VARIATION IN THE PHYSICAL AND CHEMICAL ENVIRONMENT OF A MARITIME ANTARCTIC MOSS-TURF

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ABSTRACT: Four blocks of moss and peat, each 400 cm² and 9 cm deep, were cut from a moss-turf on Signy Island during the 1980–81 austral summer. Each block was cut vertically into sixteen contiguous square cores and horizontally into six 1.5-cm thick layers. For each of the 384 samples the following environmental variables were recorded or analysed: dry weight, weight of water, percentage water content, vegetation cover, pH, and the total concentrations of sodium, potassium, calcium, phosphorus and nitrogen. Marked trends with depth were shown for dry weight, weight of water, percentage water content, potassium and calcium. Seasonal trends were shown by nitrogen and, to a lesser extent, phosphorus. Percentage water content, potassium, calcium, phosphorus and nitrogen were more strongly inter-correlated than the other variables. Principal components analyses showed that the system could be divided into two parts: a green moss zone (0–1.5 cm) and a dead moss zone (below 3 cm). The intermediate layer (1.5–3.0 cm) was transitional, in part an artifact of sampling. There was a marked small scale horizontal heterogeneity. Sodium was distributed approximately randomly, whilst potassium, phosphorus and nitrogen showed trends across a layer, as well as through the profile.

INTRODUCTION

Of the six cryptogammic communities of the maritime Antarctic recognized by Longton (1967), the moss-turf subformation is probably the best studied terrestrial habitat. On well drained, stable sites, away from areas of permanent ice and snow, banks of the turf forming mosses, *Chorisodontium aciphyllum* (Hook. f. *et* Wils.) Broth. and *Polytrichum alpestre* Hoppe, may develop. These moss-turves are often very extensive and well developed, and may accumulate peat to a depth of up to 3 m, as on Elephant Island, South Shetland Islands (Allison and Lewis Smith, 1973). Fenton and Lewis Smith (1982) reviewed the moss banks of the maritime Antarctic, with particular reference to those on Signy Island, South Orkney Islands. Studies of production, decomposition and net accumulation of peat have been described by Baker (1972), Collins (1976), Fenton (1980, 1982) and Longton (1970).

Holdgate (1977) and, in greater detail, Jeffers and Holdgate (1976) analysed a series of habitat and vegetation attributes of Signy Island, recorded at a large scale of surveying (500 m squares). Of the six main vegetation clusters revealed on analysis, those containing a relatively high proportion of continuous moss-turf were restricted to the ice-free coastal belt. Holdgate (1977) also stressed that a striking small scale variability in vegetation (over 1 m or less) occurred, and that a carefully designed sampling strategy was therefore necessary, but he did not undertake such sampling. The soils of Signy Island, including the moss-turf peats, were described by Holdgate and others (1967), and aspects of the nutrient availability were discussed by Allen and others (1967). The seasonal cycles of variability of some nutrients in peat and other soils were recorded by Northover and Allen (1967) and Northover and Grimshaw (1967), whilst concentrations of elements in a variety of cryptogam species in both summer and winter were reported by Lewis Smith (1978). Allison and Lewis Smith (1973) also compared the nutrient contents of the soils of Signy and Elephant Islands, Walton and Lewis Smith (1980) determined the chemical contents of a variety of plant species from South Georgia.

Within these moss-turf habitats, communities of arthropods and other invertebrates exist. The apparent seasonal variation in abundance of mites and Collembola in a moss-turf site has been reported by Goddard (1979) and Block (1982) respectively, and the overall community structure and energy flow through the same site was synthesized by Davis (1981). Usher and Booth (1984) studied the small scale vertical and horizontal distributions of the arthropod fauna within the upper 9 cm of the moss-turf at this site.

The aim of this paper is to describe, using a small scale of sampling as suggested by Holdgate (1977), the spatial variation of the chemical and physical environment of the habitat, with particular reference to that of the arthropods. Stratification and small scale heterogeneity of the moss-turf environment are described and discussed in relation to the distribution of the mosses, whose pattern has already been described (Usher, 1983). The distribution of the arthropod community in relation to the physical and chemical characteristics of the environment of the moss-turf was studied by Booth and Usher (1984), who concluded, overall, that it was the chemical characteristics of the environment which had a greater influence on the summer distribution of the arthropods than did the physical characteristics.

Methods

Blocks of moss and peat, each 20 cm square and 9 cm deep, were collected during the 1980–81 austral summer from the Signy Island Terrestrial Reference Site 1 (SIRS 1), which is described by Tilbrook (1973). A single block of moss and peat was collected on each of four occasions, the sampling dates being 19 December 1980, 23 January 1981, 15 February 1981 and 20 February 1981. The December block was collected during the earlier part of the summer when the moss-turf profile had thawed to a depth of about 15 cm, and the January block was sampled at about the middle of the summer. Logistic arrangements precluded both a more regular sampling regime, and the collection of autumn samples during March. The method of sample collection is described by Usher and Booth (1984). Each block of moss was cut vertically into sixteen 5-cm-square cores, arranged contiguously in four rows and four columns, and the surface plant cover of each was estimated visually. Each core was then sectioned horizontally into six samples. The top layer comprised the green moss shoots and the upper dying leaves, and was approximately 1.5 cm thick, depending on the moss species and its growth form. Each subsequent layer was 1.5 cm thick. The ninety-six samples (six layers from each of sixteen cores in a block) were weighed individually and dried slowly over a period of eight days as the arthropods were extracted. Following arthropod extraction, the samples were oven dried to constant weight at 50°C, then sealed in individual polythene sachets for subsequent chemical analysis in the UK.

Chemical determinations on the dried samples were undertaken by the Subdivision of Chemistry and Instrumentation, Institute of Terrestrial Ecology. The analytical methods utilized follow Allen and others (1974), and the following six chemical variables were determined: pH, and the total concentrations of sodium, potassium, calcium, phosphorus and nitrogen (concentrations are expressed as a percentage of sample dry weight). These chemical variables are the ones that have frequently been determined in previous ecosystem studies, and were selected after consultation with S. E. Allen (personal communication) as appropriate to this Antarctic environment.

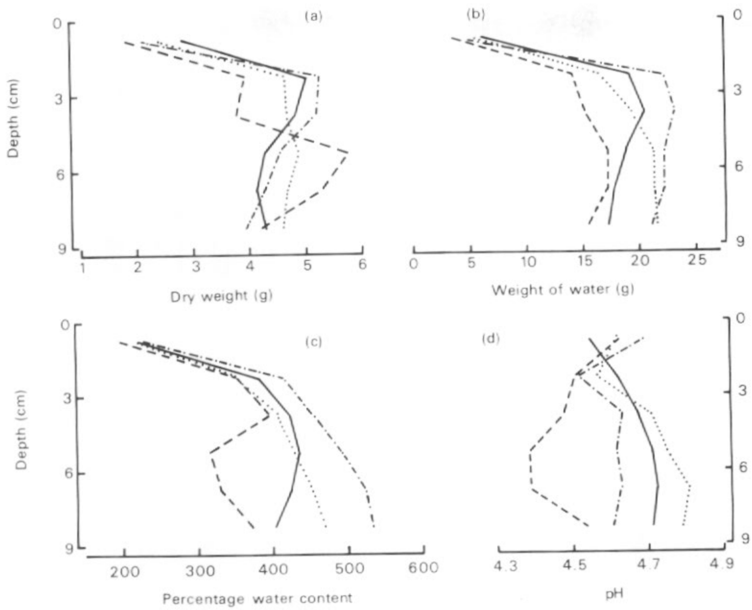

Fig. 1. The relationship between depth within a moss-turf profile and the mean values of (a) dry weight, (b) weight of water, (c) percentage water content and (d) pH for four blocks of contiguous samples. Samples were cut at 1.5 cm intervals and mean values, each based on sixteen values, are plotted at the midpoint of each depth. Sampling dates are as follows: dot-dash line, December 1980; solid line, January 1981; dotted line, 15 February 1981; dashed line, 20 February 1981. For clarity, standard errors have been omitted from the figures. Coefficients of variation averaged 16.3, 16.4, 7.6 and 2.6% in (a), (b), (c) and (d) respectively.

RESULTS

Vegetation cover

The two turf-forming mosses formed a mosaic pattern of distribution and accounted for more than 95% of the plant cover. Within each block, the plant cover of individual cores ranged from dominance, at least 80% cover, by one or the other moss species to an even mixture. The four blocks differed in the proportions of the two moss species. The ratios of *Polytrichum* to *Chorisodontium* were approximately 2:1 in the December 1980 block, 1:1 in the January 1981 block, 1:2 in the 15 February 1981 block and 1:4 in the 20 February 1981 block. These observed ratios are all consistent with the ratios expected, since there is a well developed pattern at this site, with a scale of heterogeneity at about 20 cm (Usher, 1983).

Six genera of lichens were represented, but their combined cover was low, averaging less than 5% in each of the four blocks. Only two lichen species *Usnea antarctica* Du Rietz and *Sphaerophorus globosus* (Huds.) Vain. exceeded 10% cover over any one core (the maximum lichen cover was 40%, by *S. globosus*, in one of the cores in the January 1981 block).

Dry weight and moisture content

The relationships between dry weight, weight of water, percentage water content and depth for each of the four blocks are shown in Fig. 1(a–c). The top layer, containing the green moss and upper dying leaves, was much less densely packed than the other layers, and thus its mean dry weight was only about half that of the second layer. Below 1.5 cm, sample dry weight decreased in the December 1980 and January 1981 blocks, was more or less constant in the 15 February 1981 block, but was stepped in the 20 February 1981 block, in which the fourth and fifth layers were much heavier than expected (Fig. 1a).

The weight of water in each sample (Fig. 1b) followed a similar trend to dry weight, except in the lower layers of the 20 February 1981 block. The percentage water content was also much lower in the top layer than in the deeper layers. It increased with depth in the December 1980 and 15 February 1981 blocks, and reached a maximum in the fourth layer of the January 1981 block (Fig. 1c). The drop in percentage water content of the fourth and fifth layers of the 20 February 1981 block reflected the increased dry weight of the layers, and not a decrease in the weight of water in these layers.

pH

Changes in pH with depth for the four blocks are shown in Fig. 1d. The December 1980 and 15 February 1981 blocks showed a similar trend: the pH dropped from the surface to the second layer and then increased in the third layer, thereafter remaining more or less constant below 3 cm or reaching a maximum in the fifth layer. The pH in the third, fourth and fifth layers of the 20 February 1981 block was much lower than in the previous three blocks.

Sodium

For three of the four blocks, there was little variation in sodium with depth (Fig. 2a), whilst the 20 February 1981 block had elevated sodium concentrations in the surface, fourth and fifth layers. However, as variation in sodium concentration largely reflects the recent weather conditions, the elevated levels are probably only transitory. Sea spray during stormy weather a few days previously would have elevated the sodium concentrations, and whilst the snow fall immediately prior to sampling would normally have leached some of the sodium as it melted, the snow was removed by hand before the samples were collected.

Potassium

Potassium showed very little variation within layers, and three of the four blocks followed a very similar trend of decreasing concentration with depth (Fig. 2b).

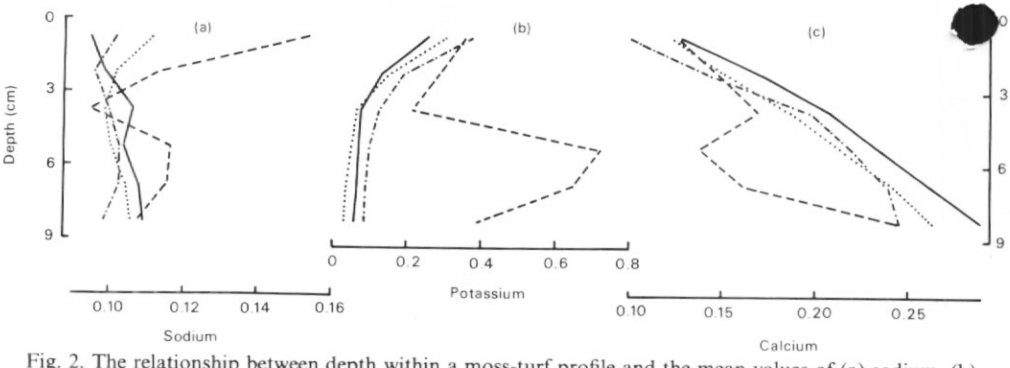

Fig. 2. The relationship between depth within a moss-turf profile and the mean values of (a) sodium, (b) potassium and (c) calcium for four blocks of contiguous samples. Details as in Fig. 1. Coefficients of variation averaged 9.6, 24.1 and 11.8% in (a), (b) and (c) respectively.

However, the 20 February 1981 block, although showing a similar trend in the upper three layers, had greatly elevated concentrations below 4.5 cm.

Calcium

Calcium generally showed a regular accumulation with depth, and the concentration in the sixth layer was at least twice that of the surface layer (Fig. 2c). The 20 February 1981 block again showed a discontinuity, with calcium concentrations in the fourth and fifth layers much reduced, mirroring the trend shown by potassium. However, the concentrations in the upper three layers and in the sixth layer were within the ranges of the other three blocks.

Phosphorus

Phosphorus showed a seasonal trend, as well as a gradual vertical trend of decreasing concentration (Fig. 3b). The concentrations in the December 1980 and January 1981 blocks more or less declined slowly with depth, but at all depths the levels in the December block were higher than those in the January block. The 15 February 1981 block showed an elevated level in the surface layer, and essentially no variation below 3 cm. The upper two layers of the two February 1981 blocks were very similar, but the second February block again contained greatly elevated levels in the fourth and fifth layers. Northover and Allen (1967) showed that there was a marked seasonal variation in extractable phosphorus: concentrations increased during the winter months, dropped rapidly in spring following the thaw, and were at a minimum during the middle of the growing season, in January. The results of the present study are consistent with such observations.

Nitrogen

Nitrogen also showed the effects of seasonal variation, since the December 1980 block contained much higher levels of nitrogen than the three blocks collected later in the season (Fig. 3a). The elevated levels present in the top layer of the 20 February 1981 block can be accounted for by the presence of a white, encrusted deposit, probably a bird pellet or dropping, which partly occupied three of the cores; the mean for the other thirteen cores was 0.62, between the values for the January and 15 February 1981 blocks. Northover and Allen (1967) showed that ammonium nitrogen increased in the peat during the winter months, and that this was mobilized at the spring thaw. They did not demonstrate any seasonal variation in nitrate nitrogen. The data in Fig. 3a are for total nitrogen and do not distinguish between ammonium and nitrate nitrogen.

Correlations between variables

Correlation coefficients were calculated initially between all possible pair-wise combinations of the following eleven variates: *Polytrichum* cover, *Chorisodontium* cover, dry weight, weight of water, percentage water content, pH, and the five chemical concentrations. These were calculated for each of the six layers in each of the four blocks of samples. However, since the correlation between *Chorisodontium* and *Polytrichum* cover was almost perfectly negative (r varied between -0.93 and -0.99), *Chorisodontium* cover was excluded from further analyses. Sample dry weight and weight of water were also almost perfectly positively correlated, and hence weight of water was excluded from further analyses. Sample percentage water content (weight of water expressed as a percentage of dry weight) was retained in further analyses as the best available index of moisture content.

Table I shows the correlation coefficients between pair-wise combinations of the nine variables considered, for each of the four blocks of samples. These correlation coefficients are the means of the individual coefficients for each of the six layers in a block, derived from a z transformation of each layer's correlation coefficient, as used by Usher and Booth (1984) on the data for the arthropods extracted from the same samples.

Table I. Matrix of correlation coefficients between pairs of environmental variables for four blocks of samples. For each pair-wise combination, the four coefficients refer to the four blocks in chronological order of the collection. The significance level of the coefficients is indicated as follows: *, $0.05 \geqslant P > 0.01$; **, $0.01 \geqslant P > 0.001$; ***, $P \leqslant 0.001$; blank, not significant. Symbols identifying each variable are as in Fig. 4.

	DW	PC	WC	pH	Na	K	Ca	P
PC	−0.43*** −0.19 0.20 0.23*							
WC	−0.38*** −0.01 0.28* −0.43***	0.36*** 0.10 0.03 0.20						
pH	−0.09 −0.03 0.21 −0.42***	0.08 0.12 0.06 −0.04	−0.11 0.12 0.35** 0.31**					
Na	−0.03 0.23* 0.11 0.42***	0.01 −0.04 −0.20 −0.16	0.38*** 0.25* 0.14 −0.30**	−0.29** −0.08 −0.04 −0.10				
K	−0.30** −0.07 −0.09 0.62***	0.44*** −0.14 0.28* −0.12	0.09 0.35** −0.35** −0.72***	0.15 −0.12 0.07 −0.28*	0.23* 0.25* 0.10 0.56***			
Ca	0.01 0.26* −0.09 −0.51***	0.02 −0.24* −0.41*** 0.04	0.30** 0.23* 0.40*** 0.71***	−0.29** 0.08 −0.03 0.56***	0.46*** 0.56*** 0.19 −0.20	−0.17 0.36** −0.58*** −0.67***		
P	−0.02 −0.16 0.16 0.53***	0.40*** −0.22 0.07 −0.19	0.20 0.50*** 0.51*** −0.52***	0.21 −0.02 0.26* −0.09	0.28* 0.09 0.17 0.24*	0.78*** 0.74*** −0.00 0.66***	0.03 0.34** 0.39*** −0.36**	
N	0.07 −0.21 0.25* 0.42***	0.39*** −0.23* −0.11 −0.22*	0.25* 0.46*** 0.61*** −0.32**	0.03 0.00 0.23* 0.35**	0.24* 0.04 0.08 0.21	0.44*** 0.58*** −0.44*** 0.46***	0.30** 0.32** 0.55*** −0.11	0.76*** 0.91*** 0.73*** 0.73***

From a total of 144 correlation coefficients, 20 (14%), 16 (11%) and 42 (29%) are significant at probability levels of 5, 1 and 0.1% respectively. *Polytrichum* cover, dry weight, pH and sodium were each less strongly correlated with all other variables (each with between 10 and 15 coefficients significant at, at least, the 5% probability level) compared with percentage water content and the four remaining chemical concentrations (each with between 18 and 23 coefficients significant). *Polytrichum* cover, dry weight and pH were not consistently correlated with any other variable in the four blocks. Sodium was correlated significantly with potassium in three of the four blocks, whilst its correlation coefficients with other variables were again not consistent. Percentage water content, potassium, calcium, phosphorus and nitrogen were generally more consistently inter-correlated, especially nitrogen and phosphorus, although some anomalies did occur, for example the correlation between nitrogen and potassium which was positive in three blocks and negative in the fourth. These five variables were also important in interpreting the principal components analyses (see below).

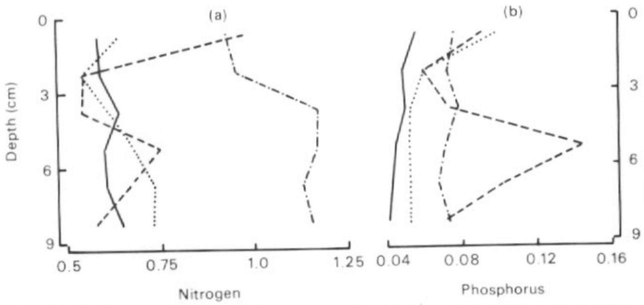

Fig. 3. The relationship between depth within a moss-turf profile and the mean values of (a) nitrogen and (b) phosphorus for four blocks of contiguous samples. Details as in Fig. 1. Coefficients of variation averaged 21.2 and 22.6% in (a) and (b) respectively.

Principal components analysis

Principal components analyses were performed on the environmental data for each of the four blocks using the nine variables listed in Table I. The percentage values for *Polytrichum* cover were arcsin transformed. The eigenvalues and eigenvectors were extracted from correlation matrices, i.e. all variates were standardized to zero mean and unit variance because of the different scales of measurement.

Analyses on the first three blocks (December 1980, January 1981 and 15 February 1981) produced very similar results. The first component accounted for 37, 43 and 53% of the total variance of the data respectively, and the associated eigenvector showed consistently large negative loadings for dry weight, percentage water content and calcium and a contrasting large positive loading for potassium (Fig. 4). Thus the first component is interpreted as relating to depth, since dry weight, percentage water content and calcium increase at least over part of the depth range, whereas potassium decreases with depth. As would be expected with this interpretation, the loading on *Polytrichum* cover is virtually zero in all three blocks, since in the data matrix all samples were assumed to be composed of the same moss as the sample at the surface of the core.

The second eigenvalue accounted for 22, 20 and 18% of the total variance for the first three blocks respectively, and the associated eigenvectors had large positive loadings for phosphorus, nitrogen and, to a lesser extent, sodium (Fig. 4). Phosphorus and nitrogen were positively correlated in all blocks and the second component relates to this chemical characteristic of the environment. Although *Polytrichum* cover had a large and positive loading in the December 1980 block, its loadings in the January 1981 and 15 February 1981 blocks were smaller and negative.

The ninety-six samples forming a block are plotted on these first two principal component axes in Figs. 5 and 6a. For clarity, the ninety-six individual points have been omitted from each plot, but a polygon has been drawn to enclose all sixteen points

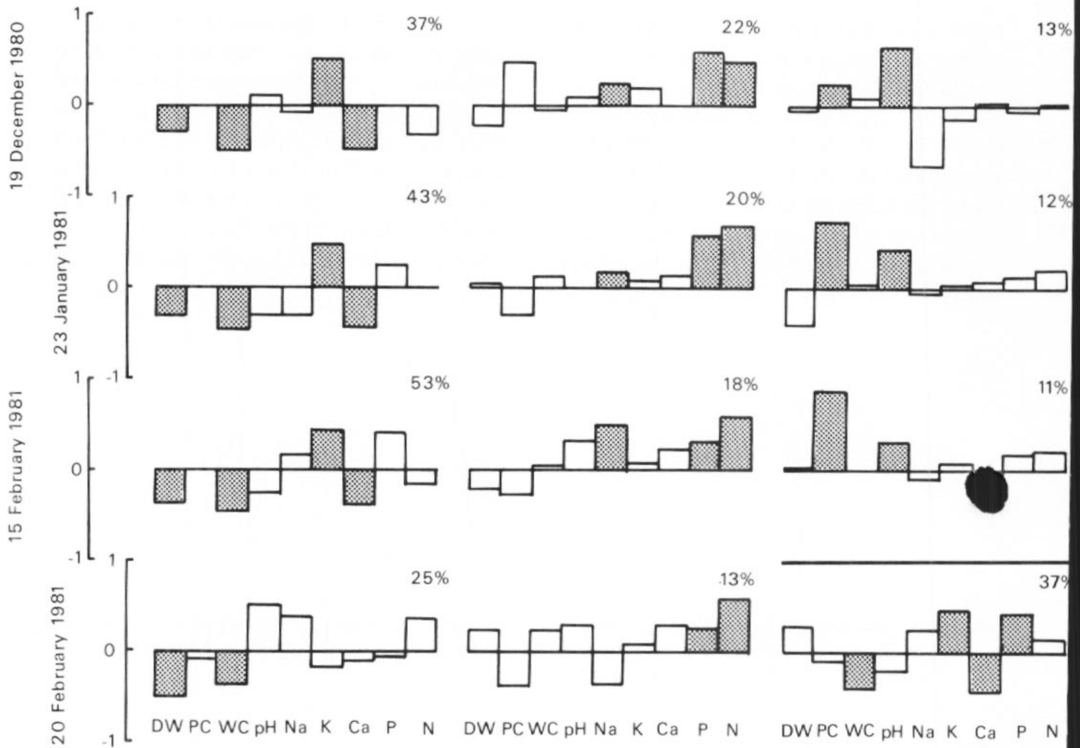

Fig. 4. The loadings on the first three principal components of the data for nine environmental variables for each of the four blocks of samples. The percentage of the variance accounted for by each eigenvector is indicated. The 20 February 1981 components are rearranged below the other three components with similar interpretations. The solid bar separates those components with different interpretations. The symbols identifying each variable are as follows: DW, dry weight; PC, *Polytrichum* cover; WC, percentage water content; pH and conventional chemical symbols.

in a layer, and mean scores for the sixteen points in each layer are superimposed. The mean points are not evenly distributed along the depth axis (axis I): the polygon for the surface layer is always separated from the others and never overlaps with the other layers' polygons. The polygons for layers three to six overlap to a considerable extent (Table II), and the means for each of these layers are only narrowly separated. The second layer's polygon lies more or less adjacent to the deeper layer polygons, overlapping only to a limited extent into the deeper layers. The separation of the surface layer from the other layers will be discussed below.

The third eigenvalue accounted for 13% or less of the total variance, and the associated vectors had large and consistent positive loadings on only *Polytrichum* cover and pH. This also implies that either *Chorisodontium* grows in more acidic areas, or that its litter has a lower pH. The smaller eigenvalues are not considered further since they accounted for only a small percentage of the variance: they are probably associated with random variation in the data (Gauch, 1982).

The results of the principal components analysis on the 20th February 1981 block were very different (Fig. 4). The first component (37% of variation) no longer represented depth, but with large positive vector loadings on potassium and phosphorus contrasted with negative loadings on percentage water content and calcium, it separated layers 1, 4 and 5 into one group and layers 2, 3 and 6 into another. The

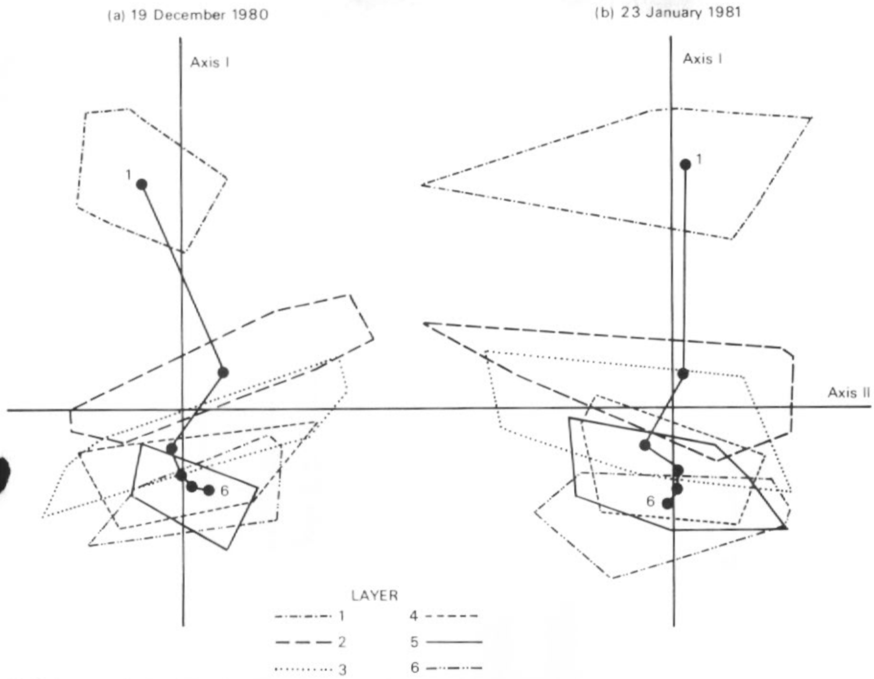

Fig. 5. Polygons defined by the first two axes of a principal components analysis of the environmental data for the two blocks of samples collected in (a) December 1980 and (b) January 1981. Individual points are omitted for clarity, but the mean of the sixteen points within each layer is shown in its polygon. The six layer means are connected in numerical order from the top layer (number 1) to the bottom layer (number 6).

unusual physical and chemical characteristics of the fourth and fifth layers in this block can be seen in Figs. 1 to 3. The second eigenvector (25% of variation) shows some similarity to the first eigenvector of the other three blocks, with large negative loadings on both dry weight and percentage water content. The third eigenvalue accounted for 13% of the total variance, and its vector was more closely similar to the second rather than to the third eigenvector of the previous blocks. It differed by having a negative loading on sodium, possibly resulting from the elevated levels of this ion in the block (Fig. 2a). When the means of the sample layer, and the polygons enclosing the sixteen points in each layer, are plotted on the second and third axes (Fig. 6b), the surface layer is entirely separated from the lower layers, and the third to sixth layers are clustered together, in a way analogous to that shown in Figs. 5 and 6a.

Horizontal variation

The horizontal distributions of the physical and chemical characteristics of the blocks were examined to determine whether the variation of an attribute within a layer was random, or whether a trend from one side of the block to the other was apparent. For each layer, the mean and standard error of each environmental variable were calculated, and each sample in the layer was scored as above average (greater than the mean plus one standard error), below average (less than the mean minus one standard error), or average (between these two ranges).

Fig. 7 shows the results for the December 1980 data. There are some clear differences in the behaviour of different environmental variables, showing either clumped or

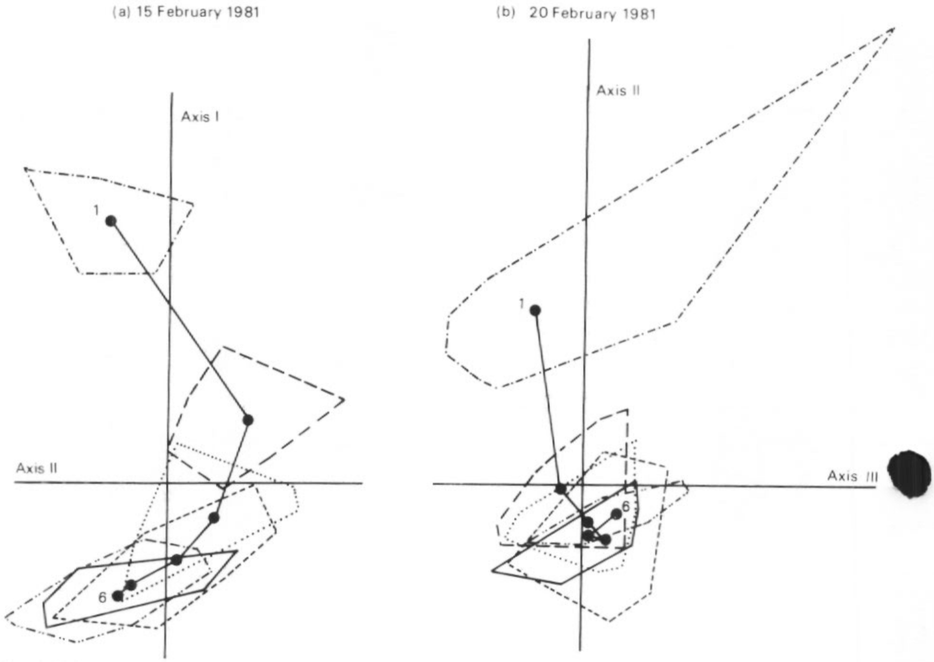

Fig. 6. Polygons defined by (a) the first two axes (15 February block) and (b) the second and third axes (20 February block) of a principal components analysis of the environmental data for these two blocks of samples. Details as in Fig. 5.

Table II. The numbers of points in each layer's polygon overlapping into the area of every other layer's polygon from a principal components analysis on the environmental data for four blocks from the moss-turf (Figs. 5 and 6). Layers are numbered from 1 to 6 from the surface downwards, and dashes are shown in the leading diagonals since each layer overlaps itself perfectly.

No. of points belonging to the polygon of layer	*which are enclosed by the polygon of layer*											
	19 December 1980						*23 January 1981*					
	1	2	3	4	5	6	1	2	3	4	5	[illegible]
1	—	0	0	0	0	0	—	0	0	0	0	0
2	0	—	4	0	0	0	0	—	7	1	1	0
3	0	2	—	8	3	0	0	4	—	8	7	3
4	0	0	7	—	6	9	0	3	9	—	10	7
5	0	0	4	15	—	12	0	1	5	10	—	10
6	0	0	3	12	9	—	0	0	1	7	11	—
	15 February 1981						*20 February 1981*					
	1	2	3	4	5	6	1	2	3	4	5	6
1	—	0	0	0	0	0	—	0	0	0	0	0
2	0	—	1	0	0	0	0	—	6	3	1	0
3	0	1	—	11	1	2	0	10	—	13	9	7
4	0	0	8	—	5	6	0	5	5	—	6	4
5	0	0	3	11	—	10	0	6	11	15	—	7
6	0	0	3	9	9	—	0	8	8	14	5	—

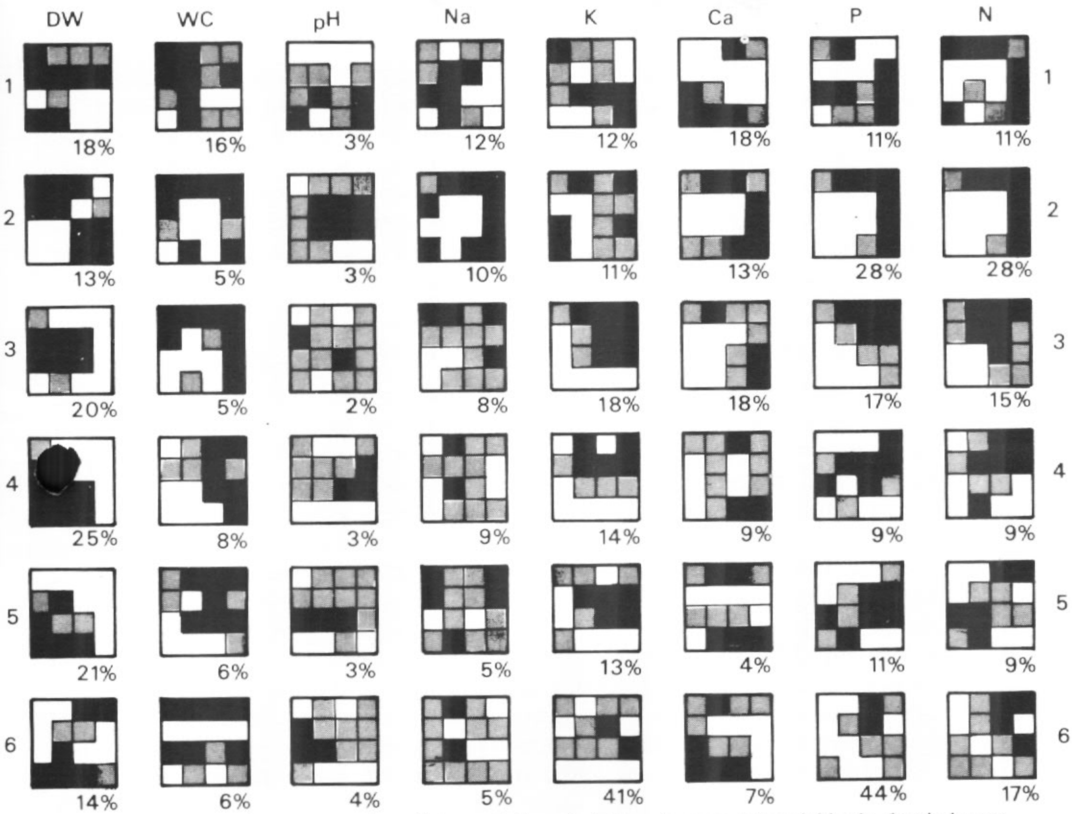

Fig. 7. A diagrammatic representation of the variation of eight environmental variables in the six layers of the December 1980 block of samples. Layers are numbered from 1 to 6 from the surface downwards and the symbols denoting the variables are as in Fig. 4. The coefficient of variation of each variable in each layer is indicated. For each layer, samples above the layer average are shown in black, those below average in white, and stippling denotes average samples (see text for the criterion used for assessing above and below average).

scattered distributions which may or may not be traceable through the layers. Sodium concentration is most variable in the surface layer (coefficient of variation 12%) and least variable in the deeper layers (coefficient of variation 5%), but the distribution of samples with above or below average concentrations is essentially random, with no obvious regions of high or low concentrations. The pH determinations varied least of all the variables, the coefficients of variation lying between 2 and 4%. Areas of high or low pH were grouped to some extent, but there was little continuity between the layers. In contrast, potassium, phosphorus and nitrogen showed some striking trends from high to low levels within a layer, which were traceable through two or more layers, especially deeper in the peat. Dry weight and percentage water content also showed trends across the block, particularly in the dead moss zone, although the patterns of distribution on the surface were rather more variable. The coefficients of variation for dry weight were large, varying from 13 to 25% within the profile, compared with those for percentage water content, which ranged from 16% in the surface layer to between 5 and 8% below the surface. Thus there is a considerable small scale heterogeneity over a range of 20 cm, which could have important consequences both for the moss and lichen plants and for the fauna.

Discussion

All the previously published results of chemical analyses of moss-turf material from Signy Island refer to samples collected during the early and mid 1960s. Most of the analyses were performed on small numbers of samples collected at one or two times of the year. Only Northover and Grimshaw (1967) have reported on a series of samples collected regularly over a period of one year. The present results can be discussed from three points of view: first, in relation to these previous studies; second, in relation to the biological processes taking place within the layered structure of the habitat; and finally, in relation to the consequences of small scale heterogeneity.

The physical and chemical environment of the moss-turf

The results of the physical and chemical analyses presented in this paper are derived from four blocks of contiguous samples, collected approximately at random from within a single moss-turf site (SIRS 1), during one summer season. They should not therefore, be used to describe the overall chemical conditions of the moss-turf, or to indicate temporal variation throughout the summer season in the absence of independent corroborative evidence. Although random sampling has been used in most previous studies, the size of a single block in this study was between one and two orders of magnitude greater than that of a single core used in earlier arthropod (Goddard, 1979), microbiological (Wynn-Williams, 1979) or nutrient content (Northover and Grimshaw, 1967) sampling programmes. The previous and present studies can be discussed in relation both to their results and to the different sampling strategies. Seasonal factors have been shown to affect the concentrations of ammonium nitrogen, extractable phosphorus, sodium and potassium in the upper 4 cm of the peat profile (Northover and Grimshaw, 1967) and the sodium and potassium contents of the growing shoots of a variety of moss and lichen species (Lewis Smith, 1978). Seasonal influences were also apparent on the concentrations of nitrogen and phosphorus in the present samples.

pH was the least variable chemical characteristic determined, and only the unusual fourth and fifth layers, and the contaminated surface layer samples (see nitrogen above) of the 20 February 1981 block showed much deviation. However, since the measurements were derived from dried samples, they cannot be compared confidently with recent measurements made *in situ*, or on fresh material (for example Wynn-Williams, 1983).

The sodium concentration in the upper layers of the moss-turf profile from Signy Island has been consistently determined at between 0.09 and 0.16% of dry weight: the overall range in the present study was 0.06–0.21%. The major source of sodium is marine, via precipitation and storm driven sea spray. Allen and others (1967) showed that most of the total sodium was either in soil solution or was readily extractable, and thus the elevated levels in the surface layer of the 20 February 1981 block are considered to be only the transitory effects of a previous storm. During the summer, the sodium would be rapidly leached, but in autumn, when the ground was frozen, sodium would accumulate until leached the following spring (Northover and Allen, 1967).

Potassium, in contrast to sodium, is present mainly in the moss-turf in a non-extractable form and the major source of supply is from the breakdown of the parent rock (Allen and others, 1967). The present study showed that potassium concentration was relatively high in the surface layer (overall range, 0.19–0.45%), but that the concentration decreased rapidly below the surface. The high levels of potassium encountered in the lower layers of the 20 February 1981 block are atypical. Lewis Smith (1978) showed that potassium concentration in the apical 10 mm of the growing shoots of *Chorisodontium* and *Polytrichum* was two to three times that in the 10–20 mm section. Thus the vegetation is actively concentrating potassium at the surface and it can therefore be inferred that its availability is limited.

The present study shows that calcium concentration increased steadily to a depth of 9 cm, with surface values being in the range 0.07–0.18%, increasing to a maximum of over 0.3% at 9 cm. Most previously published values for surface vegetation and underlying peat are higher than those found in the present study, ranging from 0.22 to 0.29% for surface vegetation, although the values reported by Lewis Smith (1978) for growing shoot material are mostly within the range of the present study. Higher calcium concentrations were evident in the deeper peat layers analysed by Holdgate and others (1967). In general, calcium concentrations appear to be very variable, with the differences in accumulation, between both plant species and sites, not being related to the calcium content of the parent material (Holdgate and other, 1967; Lewis Smith, 1978).

Total concentrations of phosphorus and nitrogen were strongly correlated in all four blocks of samples in the present study, and, in both, seasonal trends were apparent. Determinations of total phosphorus for the surface layers of all four blocks ranged from 0.04 to 0.13%, and most previously published values are towards the upper limit of this range, or sometimes above it. The range of typical nitrogen values determined (0.37–1.65%) compared well with the range (0.57–2.0%) from previous studies of uncontaminated sites. Extractable phosphate and ammonium nitrogen have both been shown to increase during the winter, but concentrations declined rapidly following the spring thaw (Northover and Allen, 1967). The present data suggest that, for nitrogen at least, leaching of extractable nitrogen must be important, since the results (Fig. 3a) show that the December 1980 levels of nitrogen were very much higher than those during January and February 1981 (except for a localized high concentration of nitrogen in the 20 February 1981 block, resulting from a bird pellet or dropping). The mean levels of phosphorus in December 1980 were generally higher than those in blocks sampled later in the season, except for the unusually high levels in the lower layers of the 20 February 1981 block and the surface layers of both February blocks. The proportion of phosphorus that can be leached from the system in spring is uncertain. Allen and others (1967) showed that most of the phosphorus in the living moss and in the peat was non-extractable, but their determinations were based on samples collected in February when phosphorus levels are seasonally low. The extent to which the ratio of extractable to non-extractable phosphorus varies throughout the year is unknown.

Allen and others (1967) suggested that the physical weathering of the rocks provided an important source of potassium and calcium for the Signy Island vegetation and soils, and that the fauna supplied the nitrogen and phosphorus. With the published data available, one could only speculate on the relative importance of leaching, rock weathering, faunal input or microbial fixation to the nutrient budget or movement within a moss-turf habitat. Such a study would make an important contribution to the understanding of the functioning of the system.

The data for the first three blocks behaved similarly, but contrasted with the data for the fourth block. In particular, the fourth and fifth layers of the 20 February 1981 block were atypical for most environmental features. Assuming that the moss growth rate was unaffected, and that the rate of subsequent accumulation lay between 1 and 2 mm per annum (Fenton, 1980), then the event affecting the moss-turf at this site would have occurred between 25 and 50 years ago. No animal remains, for example bones, fur or feathers were obvious and it is possible that previous human activity, for example the remains of a small fire, was the cause.

Vertical zonation in the moss-turf

Usher and Booth (1984) proposed that the arthropods inhabiting the moss-turf could be divided into two quantitatively different communities, inhabiting the surface layer, termed the green moss zone, and the layers below 3 cm, termed the dead moss zone. Sample dry weight, weight of water, percentage water content, calcium and potassium all showed marked trends over, at least, part of the depth range. The rapid change in dry weight, water content and potassium from the surface to the second and third layers suggested that some form of zonation would be appropriate for the habitat, as well as for the arthropods inhabiting it. The results of the principal component analyses showed that, for normal profiles, the greatest source of variation in the physical and chemical environment of the moss-turf can be accounted for by depth. However, the effects are not directly proportional to depth. Below 3 cm the changes are very gradual and the habitat appears to change very little, as shown by the strongly overlapping polygons of the four lower layers in Figs. 5 and 6. The top layer samples are very distinct from the rest of the profile, and the principal components analyses clearly separated these samples from the remainder. The data from the second layer are intermediate between the surface and the deeper layers, but the polygons enclosing the samples of this layer lay adjacent to the deeper layer polygons, although they only overlapped to a limited extent (Table II). These results suggest that the changes in the character of the moss-turf profile, from the surface down into the peat, are not directly proportional to depth, but are a step function. The surface layer (0–1.5 cm) of the profile, termed the green moss zone, is primarily the site of production. The layers below 3 cm deep, termed the dead moss zone, are primarily associated with decomposition and an active microbial population. The moss in this latter zone retains its fibrous nature and, although some rhizoids and stems are probably living and active in water transport, the leaves are dead. The intermediate nature of the second layer is a sampling artifact, resulting from cutting the cores at 1.5 cm intervals to enable comparisons to be made with previous arthropod work (Goddard, 1979; Block, 1982) where 3 cm intervals were cut from cores. Thus the rapid transition from the green moss to the dead moss zone occurs within the second layer: due to the position of the polygons in Figs. 5 and 6 it can be assumed that the transition is nearer to the upper than the lower limit of this layer, i.e. about 2 cm deep in the profile.

These concepts are not entirely new, since Holdgate and others (1967) and Allen and others (1967) clearly recognized the importance of zonation when they distinguished three organic zones in their chemical analyses of moss and peat from moss-turf habitats. The upper layer of 'living moss', about 8 cm thick, was divided into the 'surface green' layer and the 'underlying brown' layer, which consisted of firm, brown material retaining the fibrous structure of the parent vegetation. Below 8 cm, there was a 'peat' layer, in which the moss stems were still distinct, and this overlay a basal, almost structureless and more mineral brown soil. The upper part of this looser peat layer, although structurally distinct from the fibrous brown material, did not appear to differ chemically from the brown layer in the analyses reported here.

Small scale heterogeneity in the moss-turf

Most previous analytical studies of material from the maritime Antarctic have been concerned with determining the nutrient contents of a variety of plant and soil types from a variety of habitats, and hence the number of samples from any one area is small. Thus, although they give a general idea of the levels of nutrients in particular Antarctic habitats, and enable comparisons to be made between different areas, no attempts have been made to examine the level of small scale heterogeneity within a habitat. In the moss-turf of SIRS 1, most of the arthropod populations are strongly aggregated (Usher and Booth, 1984), and it is only studies of small scale variation that can explore the relationships between the physical and chemical environment, the occurrence of various plant species, and the arthropod populations living within the moss-turf.

To what extent is the observed heterogeneity of the physical and chemical characteristics of the moss-turf reflected in the species of moss growing at the surface of each core? One might expect there to be differences in the characteristics of the peat formed by the two major moss species. In the December 1980 block, *Polytrichum* cover is high on one side of the block, and low on the other. *Polytrichum* cover was positively correlated with water content, potassium, phosphorus and nitrogen, and negatively correlated with dry weight (Table I). The principal components analysis also suggested that there was an association of *Polytrichum* cover and pH. This suggests that peats formed by the two moss species do differ. However, five of the eleven significant correlations in Table I involving *Polytrichum* (and five of the six coefficients significant at the 0.1% probability level) are in the December 1980 block, and the correlations in the other three blocks fail to provide any corroboration.

Usher (1983) showed that more than one scale of vegetation cover pattern occurred in the moss-turf. There was a small scale of pattern at about 20 cm, the size of the blocks sampled, and a larger scale pattern between 1.2 and 2 m. Although no consistent correlations between the moss cover and the chemical composition of the peat was apparent at the small scale of pattern, it is possible that an effect could be operating at the larger scale of pattern. Usher and Booth (in prep.) showed that the arthropods also exhibited varying scales of pattern, and that correlations between the arthropods and the physical environmental features were more apparent at larger scales of 40–50 cm and over. Thus the components of the system cannot be regarded as randomly scattered throughout the system, and therefore future studies should take into consideration the varying scales of heterogeneity of the environment, of the mosses and lichens, and of the arthropods, when sampling or experimental strategies are devised.

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References

ALLEN, S. E., GRIMSHAW, H. M. *and* HOLDGATE, M. W. 1967. Factors affecting the availability of plant nutrients on an Antarctic Island. *Journal of Ecology*, **55**, 381–96.

ALLEN, S. E., GRIMSHAW, H. M., PARKINSON, J. A. *and* QUARMBY, C. 1974. *Chemical analysis of ecological materials*. Blackwell, Oxford.

ALLISON, J. S. *and* LEWIS SMITH, R. I. 1973. The vegetation of Elephant Island, South Shetland Islands, *British Antarctic Survey Bulletin*, Nos. 33 and 34, 185–212.

BAKER, J. H. 1972. The rate of production and decomposition of *Chorisodontium aciphyllum* (Hook. f. & Wils.) Broth. *British Antarctic Survey Bulletin*, No. 27, 123–9.

BLOCK, W. 1982. The Signy Island terrestrial reference sites: XIV. Population studies on the Collembola. *British Antarctic Survey Bulletin*, No. 55, 33–49.

BOOTH, R. G. *and* USHER, M. B. (1984). Arthropod communities in a maritime Antarctic moss-turf habitat: effects of the physical and chemical environment. *Journal of Animal Ecology*, **53**, 879–893.

COLLINS, N. J. 1976. Growth and population dynamics of the moss *Polytrichum alpestre* in the maritime Antarctic. Strategies of growth and population dynamics of tundra plants 2. *Oikos*, **27**, 389–401.

DAVIS, R. C. 1981. Structure and function of two Antarctic terrestrial moss communities. *Ecological Monographs*, **51**, 125–43.

FENTON, J. H. C. 1980. The rate of peat accumulation in Antarctic moss banks. *Journal of Ecology*, **6**[illegible] 211–28.

FENTON, J. H. C. 1982. The formation of vertical edges on Antarctic moss peat banks. *Arctic and Alpine Research* **14**, 21–6.

FENTON, J. H. C. *and* LEWIS SMITH, R. I. 1982. Distribution, composition and general characteristics of the moss banks of the maritime Antarctic. *British Antarctic Survey Bulletin*, No. 51, 215–36.

GAUCH, H. G. 1982. Noise reduction by eigenvector ordinations. *Ecology*, **63**, 1643–9.

GODDARD, D. G. 1979. The Signy Island terrestrial reference sites: XI. Population studies on the Acari. *British Antarctic Survey Bulletin*, No. 48, 71–92.

HOLDGATE, M. W. 1977. Terrestrial ecosystems in the Antarctic. *Philosophical Transactions of the Royal Society of London, Series* B, **279**, 5–25.

HOLDGATE, M. W., ALLEN, S. E. *and* CHAMBERS, M. J. G. 1967. A preliminary investigation of the soils of Signy Island, South Orkney Islands. *British Antarctic Survey Bulletin*, No. 12, 53–71.

JEFFERS, J. N. R. *and* HOLDGATE, M. W. 1976. Signy Island: a case study of ecological characterisation. *Merlewood Research and Development Paper*, No. 66.

LEWIS SMITH, R. I. 1978. Summer and winter concentrations of sodium, potassium and calcium in some maritime Antarctic cryptogams. *Journal of Ecology*, **66**, 891–909.

LONGTON, R. E. 1967. Vegetation in the Maritime Antarctic. *Philosophical Transactions of the Royal Society of London, Series* B, **252**, 213–35.

LONGTON, R. E. 1970. Growth and productivity of the moss *Polytrichum alpestre* Hoppe in Antarctic regions. (*In* HOLDGATE, M. W., *ed. Antarctic Ecology*. Academic Press, London, 818–37.)

NORTHOVER, M. J. *and* ALLEN, S. E. 1967. Seasonal availability of chemical nutrients on Signy Island. *Philosophical Transactions of the Royal Society of London, Series B*, **252**, 187–9.

NORTHOVER, M. J. *and* GRIMSHAW, H. M. 1967. Some seasonal trends in nutrient content of the soils of Signy Island, South Orkney Islands. *British Antarctic Survey Bulletin*, No. 14, 83–8.

TILBROOK, P. J. 1973. The Signy Island terrestrial reference sites: I. An introduction. *British Antarctic Surv[illegible] Bulletin*, Nos. 33 and 34, 65–76.

USHER, M. B. 1983. Pattern in the simple moss-turf communities of the Sub-Antarctic and maritime Antarctic. *Journal of Ecology*, **71**, 945–58.

USHER, M. B. *and* BOOTH, R. G. 1984. Arthropod communities in a maritime Antarctic moss-turf habitat: three-dimensional distribution of mites and Collembola. *Journal of Animal Ecology*, **53**, 427–41.

USHER, M. B. *and* BOOTH, R. G. (in prep.). Arthropod communities in a maritime Antarctic moss-turf habitat: multiple scales of pattern in the mites and Collembola. (Submitted to *Journal of Animal Ecology*).

WALTON, D. W. H. *and* LEWIS SMITH, R. I. 1980. The chemical composition of South Georgian vegetation. *British Antarctic Survey Bulletin*, No. 49, 117–35.

WYNN-WILLIAMS, D. D. 1979. Techniques used for studying terrestrial microbial ecology in the maritime Antarctic. (*In* RUSSELL, A. D. *and* FULLER, D., *eds. Cold tolerant microbes in spoilage and the environment. Society for Applied Bacteriology Technical Series*, 13, 67–81.)

WYNN-WILLIAMS, D. D. 1983. Distribution and characteristics of *Chromobacterium* in the maritime and sub-Antarctic. *Polar Biology*, **2**, 101–8.