (mg/kg)	74/54			2036 \pm 144	5966 \pm 634.7*		-7.25	1942 \pm 385.1	5999 \pm 390.7*
Total Mg (mg/kg)	74/54	14.07		2770 \pm 596.3	6782 \pm 630.2*	0.87	-8.91*	2761 \pm 584.9	6818 \pm 593.4*
Exchangeable Na (meq/100g)	77/55	-0.07	-1.97*	0.29 \pm 0.086 (1.33)	1.15 \pm 0.101* (3.17)	-0.54	-1.35*	0.21 \pm 0.081 (1.23)	1.12 \pm 0.096* (3.08)
Exchangeable K (meq/100g)	77/55	-21.13	-54.62	0.84 \pm 0.057	0.56 \pm 0.062*	-1.54	-4.49	0.86 \pm 0.06	0.56 \pm 0.06*
Exchangeable Ca (meq/100g)	77/55		-549.93	3.5 \pm 0.44	5.4 \pm 0.469*		-35.37	3.7 \pm 0.46	5.4 \pm 0.48
Exchangeable Mg (meq/100g)	77/55	-0.58	-1.01	1.3 \pm 0.09 (3.50)	2.1 \pm 0.109* (7.91)	-0.433	-0.643	1.2 \pm 0.09 (3.30)	2.1 \pm 0.12* (7.84)

significantly with increasing altitude or distance inland. Saltspray and aerosols of seawater (together, these are henceforth termed seaspray) is the sole source of Na, and the main sources of Mg and K, at the island [12], so this is unsurprising. It also explains the decrease in total Na with increasing distance inland.

On the east side, total C, total N and soil moisture content declined significantly, while bulk density increased significantly, with increasing altitude and distance inland. The four variables varied in a similar pattern on the west side but the effect of the both covariates was significant only for moisture content. That total C, total N and bulk density did not change significantly with increasing distance inland on the west side can be explained as follows.

Soil moisture content and total N concentration are positively, and bulk density negatively, strongly corre-

lated with total C concentration [13]. Organic soils (peats) are wet, have low bulk density and high total C and N concentrations. Mineral soils are dry, with a high bulk density and low total C and N concentrations. Mineral soils also tend to have high total Ca and Mg concentrations, since much of the total complement of these two elements is found in the parent volcanic rock and ash. On the eastern side, total C, total N and soil moisture all decline significantly as one moves away from the sea and up in elevation, reflecting the change from organic, wet, low bulk density peats characteristic of lowland coastal regions to the mineral, dry, high bulk density volcanic soils characteristic of inland areas. On the island's west side, a narrow (400 to 900 m wide) coastal plain meets an escarpment rising up very steeply to the mountainous interior. Soils are rare on the escarpment and absent in the interior, the substrate being lava or volcanic ash.

Most samples on the western side were of the coastal plain soils; sampling did not extend as far inland or as high up as it did on the eastern side. There was thus not the same strong gradation from organic to mineral soils with increasing distance inland as there was on the eastern side. This accounts for the lack of a significant relationship of total C, total N and bulk density with altitude or distance to the sea on the western side.

On the eastern side, total Mg concentration increased significantly, whereas on the western side it decreased significantly, with increasing distance from the sea. This is also attributable to the fact that on the west the sampling did not extend over as a wide range of organic versus mineral soil types as on the east coast. Most total Mg is in the mineral fraction of the soil (the basaltic parent lava and scoria). The organic, exchangeable and dissolved forms contribute little to total Mg, except perhaps in peats close to the sea. On the east side, the gradual transition from highly organic peats to very mineral soils represented by the samples results in an increase in total Mg with increasing distance inland. On the west side there was not this range of soil minerality and the change (decrease) in total Mg with increasing distance inland reflects the decreasing intensity of seaspray. This is not to say that west side soils are not more mineral, on the whole, than east side soils—it is the change in minerality that is important, and that is greater on the east side. West side soils are actually intrinsically more mineral than east side soils, as is shown by the significantly lower total C concentrations of the west side soils when adjusted for the effect of altitude or distance from the sea. Mineral soils have a higher bulk density and are drier than organic soils, and the altitude- or distance to sea-adjusted differences in bulk density and moisture content between the west and east sides of the island, although not significant at $P \leq 0.05$, also point toward west side soils being intrinsically more mineral and less organic than the east side soils.

Because of their greater minerality, west side soils have higher concentrations of total Ca, Mg and K than east side soils. Because the wind (especially strong wind) is predominantly westerly, west side soils also have higher concentrations of total Na and exchangeable forms of Na, Ca, and Mg than do east side soils. In contrast, soil exchangeable K concentrations are lower on the west side than the on east side. The reason for this is uncertain. K does possess cation exchange properties not shown by the other exchangeable cations; an important one is that it can convert from an easily exchangeable to a fixed form in some types of clay [14]. The identities of clay minerals in Marion Island soils are a matter of some controversy [3]; indeed, most of the controversy concerns whether there are any clays at all [15]. However, recent Raman spectroscopic analysis reveals that crystal-

line minerals such as biotite and muscovite, both capable of weathering into K-fixing clays, are common on the island [16]. Possibly, K-fixation is more intense in the mineral-rich west coast soils than in the organic east coast ones. Another possible explanation for the lower exchangeable K concentration in the west side than east side soils is that the high amount of Na reaching the soil surface through seaspray on the western side displaces exchangeable K as it percolates through the soil. On the east coast, replacement of K by Na on the cation exchange complex would be much less intense because of the much less intense deposition of seaspray.

4. Conclusions

Altitude and nearest distance to the sea are strongly interrelated, so it is not surprising that soil chemical composition is influenced by both. The influence is through a decreasing influence of seaspray with increasing distance inland and a change from organic peats characteristic of the coastal plain to mineral soils more influenced by parent basalts further inland and higher up. Furthermore, the dependence of soil chemical composition on altitude or distance from the sea is a function of aspect—here we showed that it differs markedly between the west and east sides of the island. There are intrinsic differences (*i.e.* once this between-side difference in the influence of altitude and distance from the sea on soil chemical composition has been accounted for) in soil chemical composition between east and west sides. These findings are crucial for modeling nutrient cycling budgets on a whole island basis.

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