SOIL MICROBIOLOGICAL STUDIES AT SIGNY ISLAND, SOUTH ORKNEY ISLANDS

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ABSTRACT. The numbers of heterotrophic bacteria and fungi were determined at six sites on Signy Island over a 2 year period. Total and viable microbial counts at 10° and 25° C were compared within and between sites, and a correlation matrix including soil variables was prepared. Unlike direct bacterial counts, viable bacterial counts did not correlate with either fungal count or any soil factor except total phosphorus. Conversely, all fungal counts correlated to some extent with soil variables. Microbial populations at Signy Island, although distinctive, were comparable with other maritime Antarctic areas and various Arctic sites studied in the International Biological Programme. Some fungal isolates had a bi-polar distribution.

MICROBIOLOGICAL investigations of terrestrial habitats in the maritime Antarctic were pioneered by Ekelöf (1908), Tsiklinsky (1908) and Pirie (1912). Several years elapsed before further studies were made of the fungi (Corte and Daglio, 1963, 1964) and total microbial populations of the Antarctic Peninsula (Margni and Castrelos, 1963, 1964; Richter and [illegible]ers, 1967; Boyd and Rothenberg, 1968; Boyd and others, 1970; Cameron and Benoit, 1970; Cameron and others, 1972). Similar investigations have also been made of islands in the Scotia arc, namely South Georgia (Dennis, 1968; Smith and Stephenson, 1975) and Signy Island, South Orkney Islands (Heal and others, 1967; Baker, 1970*a*, *b*; Latter and Heal, 1971; Baker and Smith, 1972).

The aims of the present survey at Signy Island were to provide basic information on microbial distributions and their seasonal variation using data collected during the period December 1962 to March 1965. This enables comparisons to be made between Signy Island in the maritime Antarctic zone and other, mainly northern, tundra sites studied during the International Biological Programme (IBP) (Holding and others, 1974).

The general topography and climate of Signy Island have been described by Holdgate (1967, 1977), Collins and others (1975) and characterized by Jeffers and Holdgate (1976). Antarctic soil characteristics in general (Ugolini, 1970) and those of Signy Island in particular have been investigated by Allen and Northover (1967), Holdgate and others (1967) and related to other IBP sites by Brown and Veum (1974). During the austral summer about 50% of the surface of Signy Island is free from snow and ice. The lowland and coastal zone varies from bare rock and mineral soil to extensive areas of closed bryophyte communities. Under some of the turf-forming mosses deep organic layers have accumulated. The range of soils thus provides diverse habitats for micro-organisms.

SAMPLE SITES

Six different soil types were selected for study. Fig. 1 indicates the locations of the sampling sites, and their main characteristics are given in Table I and in the following notes.

Hut bank site (site 1)

This was a mixed *Polytrichum alpestre–Chorisodontium aciphyllum* community which, on Signy Island, is the most prominent feature of fairly well-drained stable slopes facing from west through north to east, which thus receive optimal radiation. Moreover, these mosses are the most significant peat-formers on Signy Island, frequently overlying peat deposits up to 2 m deep. The moss banks are often extensive, giving continuous cover commonly for 50–100 m along rocky slopes in several localities. The surface of these banks is often

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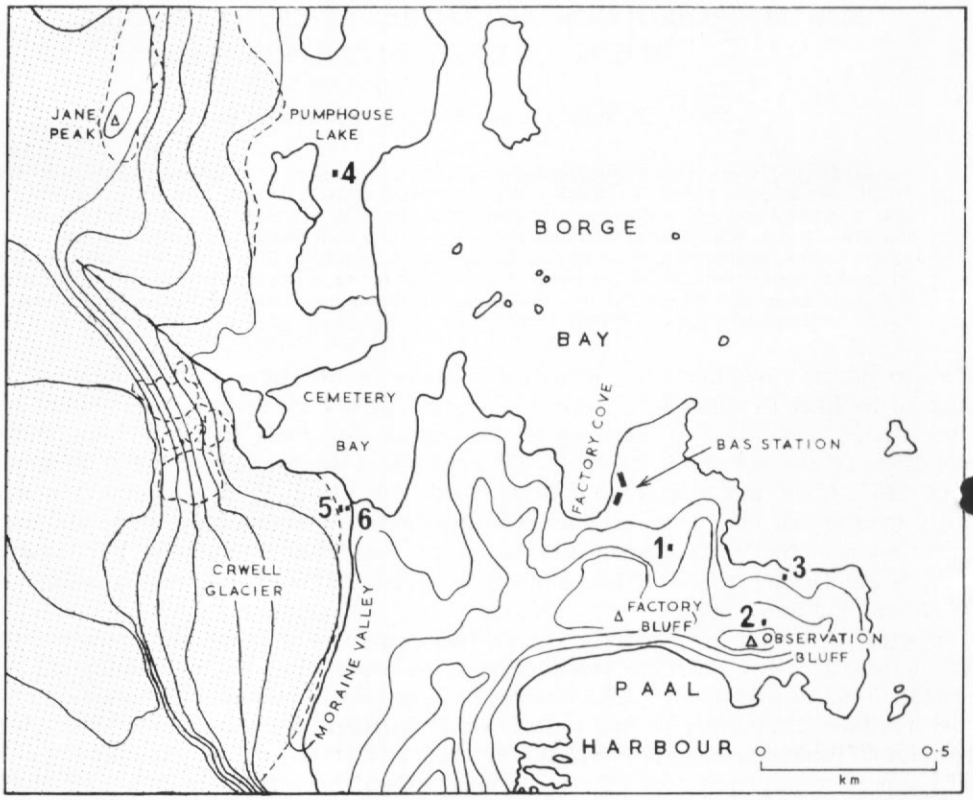

Fig. 1. Map of the area studied at Signy Island showing the locations of the sample sites.
1. Hut bank. 2. Mountain. 3. Grass. 4. Marble knolls: a. marble; b. schist. 5. New moraine. 6. Old moraine. The contour interval is 100ft. Stippled areas are permanent ice.

rippled and hummocked, and dissected by long sinuous fissures resulting from frost heave. The relative proportions of *P. alpestre* and *C. aciphyllum* vary according to slope, aspect and soil-moisture content. At the study site beneath Factory Bluffs the proportions of the two species were approximately equal.

Mountain site (site 2)

This site was a large (10 m by 10 m) patch of moss consisting almost entirely of *P. alpestre* on a col between Observation Bluff and Factory Bluffs at a somewhat higher altitude and considerably more exposed situation than site 1.

Grass site (site 3)

The two vascular plants of Signy Island, a grass, *Deschampsia antarctica* and a herb, *Colobanthus quitensis*, grow in the coastal zone in flushed sites sloping to the north and sheltered from the south, and hence effective radiation traps. The soil formed beneath these plants shows some degree of mixing in contrast to the highly organic layers beneath the moss turves. This site was located in a shallow gully near Pinder Gully, where the two species

TABLE 1. SOIL-PROFILE DESCRIPTIONS OF THE SAMPLE SITES AT SIGNY ISLAND

Site	*Vegetation*	*Horizons*	*Horizon depths* (cm)	*Colour*	*Texture*	*Structure*	*Drainage*	*Consistency*	*Parent material*	*Mean % H_2O (of fresh weight)*	*pH*
1. Hut bank (SHB)*	Moss bank dominated by *P. alpestre* and *C. aciphyllum*	Green shoots Peat Basal peaty soil	0–1 1–15 15–26	Brown Dark brown; upper boundary clear	Peaty	Fibrous	Poor	Not greasy	Quartz-mica-schist	82.9 86.4 76.8	4.8–5.0
2. Mountain (SMt)	Moss mat dominated by *P. alpestre* and lichens	Green shoots Peat Basal peaty soil	0–1 1–12 12–17	Dark brown Very dark brown; upper boundary clear	Peaty	Fibrous	Poor	Not greasy	Quartz-mica-schist	81.0 83.5 72.3	5.1–5.2 5.4
3. Grass (SG)	Turf of *D. antarctica* with some *C. quitensis*	Brown earth	0–10	Dark brown	Loamy with a little small gravel	Crumb; weak strength	Free	Friable	Quartz-mica-schist	50.6	5.4–5.6
4. Marble knolls a. Marble (SMK)	Nil	Almost pure nodular marble with a little acid schist		Brownish yellow	Gravelly with many larger stones	Structureless	Excessive	Loose	Marble	7.3	8.6
b. Schist (SMKS)	Sparse black and orange crustose lichens and grey-green fruticose lichens	Almost pure acid schist with a little marble		Grey	Silty clay loam with many stones	Cloddy; moderate strength	Poor	Sticky	Quartz-mica-schist	12.5	8.9
5. New Moraine (SNM)	Mostly bare, very little moss and few lichens	Surface till		Grey	Silty clay loam with many large stones	Cloddy; moderate strength	Very poor	Sticky	Drift of predominantly acid schist, amphibolite and marble	12.3	9.2
6. Old moraine (SOM)	60% cover of mosses with some lichens	Surface till		Greyish brown	Silty clay loam with many large stones	Crumb; weak strength	Very poor	Friable	Drift of predominantly acid schist, amphibolite and marble	19.3	6.4

* Site abbreviations of the International Biological Programme (Holding and others, 1974).

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were particularly well established, the grass forming a continuous cover over an area of approximately 1 m square.

Marble knolls site (site 4)

In the vicinity of Pumphouse Lake in Three Lakes Valley, there is a series of prominent marble knolls. Unlike the other mineral soils studied, the marble soil was very thin and did not appear to contain much drift, being formed instead from the bedrock *in situ*. Because the marble bands are narrow, there is juxtaposition of calcicole communities with *Andreaea* carpets and other vegetation developed on the adjacent schists. Samples were taken from the soils overlying both marble and schist.

New and old moraine sites (sites 5 and 6)

Many of the Signy Island soils have resulted from glacial debris which has been re-worked by solifluction and outwash. These two sites were located on such material which formed the most recent moraines of Orwell Glacier at the junction of Moraine Valley and Cemetery Bay. These moraines, which rise about 15 m from the sea, have been tentatively aged at 190±15 years for the inner and 390±90 years for the outer (Baker, 1972). The inner younger moraine (new moraine site) consists of raw glacial debris which was subject to considerable frost movement. The material varied widely in particle size and showed no layering. The surface was almost devoid of plants, supporting only a few tufts of the mosses *Pohlia cruda*, *Tortula* spp. and *Dicranoweisia*, with small patches of crustose lichen on the larger rocks.

The outer older moraine (old moraine site) is much more stable and consists of coarser material. The surface stability has allowed plant colonization with up to 60% cover in places. *Drepanocladus* and *Tortula* spp. dominated the mosses and there were various lichens on the rocks. The increase in plant cover provides organic matter for incorporation in the soil but nevertheless the nutrient status of similar material (Holdgate and others, 1967) is low compared with the other sites.

Methods

On each site an area was marked out using poles, so that the sampling areas could be located in winter. At sites 1, 2 and 3 the sampling area was *c.* 10 m square but on the other sites the sampling area was smaller owing to the restricted space available. The sampling procedure and subsequent treatment varied according to the nature of the sites.

On sites 1, 2 and 3 the substrate permitted cores to be taken. In summer, a simple metal corer 3.8 cm in diameter and 30 cm height was inserted by hand and in winter, when the ground was frozen, an ice auger of the same diameter and rotated by a carpenter's brace was used. Each sample consisted of six cores. On sites 4, 5 and 6 the nature of the soil prevented coring. During the summer months, small samples were collected with a spatula which had first been pushed into adjacent soil two or three times. In winter, when the soils were frozen, samples were chipped off with a chisel and hammer. In all cases, cores or fragments were transported back to the laboratory in pre-sterilized aluminium containers. The samples were thawed out overnight at approximately 1° to 4° C.

Cores from sites 1, 2 and 3 were sub-sampled by removal of three layers, each 1.3 cm thick, from different depths. The upper sub-sample was from just below the green surface layer at all three sites. At sites 1 and 2, the middle sub-sample was taken between 6.3 and 7.6 cm and the lower one at a variable depth but always from the basal peaty soil. At site 3 the middle sub-sample was taken between 3.8 and 5.1 cm and the lower one between 7.6 and 8.9 cm. From each sub-sample three portions (each approximately 1.0–1.5 g fresh weight) were taken and treated as follows:

i. One portion was weighed, dried at 105° C and re-weighed to determine the moisture content of the sub-sample.

ii. One portion was either homogenized (sites 1, 2 and 3) or ground in a flamed pestle and mortar (sites 4, 5 and 6) in sterile distilled water. The number of bacteria and length of fungal mycelium in the resulting suspension were determined by the agar-film direct-count method (Jones and Mollison, 1948). Five films per horizon were stained for 1 1/4 h with phenolic aniline blue prior to mounting. Bacterial numbers in ten fields per film were determined by counting the colonies within a grid inserted into the microscope eyepiece and an attempt was made to count rods and cocci separately. The amount of fungal mycelium was determined by projecting magnified images of the agar films on to a screen and measuring the lengths of the individual hyphae with an opisometer. Thus, lengths of mycelium per unit weight of soil were assessed by taking into account the area of the fields observed, the depth of the agar film, the number of fields viewed, the total volume of suspension observed and the degree of dilution of the original soil sample. An attempt was made to differentiate between stained and unstained mycelium.

iii. A third portion was also either homogenized or ground up in sterile distilled water as in ii above. A dilution count by the pour-plate method was then performed to determine the numbers of bacteria in the original sub-sample, and the fungal colonies derived from spores and hyphal fragments after homogenization. Tryptone soya agar was used for the triplicate bacterial plates. Apart from its high pH (7.0), this medium was not inhibitory to yeasts, which may therefore constitute a small proportion of the dilution count. Czapek-Dox agar plus 0.5% Bacto yeast extract and 0.007% rose bengal was used for the triplicate fungal plates. Initially, all the dilution plates were incubated at 25° C. Towards the end of the programme, a cooled incubator was available and duplicate sets of plates were then prepared, one being incubated at 25° C and the other at 10° C. After an incubation period which varied with site, incubator temperature and whether fungi or bacteria were being cultured, the numbers of fungal and bacterial colonies on the plates were recorded. Some of the fungi were sub-cultured on to fresh plates, cleaned and put on Oxoid potato-glucose agar slopes in Universal McCartney bottles for later identification. Fungal isolates were also obtained from soil-crumb plates prepared according to the method of Warcup (1950).

The dilution and direct counts are expressed on both a dry weight and a volume basis. Results per unit volume were calculated after determining the bulk density of peaty soils by dimensions and dry weight, and of mineral soils by dry weight and displacement.

Statistical analyses of the data

Analysis of each group of microbial data (e.g. dilution count at 10° C of fungi g^{-1} dry weight of upper peat from hut bank) by ranking and plotting on arithmetic probability paper (Chartwell No. 5571) showed that untransformed, log-transformed and square-root-transformed data were all approximately normally distributed. Plots of sample means against their variances, calculated by analysis of variance of untransformed data, showed that log-transformation was the most appropriate. Additional analyses of variance of log- and square-root-transformed data all subjected to Bartlett's test, confirmed that the log-transformed data were the most homogeneous. However, in nearly all cases the significance of the F ratios was the same for both log-transformed and untransformed data. The slight improvement in homogeneity of the data caused by log transformation was therefore not significant, and the summarized data presented and analysed here are in their untransformed state.

Results

The counts of fungal and bacterial populations are summarized in Tables II and III. The environmental parameters of these sites are summarized in Table IV; pH, percentage loss on ignition, percentage total nitrogen and percentage total phosphorus are based on data from comparable sites at Signy Island (Holdgate and others, 1967), whereas percentage moisture is a mean value derived from the moisture content prevailing at each site during sampling. In the following consideration of the results, the main patterns of distribution and fluctuation in microbial populations will be examined, but interpretation is limited by the high variability of the data and by the limited replication both within and between sites. However, the peat site at hut bank was sampled intensively and provides a measure of within-site variation. The results therefore provide a preliminary description of the level of microbial populations in relation to each other and their environment.

An analysis of variance examined the modes of expression (weight or volume basis) of microbial counts and the effects of incubation temperature on microbial populations at each of the six sites (Table V). A similar analysis determined the presence of distinct psychrotolerant (showing significant growth after 14 d at 10° C) and mesophilic (significant growth at over 20° C; Ingraham and Stokes, 1959) populations in hut bank soils as summarized in Table VI.

A correlation and regression analysis between microbial numbers and environmental variables was utilized to explore possible linear or exponential relationships, and a matrix for linear (Table VII) and selected logarithmic (Table VIII) correlations is presented. Significant associated regression coefficients are given in Table IX. It is important to recognize that correlation between variables in such data does not necessarily imply a causal relationship.

Variation in population size between sites

The six sites, summarized in Table I, differed greatly in topography, soil type and substrate quality. These differences are reflected in the analysis of variance of microbial populations, incubated at both 10° C (psychrotolerant) and 25° C (mesophilic), which demonstrate significant differences in population size between sites relative to the within-site variation (Table V). The comparability of weight and volume-based analyses of variance is consistent with the significant correlations found between all weight and volume-based expressions of the microbial data (Table VII). Differences in both viable and direct fungal and bacterial population levels are illustrated in Figs 2 and 3 on a volume basis, which facilitates comparison between such dissimilar soils. For the fungi, the two peat soils (sites 1 and 2) followed by the grassland soil (site 3) exhibited the highest counts, whereas the mineral soils (sites 4, 5 and 6) generally showed lower counts, although direct counts of marble (site 4a) and grassland (site 3) populations were similar. The old moraine (site 6) fungal population was consistently higher than that of the new moraine (site 5), probably owing to its greater organic content.

The bacterial population of the grassland soil clearly predominated over that of all other sites (Fig. 3), and again the old moraine population was higher than that in the new moraine site. In the peat sites, the viable bacterial population was low relative to the direct count, possibly due to limitations of the culturing method. These features are substantiated by the results of correlation and regression analyses given in Tables VII to IX. When viable counts are expressed g^{-1} of organic matter (Table X), which is potentially available for decomposition, the fungal population sizes generally follow the same distribution pattern as the conuts on a volume basis (Fig. 2). The exception is a high fungal count at 10° C in the old moraine site relative to low organic content. This may be due to minerals not being rate limiting. Bacterial data in Table X and Fig. 3 also follow a similar pattern but with proportionally

TABLE II. FUNGAL POPULATION MEASUREMENTS BY TWO METHODS FOR THE SIX SITES AT SIGNY ISLAND

Site	*Horizon*	*Dilution (viable) count*				*Direct (total) measurement*		
		Mean (±SE) × 10⁻³ number of colonies (g^{-1} dry weight)		*Mean (±SE) × 10⁻³ number of colonies* (cm^{-3})		*Mean (±SE) length* (m)		*Stained hyphae* (%)
		10° C	25° C	10° C	25° C	(g^{-1} dry weight)	(cm^{-3})	
1. Hut bank	Upper peat*	2 065±207	1 015±200	165±17	81±16	6 328±1 194	506± 95	88.7
	Mid peat*	888±107	219± 31	71± 9	18± 2	8 121±2 381	650±190	73.5
	Basal peaty soil	—	320±135	—	26±11	938	75	81.3
2. Mountain	Upper peat*	940	158± 50	113	19± 6	2 783± 410	334± 49	84.4
	Mid peat*	192	74± 47	23	9± 6	3 742± 107	450± 13	76.7
	Basal peaty soil	—	296±275	—	36±33	796± 22	96± 3	79.2
3. Grass	Upper soil*	119± 40	11± 4	85±28	8± 3	288± 90	205± 64	97.6
	Mid soil*	143± 94	8± 3	101±67	6± 2	344± 244	244±173	96.7
	Lower soil	—	8± 3	—	6± 2	154± 90	109± 64	96.3
4. Marble knolls	Marble soil*	3	0.5±0.1	3	0.7±0.2	144± 13	195± 17	37.9
	Schist soil*	14	6± 2	21	9± 2	44± 8	63± 11	73.0
5. New moraine	Surface soil*	3	0.02±0.01	4	0.03±0.02	4	6	100.0
6. Old moraine	Surface soil*	22	0.5±0.3	33	0.7±0.4	84	125	99.2

* Horizons considered in the correlation analyses (Tables VII–IX).

TABLE III. BACTERIAL POPULATION ESTIMATES BY TWO METHODS FOR THE SIX SITES AT SIGNY ISLAND

Site	*Horizon*	*Dilution (viable) count*				*Direct (total) count*	
		Mean (±SE) × 10⁻⁶ number of colonies (g^{-1} dry weight)		*Mean (±SE) × 10⁻⁶ number of colonies* (cm^{-3})		*Mean (±SE) × 10⁻⁹ number of bacteria* (g^{-1} dry weight)	*Mean (±SE) × 10⁻⁹ number of bacteria* (cm^{-3})
		10° C	25° C	10° C	25° C		
1. Hut bank	Upper peat*	2.5±0.8	5.1±1.0	0.2 ±0.1	0.4 ±0.1	67.0±10.3	5.4±0.8
	Mid peat*	0.2±0.02	0.4±0.1	0.01±0.002	0.04±0.01	80.5± 1.2	6.4±0.1
	Basal peaty soil	—	1.3±0.6	—	0.1 ±0.05	43.3	3.5
2. Mountain	Upper peat*	0.2	0.9±0.4	0.02	0.1 ±0.04	58.8±11.3	7.1±1.4
	Mid peat*	0.3	0.2±0.1	0.04	0.03±0.01	85.4±10.9	10.2±1.3
	Basal peaty soil	—	0.3±0.1	—	0.04±0.01	44.9± 0.2	5.4±0.02
3. Grass	Upper soil*	23.4±0.5	10.5±3.7	16.6 ±0.4	7.4 ±2.6	17.0± 3.8	12.1±2.7
	Mid soil*	2.9±2.0	0.9±0.2	2.1 ±1.4	0.7 ±0.2	22.9±13.5	16.3±9.6
	Lower soil	—	0.7±0.4	—	0.5 ±0.3	13.0± 7.2	9.2±5.1
4. Marble knolls	Marble soil*	0.3	0.2±0.1	0.4	0.2 ±0.1	1.4± 0.4	1.9±0.6
	Schist soil*	4.3	2.3±0.5	6.1	3.3 ±0.7	1.1± 0.2	1.7±0.4
5. New moraine	Surface soil*	1.5	1.2±0.1	2.4	1.9 ±0.1	0.4	0.6
6. Old moraine	Surface soil*	2.5	1.7±0.1	3.7	2.5 ±0.2	6.3	9.4

* Horizons considered in the correlation analyses (Tables VII–IX).

TABLE IV. ENVIRONMENTAL VARIABLES FOR THE SIX SITES AT SIGNY ISLAND

Site/soil horizon	*pH*	*Loss on ignition* (%)	N (total) (%)	P (total) (%)	H_2O (% of fresh weight)
1. Hut bank (≡ Factory Bluffs)					
Upper: 1–5 cm brown peat*	4.5	97.3	1.08	0.07	82.88
Middle: 5–10 cm brown peat*	4.3	97.0	1.30	0.09	86.39
Basal peat: >15 cm	4.7	81.9	1.56	0.12	76.79
2. Mountain (≡ col between Observation Bluff and Factory Bluffs)					
Upper: 1–2 cm peat*	5.2	88.8	1.08	0.08	81.03
Middle: 2–6 cm peat*	5.2	88.8	1.08	0.08	83.53
Peaty soil: 6–8 cm	5.2	26.3	1.14	0.21	72.25
3. Grass (and *Colobanthus*)					
Upper: 1–5 cm mineral soil*	5.6	13.9	0.45	0.23	51.10
Middle: 5–10 cm mineral soil*	5.6	13.9	0.45	0.23	50.02
Deep loamy soil: >10 cm	5.4	13.5	0.60	0.27	47.49
4. Marble knolls					
Coarse marble soil*	8.5	1.6	0.06	0.15	7.30
Schist soil*	8.4	2.1	0.08	0.15	12.50
5. New moraine*	9.2	1.0	0.03	0.09	12.32
6. Old moraine*	6.0	2.0	0.07	0.17	19.26

* Data used in all computations of correlation of microbial and environmental parameters ($n = 10$). Data from Holdgate and others (1967).

lower populations g^{-1} of organic matter in the less organically rich sites, possibly due to the more alkaline mineral-rich conditions.

Variation in microbial populations with depth

The results in Tables II and III show no marked changes in vertical distribution of microbial populations, but dilution counts of bacteria were at a maximum in the surface horizon of each site, while both dilution and direct counts of fungi were highest in the upper two horizons at all sites. This trend of decreasing population and size with increasing depth contrasts with the increase in dilution counts of bacteria with increasing depth observed by Baker (1970*b*) at a peat site on Signy Island.

Effect of incubation temperature on population size

It is possible that the micro-flora of these maritime Antarctic sites is adapted to the prevailing low temperatures and that this could be reflected in counts obtained at the two incubation temperatures (10° and 25° C). The summary data (Table II) and Fig. 2 indicate

TABLE V. ANALYSIS OF VARIANCE BETWEEN MICROBIAL POPULATIONS FROM THE SIX SITES AT SIGNY ISLAND

Population	*Comparison*	*Degrees of freedom*	*Sums of squares*	*Mean square*	*F ratio*	*Significance* (error *P*)
Fungi						
Viable (10° C g^{-1})	Within	16	0.3×10^{13}	0.2×10^{12}		
	Between	9	1.0×10^{13}	2.0×10^{12}	9.748	<1%
Viable (25° C g^{-1})	Within	59	0.8×10^{13}	0.1×10^{12}		
	Between	12	0.9×10^{13}	0.8×10^{12}	5.976	<1%
Viable (10° C cm^{-3})	Within	16	0.3×10^{11}	2.0×10^{9}		
	Between	9	0.8×10^{9}	8.0×10^{9}	4.500	<5%
Viable (25° C cm^{-3})	Within	59	0.6×10^{11}	0.9×10^{9}		
	Between	12	0.5×10^{11}	5.0×10^{9}	4.686	<1%
Total (g^{-1})	Within	12	20×10^{6}	2.0×10^{5}		
	Between	12	200×10^{6}	20×10^{5}	9.073	<1%
Total (cm^{-3})	Within	12	0.2×10^{6}	0.2×10^{5}		
	Between	12	0.9×10^{6}	0.2×10^{5}	3.910	<10%
Bacteria						
Viable (10° C g^{-1})	Within	16	4.0×10^{9}	0.3×10^{7}		
	Between	9	0.9×10^{9}	10×10^{7}	37.801	<1%
Viable (25° C g^{-1})	Within	59	0.5×10^{9}	0.8×10^{7}		
	Between	12	0.6×10^{9}	5.0×10^{7}	6.259	<1%
Viable (10° C cm^{-3})	Within	16	0.5×10^{7}	0.3×10^{6}		
	Between	9	50×10^{7}	60×10^{6}	196.851	<1%
Viable (25° C cm^{-3})	Within	59	10×10^{7}	2.0×10^{6}		
	Between	12	30×10^{7}	20×10^{6}	9.198	<1%
Total (g^{-1})	Within	12	2×10^{5}	1.0×10^{4}		
	Between	12	20×15^{5}	20×10^{4}	13.333	<1%
Total (cm^{-3})	Within	12	0.3×10^{5}	0.2×10^{4}		Not significant
	Between	12	0.5×10^{5}	0.2×10^{4}	1.586	

TABLE VI. ANALYSIS OF VARIANCE BETWEEN BACTERIAL AND FUNGAL POPULATIONS IN HUT BANK SOILS WITH RESPECT TO INCUBATION TEMPERATURE

Peat depth	*Population*	*Comparison*	*Degrees of freedom*	*Sums of squares*	*Mean square*	*F ratio*
Upper	Dilution fungi (g^{-1})	Within	14	1.01×10^6	7.23×10^4	
	Incubation (10° and 25° C)	Between	7	1.26×10^6	1.26×10^6	17.435***
Mid	Dilution fungi (g^{-1})	Within	14	1.39×10^5	9.95×10^3	
	Incubation (10° and 25° C)	Between	7	3.22×10^5	3.22×10^5	32.322***
Upper	Dilution bacteria (g^{-1})	Within	14	2.84×10^7	2.03×10^6	
	Incubation (10° and 25° C)	Between	7	5.65×10^6	5.65×10^6	2.786
Mid	Dilution bacteria (g^{-1})	Within	14	1.34×10^5	9.54×10^3	
	Incubation (10° and 25° C)	Between	7	6.11×10^4	6.11×10^4	6.401*

*** Significant at $P < 0.001$ between counts at 10° and 25° C.
* Significant difference at $P < 0.05$ between counts at 10° and 25° C.

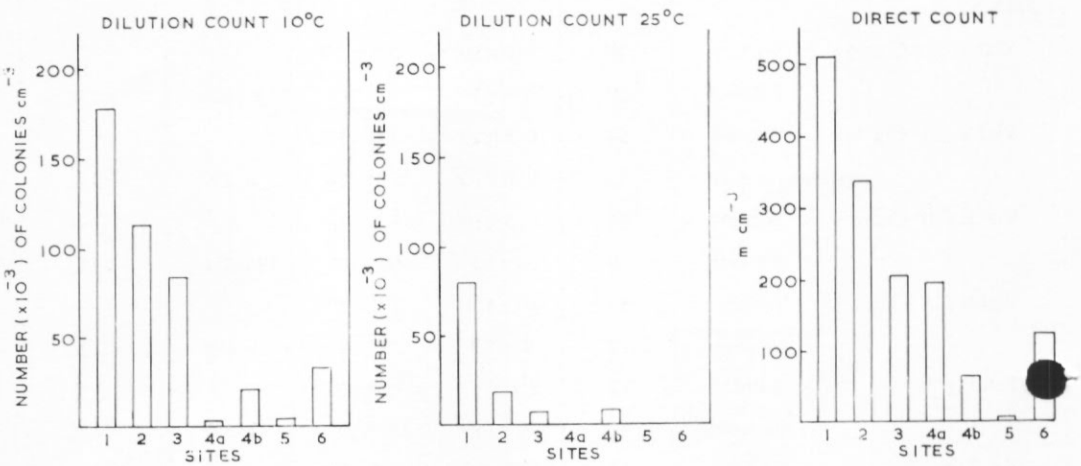

Fig. 2. Comparison of fungal counts, expressed on a volume basis, from the upper horizons of each site (see Fig. 1).

TABLE VII. SIGNIFICANCES OF CORRELATIONS BETWEEN MICROBIAL POPULATIONS AND SOIL PARAMETERS OF SIX SITES AT SIGNY ISLAND

1 Dilution bacteria (10° C g^{-1})															
xxx	2 Dilution bacteria (25° C g^{-1})														
xxx	xxx	3 Dilution bacteria (10° C cm^{-3})													
xxx	xx	xxx	4 Dilution bacteria (25° C cm^{-3})												
0	0	0	0	5 Direct bacteria (g^{-1})											
0	0	0	0	0	6 Direct bacteria (cm^{-3})										
0	0	0	0	0	0	7 Dilution fungi (10° C g^{-1})									
0	0	0	0	0	0	xxx	8 Dilution fungi (25° C g^{-1})								
0	0	0	0	0	0	xx	xx	9 Dilution fungi (10° C cm^{-3})							
0	0	0	0	0	0	xxx	xxx	xx	10 Dilution fungi (25° C cm^{-3})						
0	0	0	0	xxx	0	xxx	x	0	x	11 Direct fungi (m g^{-1})					
0	0	0	0	xxx	0	x	0	0	0	xxx	12 Direct fungi (m cm^{-3})				
0	0	0	0	−xx	−x	−x	0	−xx	0	−x	−xx	13 pH			
0	0	0	0	xxx	0	xx	0	0	x	xxx	xxx	−xx	14 % loss on ignition		
0	0	0	0	xxx	0	x	0	x	0	xxx	xxx	−xx	xxx	15 % N (total)	
xx	0	x	x	−x	0	0	0	0	0	−x	0	0	−x	0	16 % P (total)
0	0	0	0	xxx	0	x	0	x	0	xx	xxx	−xxx	xxx	xxx	0	17 % H_2O

0 No significant correlation; x $P<0.05$; xx $P<0.01$; xxx $P<0.001$; − Negative correlation.

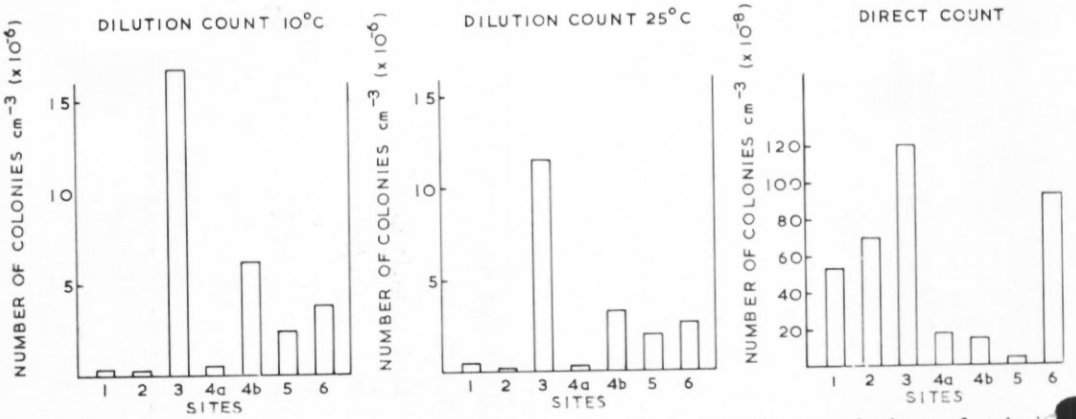

Fig. 3. Comparison of bacterial counts, expressed on a volume basis, from the upper horizons of each site (see Fig. 1).

TABLE VIII. SIGNIFICANCES OF CORRELATIONS BETWEEN $\log_{10}$ MICROBIAL COUNTS AND SOIL PARAMETERS OF SIX SITES AT SIGNY ISLAND

Microbial count	*pH*	*Loss on ignition*	N (%)	P (%)	H_2O (%)
Bacteria					
Dilution (10° C g^{-1})	0	0	0	x	0
Dilution (25° C g^{-1})	0	0	0	0	0
Dilution (10° C cm^{-3})	0	−xxx	−xx	xx	−x
Dilution (25° C cm^{-3})	0	−xx	−xx	x	−x
Direct (g^{-1})	−xxx	xx	xxx	0	xxx
Direct (cm^{-3})	−xx	0	0	0	x
Fungi					
Dilution (10° C g^{-1})	−xxx	xxx	xxx	0	xxx
Dilution (25° C g^{-1})	−xx	xxx	xxx	0	xxx
Dilution (10° C cm^{-3})	−xxx	0	x	0	xx
Dilution (25° C cm^{-3})	−xx	xx	xx	0	xx
Direct (m g^{-1})	−xxx	xxx	xxx	0	xxx
Direct (m cm^{-3})	−xx	x	xx	0	xx

0 No significant correlation; x $P<0.05$; xx $P<0.01$; xxx $P<0.001$; − Negative correlation.

TABLE IX. REGRESSION COEFFICIENTS FOR SIGNIFICANT CORRELATIONS OF MICROBIAL AND SOIL PARAMETERS OF SIX SITES AT SIGNY ISLAND

y	*x*	*Regression coefficient*	*Constant*
Bacterial counts			
Dilution ($\times 10^6$) 10° C g^{-1}	Dilution bacteria ($\times 10^6$) 10° C cm^{-3}	1.324	−0.369
Dilution ($\times 10^6$) 10° C g^{-1}	Dilution bacteria ($\times 10^6$) 25° C g^{-1}	2.024	−0.927
Dilution ($\times 10^6$) 10° C g^{-1}	Direct bacteria ($\times 10^9$) g^{-1}	NS	–
Dilution ($\times 10^6$) 10° C g^{-1}	Dilution fungi ($\times 10^3$) 10° C g^{-1}	NS	–
Dilution ($\times 10^6$) 10° C g^{-1}	% P (total)	71.287	−5.742
Direct ($\times 10^9$) g^{-1}	pH	−15.740	132.452
Direct ($\times 10^9$) g^{-1}	% loss on ignition	0.748	3.693
Direct ($\times 10^9$) g^{-1}	% N (total)	66.178	3.509
Direct ($\times 10^9$) g^{-1}	% H_2O (wet basis)	0.993	−14.198
Direct ($\times 10^9$) g^{-1}	Direct fungi m g^{-1}	0.010	11.438
Fungal counts			
Dilution ($\times 10^3$) 10° C g^{-1}	Dilution fungi ($\times 10^3$) 10° C cm^{-3}	10.230	−194.354
Dilution ($\times 10^3$) 10° C g^{-1}	Dilution fungi ($\times 10^3$) 25° C g^{-1}	2.032	135.713
Dilution ($\times 10^3$) 10° C g^{-1}	Direct fungi m g^{-1}	0.176	53.786
Dilution ($\times 10^3$) 10° C g^{-1}	pH	−234.940	1 907.270
Dilution ($\times 10^3$) 10° C g^{-1}	% loss on ignition	11.492	−28.125
Dilution ($\times 10^3$) 10° C g^{-1}	% N (total)	937.610	−93.662
Dilution ($\times 10^3$) 10° C g^{-1}	% P (total)	−6 059.812	1 250.915
Dilution ($\times 10^3$) 10° C g^{-1}	% H_2O (wet basis)	13.954	−239.736
Direct m g^{-1}	pH	−1 190.290	9 627.517
Direct m g^{-1}	% loss on ignition	59.520	−230.677
Direct m g^{-1}	% N (total)	5 165.002	−745.521
Direct m g^{-1}	% P (total)	−30 791.360	6 314.240
Direct m g^{-1}	% H_2O (wet basis)	73.006	−1 362.316

that fungal counts at all sites were consistently higher at 10° C (mean ratio 21.00 : 1.00, S.E.$\pm$10.89) than at 25° C but bacterial populations (Table III, Fig. 3) were inconsistent, being highest at 25° C in hut bank samples and the upper peat zone of the mountain site. At other sites, bacterial numbers were highest at 10° C. The hut bank site was sampled sufficiently to permit an analysis of variance to compare fungal and bacterial counts at 10° and 25° C. This confirmed a highly significant difference between the psychrotolerant and mesophilic fungal population size in upper and mid peat horizons, whilst also demonstrating the inconsistency of the corresponding bacterial populations. This may be

due to seasonal variations in the ratio of psychrotolerant to mesophilic bacteria predictable with a seasonal soil-temperature range from *c.* −20° to +30° C (Walton, 1977).

Comparison of dilution and direct counts

These modes of expression of fungal populations are not strictly comparable, the dilution count representing the population of viable hyphal fragments and spores after homogenization, while the direct count estimates the length of mycelium in the sample. The distinction between stained and unstained mycelium (Table II) is an attempt to assess the proportion of the live mycelium (Jones and Mollison, 1948; Nagel-de Boois and Jansen, 1971), although techniques developed later may be superior (Frankland, 1975). In the present survey, stained mycelium was 83.4%±4.70 S.E. of the total measurement. Similar problems occur when bacteria form clumps but the concept of the "colony-generating unit" (Lewin, 1974) is useful with both microbial groups. Dilution counts of bacteria reflect the viable population capable of growing on the medium at a selected temperature as compared with the total population (direct count), only a proportion of which will be viable *in situ*. The direct counts are usually several orders of magnitude greater than dilution counts. In the recent data they are 10^4 to 10^5 times greater in peat samples, 10^3 to 10^5 times greater in grassland soil and 10^2 to 10^4 times greater in the highly mineral moraine and marble soils.

Except for inconsistent direct counts on a volume basis, both dilution and direct counts of bacteria and fungi were equally effective in demonstrating the difference in population size at the six sites. This contrasts with the disparity in grouped results from all sites (Table VII) between a highly significant dilution/direct-count correlation for fungi and no dilution/direct-count correlation for bacteria. It implies within-site consistency of bacterial dilution:direct-count ratios but variation in the ratio from one site to another. The fungal dilution:direct-count ratio is similar for all sites.

TABLE X. RELATIVE MEAN MICROBIAL POPULATION SIZES AT THE SIGNY ISLAND SITES (DILUTION COUNTS g^{-1} ORGANIC MATTER AT 10° AND 25° C)

Site	*IBP code*	*Horizon*	*Fungi*		*Bacteria*	
			10° C	25° C	10° C	25° C
1. Hut bank	SHB	Upper	14.8	613.3	13.2	5.4
2. Mountain	S Mt	Upper	7.4	104.9	1	1
3. Grass	SG	Upper	6.0	45.3	855.9	78.8
4. a. Marble knolls: marble	SMK	Upper	1.1	18.5	90.8	10.5
b. Marble knolls: schist	SMKS	Upper	4.8	174.9	1 030.7	112.9
5. New moraine	SNM	Upper	1	1	777.5	128.7
6. Old moraine	SOM	Upper	15.5	13.2	637.1	89.0
1. Hut bank	SHB	Mid	6.4	133.0	0.9	0.5
2. Mountain	S Mt	Mid	1.5	49.0	1.7	0.3
3. Grass	SG	Mid	7.2	35.0	107.2	7.0

Comparison of bacterial and fungal populations

The correlations and regressions in Tables VII, VIII and IX enable patterns of variation in bacterial and fungal populations to be examined. Such patterns are probably due to a common response to environmental factors by the two groups.

Although analysis of variance of hut bank bacterial counts showed real differences between populations growing at 10° and 25° C, there is good correlation between them on both weight and volume bases, implying similar responses to environmental parameters. However, the lack of association between viable bacterial and viable fungal populations suggests that they respond differently to such parameters. This is consistent with the growing evidence that bacteria predominate over fungi in nutritionally good conditions and fungi predominate in acid oligotrophic peaty soils (Maltby, 1975). Logarithmic transformation of the data did not enhance the relationship. Paradoxically, there was good correlation between total bacterial and total fungal populations, possibly indicating a high proportion of non-viable organisms in both populations, unaffected by the environmental parameters.

As with bacteria, there was good correlation between fungal dilution counts at 10° and 25° C but, unlike bacteria, there was also a close connection between the viable and total fungal population counts. The different responses of viable and total bacterial populations to changes in soil environment may be due to slower decomposition of bacterial cells than fungi. The similar responses in viable and total fungal measurements is consistent with the low proportion of sporing forms found among isolates from Signy Island.

Correlation between microbial populations and soil conditions.

Intercorrelation of soil factors. Although percentage total phosphorus did not correlate well with any other soil parameters, there was a strong positive correlation between percentage loss on ignition, percentage total nitrogen and percentage moisture, and strong negative association between all these factors and pH.

Because of the intercorrelation of pH, percentage loss on ignition, percentage nitrogen and percentage water, these parameters should be considered as a group and not as individual variables because correlation does not imply causation. Hence the relation between a microbial population and these four soil factors representing the association of only two variables.

Correlation of microbial populations with soil factors. The viable bacterial populations grown at 10° C, although not correlated with the group of soil factors, was correlated at $P<0.05$ with percentage phosphorus. Other microbial populations were not. Additional significant correlations emerged on comparing $\log_{10}$ dilution counts cm^{-3} at both 10° and 25° C with linear expression of the group of soil factors. A logarithmic response to factors which permitted unrestricted multiplication with adequate nutrients might be expected.

If the loss on ignition data are used to express the upper and mid horizon viable bacterial counts g^{-1} of organic matter ($\equiv$ loss on ignition), significant negative correlation emerges between both psychrotolerant and mesophilic counts and percentage total nitrogen ($r = 0.711$* and -0.735*, respectively for $n = 10$, and where * represents $P = 0.05$). Similar associations occur with percentage moisture ($r = 0.665$* and -0.701*, respectively for $n = 10$) but not with pH or percentage total phosphorus. These negative correlations suggest that small bacterial populations are associated with high nitrogen and moisture levels, an unusual effect which may be due to the intercorrelation of nitrogen and moisture content with other factors. Conversely, fungal populations are uncorrelated with these parameters when linked to organic content.

As for bacteria, correlation with soil factors was improved by $\log_{10}$ relative to linear dilution fungal counts at both 10° and 25° C but logarithmic transformation of all direct-count microbial data did not improve the relationship. This is consistent with the presence of a non-viable component in direct counts.

The negative correlation of both viable and total fungal counts with pH might be expected

but its significant negative association with total bacteria, although not with viable bacteria, is explicable by considering pH as one of the group of pH-linked soil factors with which the direct counts are correlated. In general, the viable fungi incubated at 25° C correlated less with soil factors than those at 10° C, although the significance increased with $\log_{10}$ expression of the counts, consistent with a growth response of a viable population. Closer $\log_{10}$ rather than linear correlation of mesophilic fungi with environmental factors suggests a fast response to nutrient availability if temperature is not rate limiting.

Correlation between total fungal population and soil factors was improved by logarithmic expression of the data, commensurate with a higher proportion of viable units in direct fungal counts.

Seasonal variation in microbial populations

During an initial 14 month period, five collections of samples from three horizons at the hut bank site were incubated at 25° C. A further eight collections of samples from the upper and mid peat horizons taken over a 6 month period were incubated at both 10° and 25° C. The results showed no significant intercorrelation between any two depths, indicating a lack of synchronization during annual population fluctuations. There were few seasonal trends, unlike the spring bloom detected by Baker (1970*a*) in a comparable moss bank on Signy Island. However, high bacterial and fungal counts were recorded at the time of thaw of the upper peat horizon, and a post-spring decrease in both upper and mid-peat numbers was a common feature of both psychrotolerant and mesophilic microbial populations. Fluctuations in the lower horizons were generally erratic.

Identity and distribution of fungal isolates

The occurrence and incubation temperatures of 14 identified fungal isolates from the Signy Island sites are summarized in Table XI. The remaining 13 unidentified isolates were sterile so that 50% of the isolates from Signy Island were non-sporing. Sterile forms were isolated twice as frequently at 25° than at 10° C, which was the converse of the sporing forms. The occurrence of these genera and species at other Antarctic and Arctic tundra sites is shown. They have not, however, been reported from the following comparable polar sites despite generally similar methodology:

Antarctic

Dry valleys of Victoria Land (Rudolph, 1970; Sugiyama, 1970).
McMurdo Sound area (Boyd and Boyd, 1963).
Mount Erebus, Ross Island (Ugolini and Starkey, 1966).
Ellsworth Station (Corte and Daglio, 1963).
Haswell Islands, Mirniy Station (Meyer and others, 1967).
Danco Coast (Tsiklinsky, 1908).
Cabo Primavera [Spring Point], Danco Coast (Corte and Daglio, 1963).
Hope Bay, north Graham Land (Corte and Daglio, 1963).
Deception Island, South Shetland Islands (Cameron and Benoit, 1970).
Ongul Islands, Syowa Station (Tubaki, 1961).
South Georgia (Dennis, 1968).
Marion Island, Prince Edward Islands (Joubert, 1966).

Arctic

Certain IBP sites (Dowding and Widden, 1974).
Several Alaskan glaciers (Cooke and Lawrence, 1959).
Taimir Peninsula, USSR (Smirnova, 1975).

TABLE XI. DISTRIBUTION OF NAMED FUNGAL ISOLATES FROM THE SIX SITES AT SIGNY ISLAND AND AT OTHER POLAR SITES, AND THEIR FREQUENCY OF ISOLATION AT 10° AND 25° C

Fungal isolate	*Signy Island sites*						*Isolation frequency*		*Other polar sites**
	Hut bank	*Mountain*	*Grass*	*Marble knolls*	*New moraine*	*Old moraine*	10° C	25° C	
Geomyces cretaceus	−	+	+	−	−	−	1	2	—
Geomyces vulgare	+	−	+	+	−	−	4	0	—
Helicoon (reticulatum?)†	−	−	+	−	−	−	0	1	—
Mortierella alpina	−	−	−	−	+	+	1	2	—
Mortierella minutissima	−	−	+	−	−	−	1	0	—
Mortierella parvispora	+	+	+	−	−	−	8	0	P, E
Mortierella turficola	−	−	−	+	+	−	3	1	—
Mortierella sp.	−	−	−	+	−	−	0	1	A, B, D, M, MH, MK
Nectria viridescens†	−	−	+	−	−	+	1	1	B
Oidiodendron sp.	+	−	−	−	−	+	1	1	A
Rhinotrichum lanosum†	−	+	−	−	−	−	1	0	—
Stephanosporium cerealis	−	+	+	−	−	−	1	1	—
Verticillium? sp.	+	−	+	−	−	+	4	3	B, D, G, MA

\+ Positive isolation.
− Not recorded.
* A Abisko (Hayes and Rheinberg, 1975); B Point Barrow, Alaska (Flanagan and Scarborough, 1974); D Devon Island, Canada (Widden and others, 1972); E Eagle Summit, Alaska (Flanagan and Scarborough, 1974); G Glenamoy (Dowding and Widden, 1974); M Macquarie Island (Bunt, 1965); MK Mackenzie Valley, North West Territories (Ivarson, 1965); MA Mount Allen, Canada (Dowding and Widden, 1974); P Prudhoe Bay, Alaska (Flanagan and Scarborough, 1974).
† On Warcup soil plates only; all other forms isolated on dilution plates.

Examination of the published lists suggests that extreme Antarctic climatic and pedological conditions limit the distribution of fungal species isolated on Signy Island but their occurrence in comparable Arctic areas is widespread.

Discussion

To date, there have been no comparative terrestrial microbiological studies of the maritime Antarctic zone. Although comparisons based on different methods must be treated with caution, the present work on Signy Island will be discussed relative to general trends apparent in investigations of the Antarctic Peninsula and Scotia arc since 1901.

Variation in population size between sites

The analysis of variance applied to the microbial data for the six sites examined on Signy Island indicates significant between-site variation despite large within-site variability and limited data. These differences are apparent in both the psychrotolerant (growing at 10° C) and mesophilic (growing at 25° C) populations whether expressed on a weight or volume basis, consistent with significant correlation ($P<0.01$) between these two modes of expressi[illegible]

The size of the bacterial population from these topographically different sites at Sig[illegible] Island parallels estimates from a wide range of Antarctic and Arctic areas, several of which have been studied in detail during IBP (Holding and others, 1974; Rosswall and Heal, 1975).

Counts of bacterial populations in the *Chorisodontium–Polytrichum* association of the hut bank site are within an order of magnitude of those at the *Chorisodontium* site at Spindrift Rocks on Signy Island (Baker 1970*a*, *b*), and similar to those in peat at site M2B on Macquarie Island (Bunt and Rovira, 1955; Bunt, 1965; Jenkin, 1975), and peat on Campbell Island (Stout, 1961). Owing to differences in soil conditions, they are to a lesser extent comparable with the palsa peat at Kevo, Finland (Baker, 1974*a*), a lichen heath at Hardangervidda, Norway (Clarholm and others, 1975), organic permafrost soil in the Mackenzie Valley, North-West Territories (Ivarson, 1965), and parts of Stordalen mire, Sweden (Clarholm, 1973; Rosswall, 1973) despite comparable climatic regimes. The bacterial population in the more extreme mountain site compares closely with a similar humus-bearing site at Paradise Harbour, Antarctic Peninsula (Boyd and others, 1970) and with the IBP polar group of soils (Holding and others, 1974). This consists of site 2 at Point Barrow, Alaska (Bunnell and others, 1975), Devon Island, Canada (Bliss, 1975) the Taimir Peninsula, USSR (Parinkina, 1974), which are similar to Alaskan coastal sites (Boyd, 1958) and soil "A" at Inuvik, North-West Territories (Boyd and Boyd, 1971).

Grassland is absent in continental Antarctica and infrequent in the maritime Antarctic zone, its limits being the immature soils under *Deschampsia antarctica* on Signy Island and at Paradise Harbour, Danco Coast (Boyd and others, 1970), which support low bacteri[illegible] populations compared with better-developed grassland soils on Macquarie Island, Devon Island and the Hardangervidda (Bunt, 1965; Bliss, 1975; Clarholm and others, 1975; Jenkin, 1975). The very low count (1.5×10^4 bacteria g^{-1} dry weight) for a comparable area of exposed *Festuca contracta* grassland (Smith and Stephenson, 1975) was probably due to limitations in methodology and incubation at 28° C.

The climatically extreme and often oligotrophic soils of coastal Antarctica support low microbial populations such as in soil No. 3 at McMurdo Sound (Boyd and Boyd, 1963), which was basically ash with a thin covering of moss and lichen, also in mainland soil No. 718 on Deception Island (Cameron and Benoit, 1970), and soils of Haswell Island, north of Mirniy Station (Meyer and others, 1967). Sites at Paradise Harbour, Cabo Primavera [Spring Point] and Bahia Esperanza [Hope Bay] on the Antarctic Peninsula (Boyd and others, 1970; Margni and Castrelos, 1971) also have low microbial populations. These immature ecosystems show similarities to the moraine sites on Signy Island and to a lesser extent to the marble

knoll sites which have higher levels of inorganic nutrients. However, the more favourable climatic regime at Signy Island permits a longer growing season than more southerly sites. The present data indicate that the microbial population size in these soils is regulated more by substrate quality and other site characteristics than by latitude. This is in agreement with the non-correlation between microbial populations and IBP site locations shown by Holding and others (1974), and the similarity of microbial population size in peat from Signy Island and Moor House (Heal and others, 1967). A striking difference between the Signy Island sites and similar moss and lichen sites at McMurdo Sound, Paradise Harbour, Deception Island, Inuvik and various Alaskan locations was the much larger fungal population in Signy Island peat, being up to 100 times larger at hut bank than at any other site. The reason for this is not clear but Baker (1970*b*) reported very high yeast populations in his Spindrift Rocks site *Chorisodontium* bank. This was not necessarily due to low pH, as indicated by a lack of correlation between fungal counts and pH at the Signy Island sites.

Variation in microbial populations with depth

The response of the microbial population to increase in soil depth appears variable. Baker (1970*b*) reported an increase in bacterial count with depth in the Spindrift Rocks *Chorisodontium* [redacted] at Signy Island, whereas the opposite was found in the hut bank *Chorisodontium–Polytrichum* turf. A tendency to a decrease in population with depth has also been found in comparable organic soils at Devon Island (Widden and others, 1972), Mackenzie Valley, NWT (Ivarson, 1965), Kevo (Baker, 1974*a*), Hardangervidda (Clarholm and others, 1975) and Moor House (Holding and others, 1974). The decrease with depth was only slight at Stordalen (Clarholm and others, 1975). Conversely, there was an increase in bacterial population with depth in non-organic sandy soils at Russian sites (Aristovskaya and Parinkina, 1972), although this was not apparent in a comparable beach-crest habitat at Devon Island (Widden and others, 1972). The difference between the hut bank and Spindrift Rocks sites at Signy Island suggests that microbial populations may respond differently in moss turves compared with relatively pure moss banks. This may be due to temperature gradients established by the level of the permafrost which may limit decomposer activity near the ice interface and thus favour net production and moss-bank formation (Latter and Heal, 1971).

Effect of incubation temperature on population size

The results of studies using the two incubation temperatures indicate that bacteria are not adapted to low temperatures, the 10° and 25° C counts being similar in most cases. Holding and others (1974) found no correlation between viable counts and temperature at IBP sites including Signy Island, while Boyd and Boyd (1971) found that viable counts and seasonal soil temperature at Inuvik were not correlated. Similarly, in the present study no correlation [redacted] apparent between soil temperature and bacterial or fungal counts, nor with the psychrophilic:mesophilic bacterial ratio. The close correlation found between bacterial counts at 10° and 25° C, reflecting parallel responses of both populations to fluctuations in soil parameters, was also noted ($P<0.01$) by Boyd (1967), who compared bacterial populations isolated at 2° and 22° C from a range of Antarctic and Arctic sites.

In contrast, the estimate of viable fungal populations at 10° C is significantly higher than at 25° C, suggesting adaptation to low temperature or an intolerance of high temperature. This difference between bacterial and fungal populations at Signy Island is confirmed by the analysis of variance on the data within and between sites (Table V). This corresponds with the results of Latter and Heal (1971), who found a greater adaptation to low temperature in fungal isolates from Signy Island soils compared with bacterial isolates, which grew better at 13° C. However, Baker (1974*b*) reported that the optimum temperatures for five psychrophilic bacterial isolates from Signy Island, capable of visible growth at 0° C in 2 weeks (Ingraham

and Stokes, 1959), was 25° C. He suggested that such isolates grew sub-optimally for most of the year and were thus protected against occasional extreme high soil temperatures during summer. There are other reports of Antarctic bacteria capable of growth at both 2° to 4° C and 25° C (Bunt and Rovira, 1955; Flint and Stout, 1960; Cameron and Benoit, 1970; Margni and Castrelos, 1971) consistent with the present results. Baker and Smith (1972) found 62% of bacterial isolates from Signy Island to be psychrophilic, suggesting that the population is capable of tolerating a broad range of seasonal soil temperatures. Cold adaptation in polar fungi has been reported from a range of sites (Soneda, 1961; Ivarson, 1965; Baker, 1974*a*) and appears to be a general trend (Harris and others, 1966), which may be related to freezing resistance (Borgstrøm, 1962).

Comparison of dilution and direct counts

As expected, there is a large discrepancy between numbers of bacteria estimated by dilution and direct methods, and the dilution count was a very small proportion of the direct estimate, the difference being 1 600–376 000 times. However, estimates of the proportion of rods and cocci in the total count suggest that this range may be exaggerated by a factor of *c.* 13 owing to difficulties in distinguishing cells from debris. Nevertheless, this ratio is high relative to those recorded for similar tundra soils (Parinkina, 1974). The lack of correlation between direct and viable bacterial counts is consistent with the large fluctuations in the ratio of viable to dead bacteria in tundra soils of western Taimyr (Parinkina, 1974), but may be related also to the efficiency of homogenization (Clarholm and others, 1975). In contrast, the present results show a close correlation between direct estimates of fungal hyphal length and viable fungal units, implying that at the Signy Island sites dilution counts provide a measure of the viable fungal material rather than merely sporing ability. This is supported by reports of a very low proportion of sporing fungi in polar areas (Dowding and Widden, 1974), and is consistent with the high proportion of sterile fungi isolated in the present study.

Comparison of bacterial and fungal populations

The limited positive correlation between direct bacterial and fungal counts here ($P<0.01$) and between viable bacterial and fungal counts ($P<0.001$) in a bi-polar study by Boyd (1967) contrasts with the broad but not invariable generalization that there is an increase in the proportion of fungal biomass with increasing acidity and organic content. However, the correlation may be the result of a response to parameters such as aeration (di Menna, 1968).

Correlation between microbial populations and soil conditions

The soil parameters used in these analyses were derived from independent studies on Signy Island by Holdgate and others (1967) at sites similar to those considered here. In view of the differences in time and location, the apparent correlations must be treated with caution. Nevertheless, the trends permit constructive preliminary comparisons to be made with polar tundra studies elsewhere.

Intercorrelation within the group of soil variables partly explains the lack of correlation between viable bacterial counts and individual factors which might be expected to be influential. Total phosphorus, which was excluded from this group, correlates slightly ($P<0.05$) with such counts, possibly in proportion to seasonal fluctuations of phosphate (Northover and Allen, 1967). In contrast, Baker (1970*b*) showed that an increase in bacterial populations in the Spindrift Rocks site correlated with slight increases in pH and moisture, but not with percentage nitrogen or potassium or any other major nutrients. Holding and others (1974) found a general correlation between viable bacterial counts and pH in tundra soils but this was not observed in the present study even when the counts were expressed per gram of organic matter (Table X), which is potentially available for decomposition. The two factors

which were significant using this mode of data expression were percentage moisture ($P<0.05$) and percentage total nitrogen ($P<0.02$), both of which probably affect organic carbon utilization directly. Results summarized by Boyd (1967) demonstrate no correlation between viable bacteria and percentage moisture, phosphorus, ammonium-N and pH in soils from Taylor Dry Valley (Antarctica), Ross Island, McMurdo Sound, Inuvik (Canada) and Point Barrow (Alaska). Thus the pattern is bi-polar. In contrast to the viable counts, the direct bacterial counts show the converse trend, only percentage total phosphorus showing virtually insignificant ($P<0.10$) correlation. This corresponds with the conclusions of Clark and Paul (1970) that a very large part of the population is in a resting state. The recommendation of using direct counts for the inclusion of energy stored in inactive bacterial cells in estimates of soil microbial biomass (Clarholm and others, 1975) is therefore supported. The importance of available organic material in maritime Antarctic soils was clearly demonstrated by Boyd and others (1970), who found a considerable increase in the bacterial population at both 2° and 22° C on amending soil from Paradise Harbour, Antarctic Peninsula, with glucose and peptone. A similar response was also shown for Moor House soils (Martin and Holding, 1978). The unexpected negative correlation ($P<0.10$) between direct bacteria and pH may be accounted for by the inclusion of pH in the group of intercorrelated factors and does not imply causation. The low pH may retard the decomposition of dead bacterial cells, thus contributing to a high direct count. A negative correlation might be expected between pH and fungal counts based on both viable and total populations at the Signy Island and IBP sites (Flanagan and Scarborough, 1974). The bi-polar analysis of soil populations by Boyd (1967) did not suggest this, probably due to the wide variety of soil types considered.

In contrast to bacteria, correlation of viable fungi with environmental factors was actually decreased when counts were expressed per gram of organic matter. Total organic nutrient thus had less influence than other soil factors. Direct fungal counts correlated well with soil variables, suggesting that the inclusion of the dead hyphal component did not obscure the response of metabolically active fungal units to changes in the soil environment.

Owing to the poor quality of peat in the hut bank and mountain sites together with their low pH, it would be expected that microbial counts per gram of organic matter would be lower in these sites and higher in the inorganic rich marble knoll and moraine soils, with the grass soil being intermediate. This was the case for bacterial populations incubated at both 10° and 25° C but the converse was observed with the fungal counts. Bacteria exploit readily assimilable organic material in the presence of unlimited inorganic nutrients, whereas fungi may be more efficient in decomposing more complex molecules (Clarholm and others, 1975).

Seasonal variation in microbial populations

Peaks in viable bacteria populations associated with rapid thaw cycles were recorded in the surface layers of the Spindrift Rocks *Chorisodontium* site (Baker, 1970*a*, *b*), in peaty soil at Point Barrow (Boyd, 1958) and moss–lichen soil at McMurdo Sound (Boyd and Boyd, 1963). However, in the hut bank soil, at Hardangervidda (Clarholm and others, 1975) and at Inuvik (Boyd and Boyd, 1971), these peaks were not pronounced. An early summer peak was recorded at Deception Island in 1960 and 1962 with comparable peaks a month later at Cabo Primavera [Spring Point] and Hope Bay, both on the Antarctic Peninsula (Margni and Castrelos, 1971), probably associated with their sequential temperature maxima due to increasing latitude.

A spring peak in viable fungal counts was observed at hut bank for populations incubated at both 10° and 20° C, comparable to a peak in the 22° C population in the moss–lichen soil at McMurdo Sound (Boyd and Boyd, 1963) and Scandinavian sites (Hanssen and Goksøyr, 1975). These peaks may be caused by a release of nutrients, a rhizosphere effect or, in the

case of bacteria, a physical break-up of clumps of cells (Boyd, 1958), which may contain up to ten individuals (Clarholm and others, 1975). The subsequent decline after these peaks may be due to a combination of predation by micro-fauna such as Protozoa (Heal, 1965) or other microbivores (Holdgate, 1977), accumulation of metabolic by-products (Hudyakov, 1957), incipient desiccation (Baker, 1970*a*) and depletion of assimilable nutrients as occurs in ombrogenous peat at Stordalen (Clarholm and others, 1975).

Identity and distribution of fungal isolates

The most conspicuous feature of the fungal isolates (Table XI) was the absence of several cosmopolitan genera. *Penicillium* and *Aspergillus* are relatively frequent in Antarctica, having been recorded from soil and air in Victoria Land, Marie Byrd Land and at Ross Island, McMurdo Sound, Ellsworth Station (*Penicillium* only), the Danco Coast, Hope Bay, Deception Island and Macquarie Island. They are essentially organisms of the aerial micro-flora (Pady and Kelly, 1954) and there may be a combination of environmental factors which precludes their development in Signy Island soils. *Trichoderma* sp. is infrequent in Antarctica but is common in temperate sites such as Moor House in the UK. There is evidence to suggest that *Trichoderma* spp. may be cold intolerant and its absence may permit the development of non-competitive sterile fungi (Sewell, 1959) common on Signy Island. *Mortierella* is not widespread in the Antarctic, being found on Signy Island and Macquarie Island only, but it is common in Arctic and sub-Arctic areas. Table XI shows that *Mortierella* and *Verticillium* were isolated more frequently at 10° than 25° C and subsequent studies by Latter and Heal (1971) have shown that *Mortierella* strains from Signy Island are better cold adapted than those from Moor House, which are predictably more so than those from the low-lying Roudsea Wood site, UK. These adaptations in temperature optima are paralleled by strains of *Verticillium* from Signy Island and Moor House but this genus has been reported only from sub-Antarctic Marion Island, although present on Devon Island and Point Barrow in the Arctic. Of the remaining named fungal isolates listed, none has been recorded elsewhere in the Antarctic but *Nectria viridescens* was found at Point Barrow and *Oidiodendron* at Abisko (Rosswall and others, 1975) and in the Mackenzie Valley. *Chrysosporium* sp. has been separately reported from Signy Island (Dowding and Widden, 1974) and has a bi-polar distribution.

The results of this work support the conclusion that the populations of bacteria and cold-adapted fungi on Signy Island, and of Antarctica in general, are cosmopolitan (Proctor, 1935; Rudolph, 1970; Latter and Heal, 1971), with their species composition and population numbers regulated by climate, topography and soil conditions.

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