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ORIGINAL PAPER

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On the distribution of terrestrial invertebrates at Cape Bird, Ross Island, Antarctica

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Abstract Terrestrial invertebrate distribution was surveyed over 12 km^2 of the ice-free area at Cape Bird, Ross Island, Antarctica. *Gomphiocephalus hodgsoni* (Collembola: Hypogastruridae), *Stereotydeus mollis* and *Nanorchestes antarcticus* (Acari: Prostigmata), *Panagrolaimus davidi*, *Plectus* sp. and *Scottnema lindsayae* (Nematoda), Tardigrada, Rotifera and Protozoa were all recorded. Invertebrates were found at 47 of 103 locations sampled. Logistic regression analysis suggested that the presence of mites and Collembola was strongly related to chlorophyll-a content of soil; but only *Stereotydeus mollis* and *N. antarcticus* were related to the presence of macroscopic vegetation, suggesting that current methods of assessing areas for protection may not adequately allow for invertebrate communities. Invertebrate communities were not dependent on ornithogenic carbon input. A better understanding of dispersal mechanisms is necessary to understand distributions of invertebrates in ice-free areas, particularly in light of potential habitat changes as a result of climate change.

Introduction

Terrestrial habitats in the continental Antarctic region are cold, dry and have low productivity and biodiversity (Spain 1971; Block 1994; Vincent 1997; Virginia and Wall 1999). It is thought that these communities are particularly sensitive to human disturbance and climate change (Kennedy 1995; Virginia and Wall 1999). Although changes in the populations and distributions of terrestrial Antarctic invertebrates are often proposed as potential bioindicators of a changing climate (e.g. Young 1991; Block 1994; Kennedy 1994, 1995; Block and Harrisson 1995; Virginia and Wall 1999; Convey and Arnold 2000), there is only limited information about these communities, particularly at the most extreme latitudes, which are thought to be particularly susceptible to change.

The McMurdo Sound area has been the major focus of research in the Ross Sea Region (Gressitt 1967; Peterson 1999). Terrestrial invertebrates have received attention there since the early forays into the area (Quartermain 1967), and surveys have established basic patterns of distribution for several groups of invertebrates (arthropods: Gressitt 1967; Wise 1967; nematodes: Wharton and Brown 1989). During the 1950s and 1960s, considerable effort was focussed on the broad-scale distribution of arthropods, and their relationship to general microclimatic conditions (Gressitt 1967; Janetschek 1967; Spain 1971). More detailed work on invertebrate distribution has tended to be focussed on a few small areas, for instance, the Canada Glacier moss flush (Schwarz et al. 1993) and Keble Valley (Sinclair and Sjursen, 2001); only one programme in recent years has surveyed invertebrates at a landscape (i.e. kilometre) scale within the Dry Valleys (Freckman and Virginia 1993; Powers et al. 1998; Treonis et al. 1999; Virginia and Wall 1999). However, the Dry Valleys are inland, experience different geo/ecological legacies and climatic conditions and are therefore not representative of coastal ice-free areas, which are common in the continental Antarctic.

In this paper, I report the distribution of terrestrial invertebrates at Cape Bird. The aims were twofold: firstly, to investigate the distribution of the soil fauna of Cape Bird, with respect to the physico-chemical properties of the soil and the immediate environmental and biological influences; secondly, to examine the distribution of invertebrates at a kilometre scale, with the intention of providing basic information on landscape-scale distribution.

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Materials and methods

Study site

Cape Bird (77°13'S, 166°26'E) is an approximately 17 km^2 ice-free area at the northern tip of Ross Island (Fig. 1). The soils are of glacially modified volcanic origin, and often have high salinity (Sinclair and Sjursen, 2001). Areas near the research hut at the northern tip of Cape Bird have been a major focus for research on terrestrial mites, springtails and nematodes on Ross Island (Smith 1970; Peterson 1971; Duncan 1979; Block 1985; Wharton 1998; Sinclair and Sjursen, 2001). Mites (Acari: Prostigmata: *Stereotydeus mollis* and *Nanorchestes antarcticus*), springtails (Collembola: Hypogastruridae: *Gomphiocephalus hodgsoni*) and four species of nematodes (*Eudorylaimus antarcticus*, *Plectus antarcticus*, *P. frigophilus*, *Panagrolaimus davidi*) have been previously recorded from Cape Bird (Block 1985; Wharton and Brown 1989), and the presence of rotifers, tardigrades and Protozoa has been noted (Wharton and Brown 1989; Sinclair and Sjursen, 2001). Macroscopic vegetation, in the form of moss, algae and cyanobacterial mats, is sparse, although photosynthetic algae and cyanobacteria may also be present cryptically in soils and at stone margins (Broady 1984). Most zoological studies have surveyed areas of conspicuous

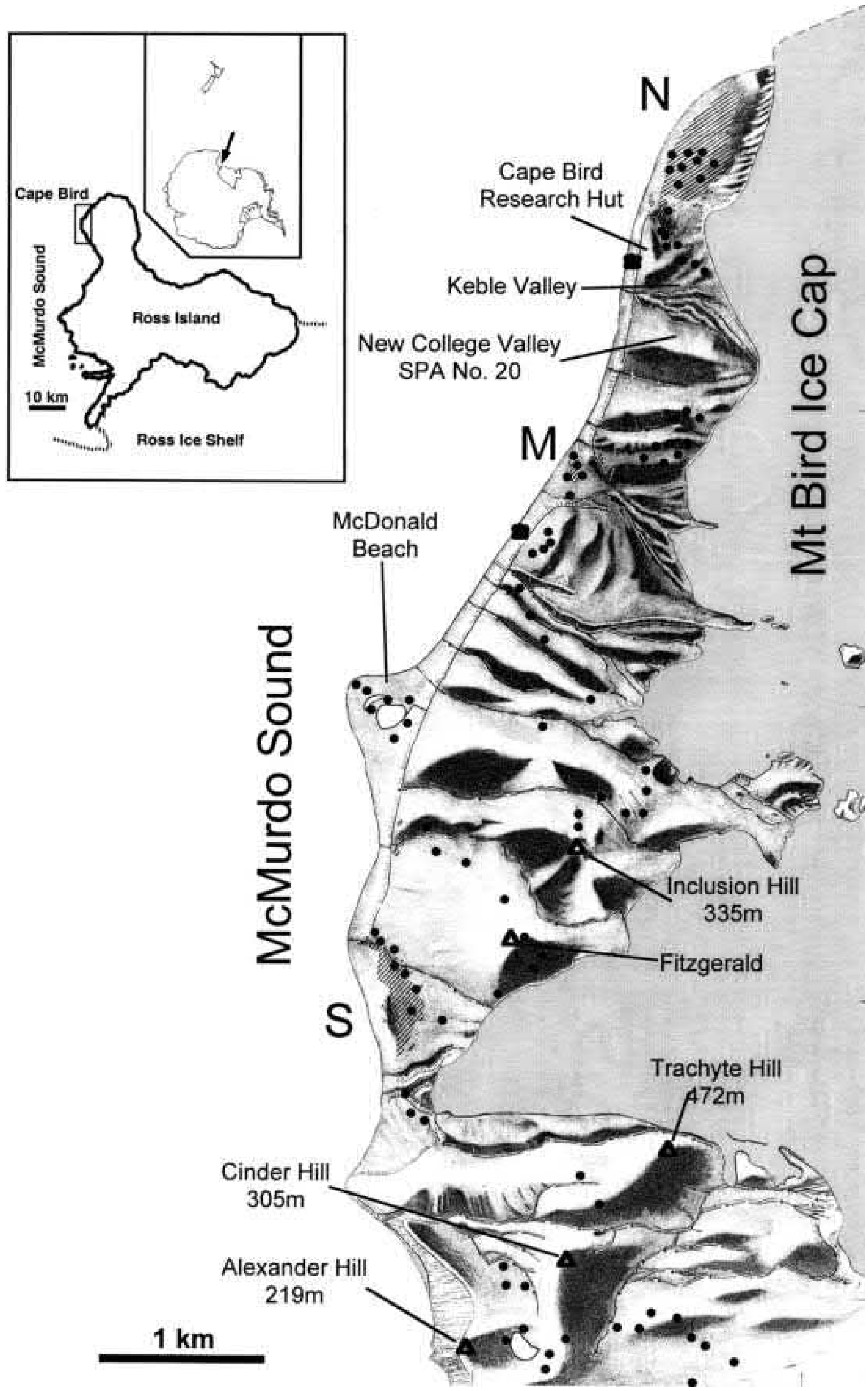

Fig. 1 Map of the majority of the Cape Bird ice-free area showing locations relevant to this paper (● = sampling locations). *Hatched areas* indicate Adélie penguin rookeries (*N* = northern, *M* = middle, *S* = southern). Drawn after NZMS 175/4 Cape Bird 1961

vegetation growth, and have sampled only the vegetation, so the fauna of vegetation-free soil remains largely uninvestigated.

Sampling site selection

Sampling sites were selected on a stratified random basis to ensure even coverage of habitat types and geographic locations within the area. Twelve square kilometres of the ice-free area at Cape Bird (excluding the restricted zone of New College Valley SPA No. 20) was divided into 14 areas, and sampling stratified within these areas. These stratifications were not used as identifiers during analysis. In penguin rookeries, sampling was conducted at pond, stream and snowbank edges, in areas between penguin mounds, and in guano-rich areas adjacent to penguin mounds. Beaches were divided into areas close to and far from streams, and sampling was conducted over the width of the beach at three even intervals from the sea. Samples were also taken near ponds at McDonald Beach and between Cinder and Alexander Hills (Fig. 1). Inland areas were sampled at ridges or other high points, snowbank edges, flat areas and adjacent to streams.

Sampling locations were chosen randomly (according to a priori stratification) from 5–50 m away. At each location a 1×1 m quadrat was laid out on the ground. The position of each quadrat was recorded on a map. Environmental variables were recorded for each site (Table 1), and every stone on the quadrat hand-searched for Collembola and *S. mollis* (*N. antarcticus* is too small to be easily seen with the naked eye). When these were found, voucher specimens were collected into ethanol to confirm identity. Two small (10–30 g) soil samples were collected into plastic ziplock bags with a teaspoon, and a further scraping of the soil surface collected for salinity determination.

Soil samples were returned to the Cape Bird hut, where one was frozen and returned to New Zealand for chlorophyll-a and organic carbon content determination, while the other was stored at outside temperatures until processed (within 3 days of collection), when soil invertebrates were extracted using water flotation and Baermann funnel techniques. See Sinclair and Sjursen (2001) for details of invertebrate extraction, and soil chlorophyll-a, organic content and salinity determination. Nematodes were identified according to Timm (1971).

Data analysis

Presence or absence of *G. hodgsoni* and *S. mollis* in a location was determined by combining presence-absence data from both stone surveys in the field and soil samples. Presence or absence of other invertebrates was determined from soil extractions. Records for all species of nematodes were combined for statistical analysis. Independence of occurrence at locations by different invertebrate groups was tested using *G* tests on 2×2 contingency tables (Sokal and Rohlf 1981). The results of single parameter logistic regression models were used to examine the relationship between abiotic variables and species presence-absence (cf. Barclay et al. 2000). All abiotic variables were included in the logistic regression analysis, with the exception of moss (which was absent from every location), water variables (apart from measured soil water), because they were too dependent on the day and time of the season in which sampling was carried out, and proximity to skua nests (because the cryptic nature of these nests made estimates unreliable). Slope was kept on a five-point scale (which was considered close to continuous), whereas aspect was reduced to two dummy variables, allowing northern, southern and neither aspects to be covered. Distance to the sea, to the nearest penguin rookery, elevation, soil surface salinity and chlorophyll-a content of soil were all $\ln(x + 1)$ transformed prior to analysis.

Results

Invertebrates (comprising 9 taxa) were found in 47 out of 103 locations sampled (Table 2, Fig. 2). This is the

Table 2 Invertebrates recorded at Cape Bird, Ross Island, Antarctica during the present study

Taxon	No sites (/103)
Collembola	
Gomphiocephalus hodgsoni	14 (+exuviae in an additional 9)
Acarina	
Stereotydeus mollis	14
Nanorchestes antarcticus	14
Nematoda	
Panagrolaimus davidi	5
Plectus sp.	2
Scottnema lindsayae	6
Tardigrada	1
Rotifera	4
Protozoa (ciliates and flagellates)	20

Table 1 Environmental variables recorded at each sampling location

Variable	Description
Algae	Presence/absence of macroscopic algae within quadrat
Moss	Presence/absence of moss within quadrat
Flowing water	Presence/absence of flowing water within 1.5 m radius of centre of quadrat
Distance to nearest water	Distance (in metres) to nearest source of water
Type of water source	Snowbank, stream, pond
Distance to sea	Estimated in metres
Surface stability	Five point scale: low (highly unstable with limited surface structure, e.g. steep moraine wall); low-medium (unstable with some stones embedded at surface e.g. shallow moraine wall); medium (low movement of substrate, stones often embedded); medium-high (most stones embedded, mineral crust often present); high (stones cemented in guano). Surface stability was analysed as a series of dummy variables, but was not significant in the analysis. This result is not reported in Table 3
Slope	Relative 5 point scale [1 = flat, 5 = very steep (> 45°)]
Aspect	In analysis, was reduced to north/south/neither
Elevation	Estimated in metres (relative to known points), or estimated with Global Positioning System
Distance to nearest penguin rookery	Estimated in metres
Distance to nearest skua nest	Estimated in metres
Bird evidence	Presence of feathers, droppings, eggshell or bones
Salt	Presence-absence of surface salt crusts. Superceded by surface salinity measurements in analysis

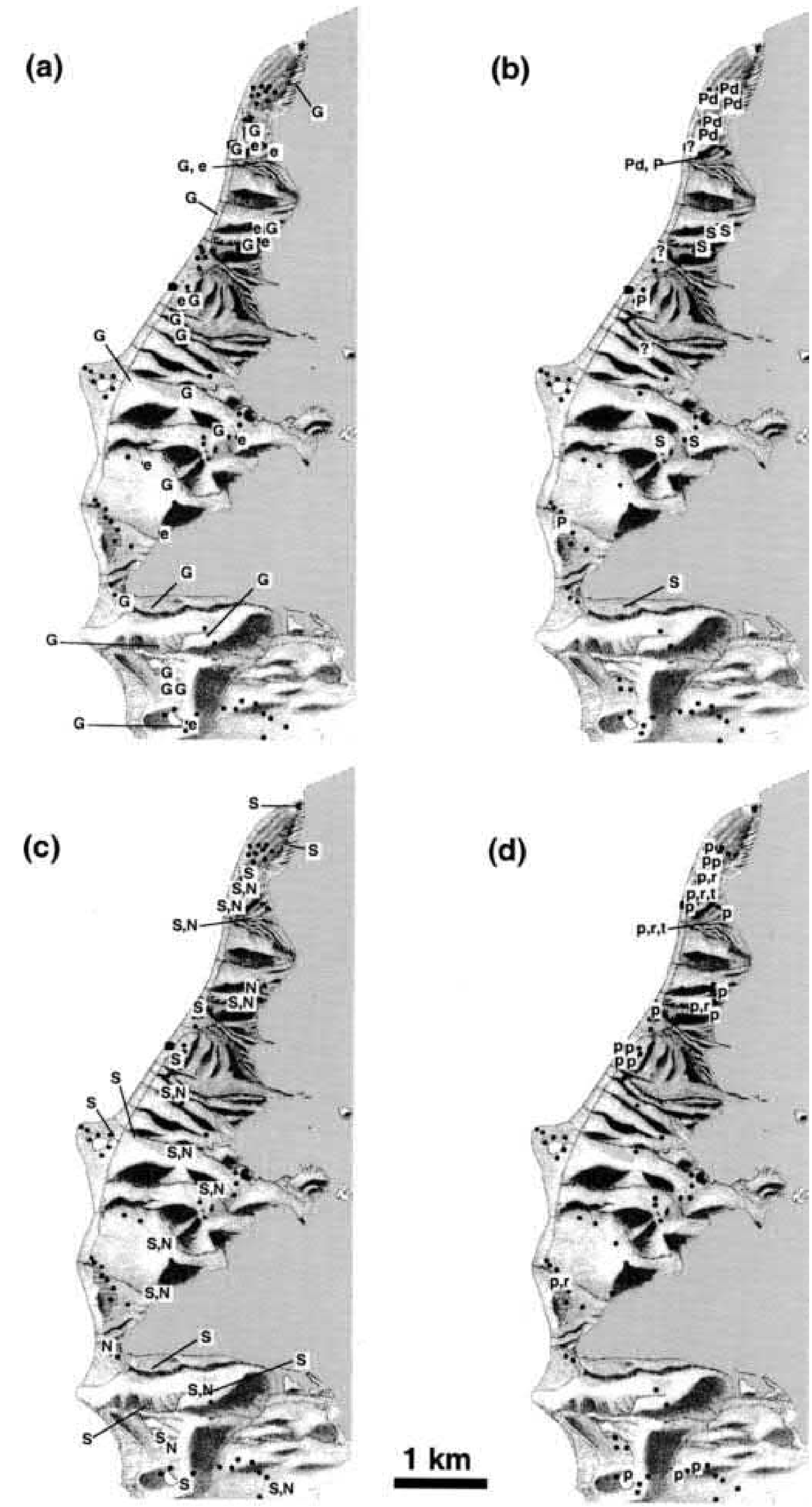

Fig. 2a–d Map of locations where invertebrates were detected at Cape Bird, Ross Island, Antarctica (● = sampling locations). **a** Collembola (*G* = *Gomphiocephalus hodgsoni*, *e* = exuviae of same). **b** Nematodes (*Pd* = *Panagrolaimus davidi*, *S* = *Scottnema lindsayae*, *P* = *Plectus* sp, *?* = unidentified or damaged nematodes). **c** Mites (*S* = *Stereotydeus mollis*, *N* = *Nanorchestes antarcticus*). **d** Other invertebrates (*p* = Protozoa, *r* = Rotifera, *t* = Tardigrada). Sites indicated with *lines* are where invertebrates were identified from samples taken from other than in the present survey

first record of *Scottnema lindsayae* at Cape Bird. Anecdotal observations of invertebrate distribution, compiled over the 1998/1999 and 1999/2000 summers, are used to supplement the records shown in Fig. 2. Subjectively, Keble Valley has high densities of arthropods, and an area with comparable arthropod density was found above McDonald Beach (Fig. 2a). Most invertebrates were found in locations bordering streams, near snowbanks or on flats, which may receive water from melting snowbanks (Fig. 3). Table 3 shows the range of soil chemistry values from the 103 locations.

Most taxa were found continuously across the ice-free area, although there was some spatial separation in nematode species (Fig. 2b). *Panagrolaimus davidi* was mostly associated with penguin colonies, although it was also present in Keble Valley (Sinclair and Sjursen, 2001). *Scottnema lindsayae* was present at higher-elevation sites near the south of the ice-free area, away from most ornithogenic input. The occurrences of *G. hodgsoni*, *Stereotydeus mollis* and *N. antarcticus* were significantly associated (G test: $P < 0.001$ in each case), but these species were not associated with the presence of nematodes (G test: $P > 0.17$ in each case). *Stereotydeus mollis* ($\chi^2 = 0.72$, $df = 1$, $P < 0.001$) and *Nanorchestes antarcticus* ($\chi^2 = 4.4$, $df = 1$, $P < 0.05$) were significantly associated with the presence of macroscopic algae. However, springtail and protozoan presence at a location were independent of the presence of macroscopic algae (springtails: $\chi^2 = 0.72$, $df = 1$, $P > 0.05$; Protozoa: $\chi^2 = 2.5$, $df = 1$, $P > 0.05$).

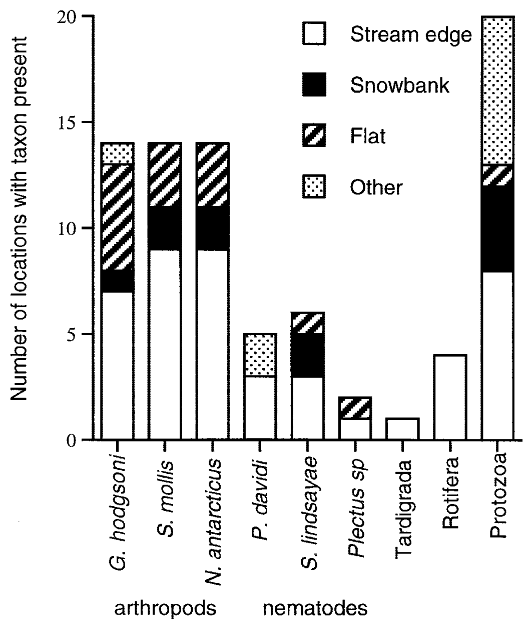

Fig. 3 Number of records of invertebrate taxa from different sampling strata at Cape Bird, Ross Island, Antarctica. "Other" includes ridgelines, penguin rookeries and pond edges

Logistic regression was used to describe the relationship between measured environmental characters and the presence of invertebrates at a location (Table 4). Logistic regression indicated a relationship between mites and macroalgae, but no relationship between macroalgae and *G. hodgsoni*, nematodes or Protozoa; this was consistent with the results from the χ^2 tests. *G. hodgsoni* and *N. antarcticus* were more likely at locations that were farther from the sea, whereas Protozoa were most commonly found at more coastal locations. There was a strong relationship between chl-a content of soil and presence of *G. hodgsoni*, *Stereotydeus mollis* and *N. antarcticus*, but this relationship did not hold for nematodes and Protozoa. Soil-dwelling nematodes, Protozoa and *N. antarcticus* presence was negatively related to soil salinity. Invertebrate presence was unrelated to organic content of the soils, or indicators of ornithogenic carbon input (distance to penguin rookeries, evidence of birds). The aspect of a location did not affect the likelihood of presence of any invertebrate. *G. hodgsoni* and *Stereotydeus mollis* were more likely to be recorded at sites with a greater slope.

Discussion

Cape Bird is a substantial ice-free area, which is highly accessible and often visited, yet in spite of the presence of an area specifically designed to protect terrestrial ecosystems (New College Valley SPA No. 20), very little is known about invertebrate distribution. This study shows that invertebrates are widespread over Cape Bird, and includes the first record of the nematode *Scottnema lindsayae* from the area. This is the first survey on Ross Island to include many invertebrate groups at a landscape scale, although the likely inefficiency of the Baermann technique (Freckman and Virginia 1993 found the Baermann technique to be ineffective for quantitative extraction of nematodes from frozen soil, and the technique is not explicitly designed to extract other invertebrates from soil) and small size of soil samples means that data for the microfauna must be viewed as preliminary. There is an interesting apparent division in nematode fauna between *Scottnema*, which is found in higher, saltier and more southern soils far from penguin

Table 3 Ranges of soil physico-chemical parameters measured at 103 locations at Cape Bird (*n.d.* not detectable)

	Max	Min	Median	Interquartile range
Sites with invertebrates present				
Soil water (g water/g dry mass)	0.253	0.008	0.095	0.086
Soil surface salinity (mOsm/kg of 3:1 slurry)	> 2000	23	69	46.5
Chlorophyll-a (µg chlorophyll/g air-dried soil)	274.86	n.d.	1.214	3.658
Organic content (g/g dry soil)	0.098	n.d.	0.008	0.008
Sites with invertebrates absent				
Soil water	1.082	n.d.	0.098	0.107
Soil surface salinity	> 2000	35	146.5	710.25
Chlorophyll-a	100.924	n.d.	0.150	1.795
Organic content	0.554	n.d.	0.010	0.012

Table 4 Single-parameter logistic regression models of invertebrate presence across 103 locations. Direction of relationship, significance of Wald chi-square of the parameter, and odds ratio are reported [*ns* = non-significant (Wald χ^2 $P > 0.05$); +,– = positive or negative relationships, respectively]. The magnitude of the odds ratio indicates the influence of the term on the outcome; a value much greater than 1 indicates a large positive effect; a value between 0 and 1 indicates a negative effect. For example, an odds ratio of 2.5 for a variable indicates that an increase in that value by 1 unit (or from 0 to 1 for a binary variable) will make the probability of presence 2.5 times more likely. All species of nematodes were pooled for this analysis

		Gomphiocephalus hodgsoni		*Stereotydeus mollis*		*Nanorchestes antarcticus*		Nematodes		Protozoa	
Algae		ns		+**	7.1	+*	3.45	ns		ns	
Distance to sea		+*	1.84	ns		+*	2.018	ns		–*	0.640
Slope		+*	2.16	+*	2.16	ns		ns		ns	
Aspect	North	ns		ns		ns		ns		ns	
	South	ns		ns		ns		ns		ns	
Distance to penguin		ns		ns		ns		ns		ns	
Bird evidence		ns		ns		ns		ns		ns	
Elevation		ns		ns		ns		ns		–*	0.723
Soil water content		ns		ns		ns		ns		ns	
Soil surface salinity		ns		ns		–*	0.299	–*	0.324	–*	0.583
Chlorophyll-a		+*	1.635	+***	2.08	+*	1.58	ns		ns	
Organic content		ns		ns		ns		ns		ns	

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

rookeries (Fig. 2b), and *Panagrolaimus davidi*, which seems to be more closely related to the nutrient-rich areas of the penguin rookeries. This pattern is very similar to that reported by Treonis et al. (1999) for *Scottnema lindsayae* and *Plectus* and *Eudorylaimus* spp. in the Dry Valleys.

With the exception of *Panagrolaimus davidi*, the invertebrate communities reported at Cape Bird do not differ substantially from the communities reported in the Dry Valleys (Gressitt 1967; Wharton and Brown 1989; Schwarz et al. 1993; Treonis et al. 1999). The soil faunas in the vicinity of bird breeding areas are often perceived as being dependent on ornithogenic input, and this may be the case in many examples (e.g. Ryan and Watkins 1989). However, the distribution of invertebrates described here is not strongly related to the distribution of penguin rookeries or ornithogenic material at Cape Bird. The exception appears to be *Panagrolaimus davidi*, which has a predominantly coastal distribution (Wharton and Brown 1989), and appears closely related to the northern Adélie penguin rookery at Cape Bird. However, there are few details of Antarctic nematode distribution outside the McMurdo Sound area, and a lack of understanding of invertebrate dispersal processes in Antarctica limits the interpretation of this apparent relationship.

On a landscape scale, arthropod distribution in the McMurdo Sound region appears partially decoupled from macroscopic vegetation distribution (Janetschek 1967; Sinclair and Sjursen, 2001), with only the two mite species significantly associated with the presence of macroscopic vegetation. This is a similar pattern to that Sinclair and Sjursen (2001) described over a scale of metres in the same area of Ross Island. However, the presence of all arthropod species was closely correlated with soil algal biomass (as measured by chlorophyll-a content). *Stereotydeus mollis* and *N. antarcticus* are thought to feed directly on macroscopic algae (Fitzsimons 1971; Rounsevell 1981), whereas *G. hodgsoni* feeds mainly on fungi and unicellular algae (Davidson and Broady 1996). In addition, as the mite fauna appears to be less tolerant of very dry conditions than *G. hodgsoni* (H. Sjursen and B.J. Sinclair, unpublished work), there is a possibility that the former favour habitats with algal mats because of their effects on drying rate of soils.

Historically, terrestrial areas selected for protection in the Ross Sea region have been proposed and designed on the basis of macroscopic vegetation (Broady 1987). The assumption is that protection of the vegetation equates to protection of the invertebrate fauna. The tenuous relationship between the invertebrate fauna and macroscopic vegetation demonstrated here suggests that if representative protection of terrestrial invertebrates has been achieved, it is due more to good luck than to good management.

It is clear that the abiotic environment has some effect on the distribution of invertebrates at Cape Bird. However, key variables, such as the presence of macroscopic vegetation and soil carbon, do not explain the distribution of many of the taxa encountered. This study does provide evidence of invertebrate dispersal to most potential habitats over an area of kilometres, although the likely time scale of this dispersal (> 8,000 years) does not provide information on the ecological processes occurring over the shorter time scales likely to be relevant to climate change scenarios. Future investigations of spatial and time scales of invertebrate dispersal within and between ice-free areas will be necessary to determine short-term responses to potential changes in habitat quality and availability.

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