Critical Review

Hydrocarbon Spills on Antarctic Soils: Effects and Management

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Antarctic exploration and research have led to some significant although localized impacts on the environment. Human impacts occur around current or past scientific research stations, typically located on ice-free areas that are predominantly soils. Fuel spills, the most common occurrence, have the potential to cause the greatest environmental impact in the Antarctic through accumulation of aliphatic and aromatic compounds. Effective management of hydrocarbon spills is dependent on understanding how they impact soil properties such as moisture, hydrophobicity, soil temperature, and microbial activity. Numbers of hydrocarbon-degrading bacteria, typically *Rhodococcus*, *Sphingomonas*, and *Pseudomonas* species for example, may become elevated in contaminated soils, but overall microbial diversity declines. Alternative management practices to the current approach of "dig it up and ship it out" are required but must be based on sound information. This review summarizes current understanding of the extent and effects of hydrocarbon spillage on Antarctic soils; the observed physical, chemical, and biological responses of such soils; and current gaps in knowledge.

Introduction

More than 100 yr of exploration and research have led to some significant although largely localized impacts on the Antarctic environment, particularly in the last 50 yr (*1*). Consultative parties to the Antarctic Treaty recognized the need for increased protection when, in 1991, they ratified the Protocol on Environmental Protection to the Antarctic Treaty. The protocol designates Antarctica as an internationally important natural reserve devoted to peace and science and provides a comprehensive environmental management regime. Many countries that maintain research stations in Antarctica (including New Zealand, Australia, and the United States) have subsequently improved management practices and developed strategies to reduce environmental disturbances, including mitigating past impacts. Many of these impacts have occurred on ice-free ground, where the majority of Antarctic scientific research stations are located.

The total ice-free area of Antarctica comprises less than 0.3% of the continent (*2*). Ice-free areas are the most biologically active terrestrial sites on the continent. They are the focus of human activity and continue to attract scientists and increasing numbers of tourists. Ice-free areas are arguably the most vulnerable to anthropogenic changes.

Several consequences arise from human activities in the ice-free areas, including local pollution due to oil spills (*3*, *4*), deposition of combustion products (*5*), landscape modification due to construction (*6*), introduction of foreign organisms (*7*), and disturbance to wildlife (*8*). It has been recognized by the Council of Managers of National Antarctic Programs that fuel spills, as the most common incidents, have the potential to cause the greatest environmental harm in and around the continent. Such spills occur mainly near the scientific stations where fuel is transported and stored in large quantities and where aircraft and vehicles are refueled (*3*, *9*).

In this paper we review properties of Antarctic soils; the sources and types of hydrocarbons that accumulate in the soils following fuel spills; the effects of the hydrocarbons on physical, chemical, and biological soil properties; and current management strategies for dealing with hydrocarbon contamination of the soils. This review of the current state of knowledge by identifying gaps in information can form the basis for directing scientific research into areas needed to ameliorate impacts of fuel spills on Antarctic soils and make rational management decisions for the continent.

Soils of Antarctica

Ice-free areas of the Antarctic, 90% of which are soil-forming, are located mainly on or near the continental coastline, particularly on the Antarctic Peninsula and in the Ross Sea region (Figure 1). Approximately half of the ice-free ground occurs within the Ross Sea region, including the largest continuous expanse of ice-free ground, the McMurdo Dry Valleys. The soils are referred to as cold desert soils and are classified as Anhyorthels (*10*). They are characterized by low soil temperatures with mean annual temperatures ranging from −15 to −40 °C (*11*) and low soil moisture. Antarctic soils are diverse, due mainly to differences in land-surface age (which ranges from a few thousand to millions of years), parent material, topographic position, and local climate variations.

Antarctic soils comprise a surface pavement and a seasonally thawed active layer over permafrost. The surface pavement is a layer of gravel, stones, or boulders formed largely by weathering and removal of fine material, mainly by wind action; and varies in appearance due to rock type

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10.1021/es0305149 CCC: $27.50
Published on Web 01/21/2004

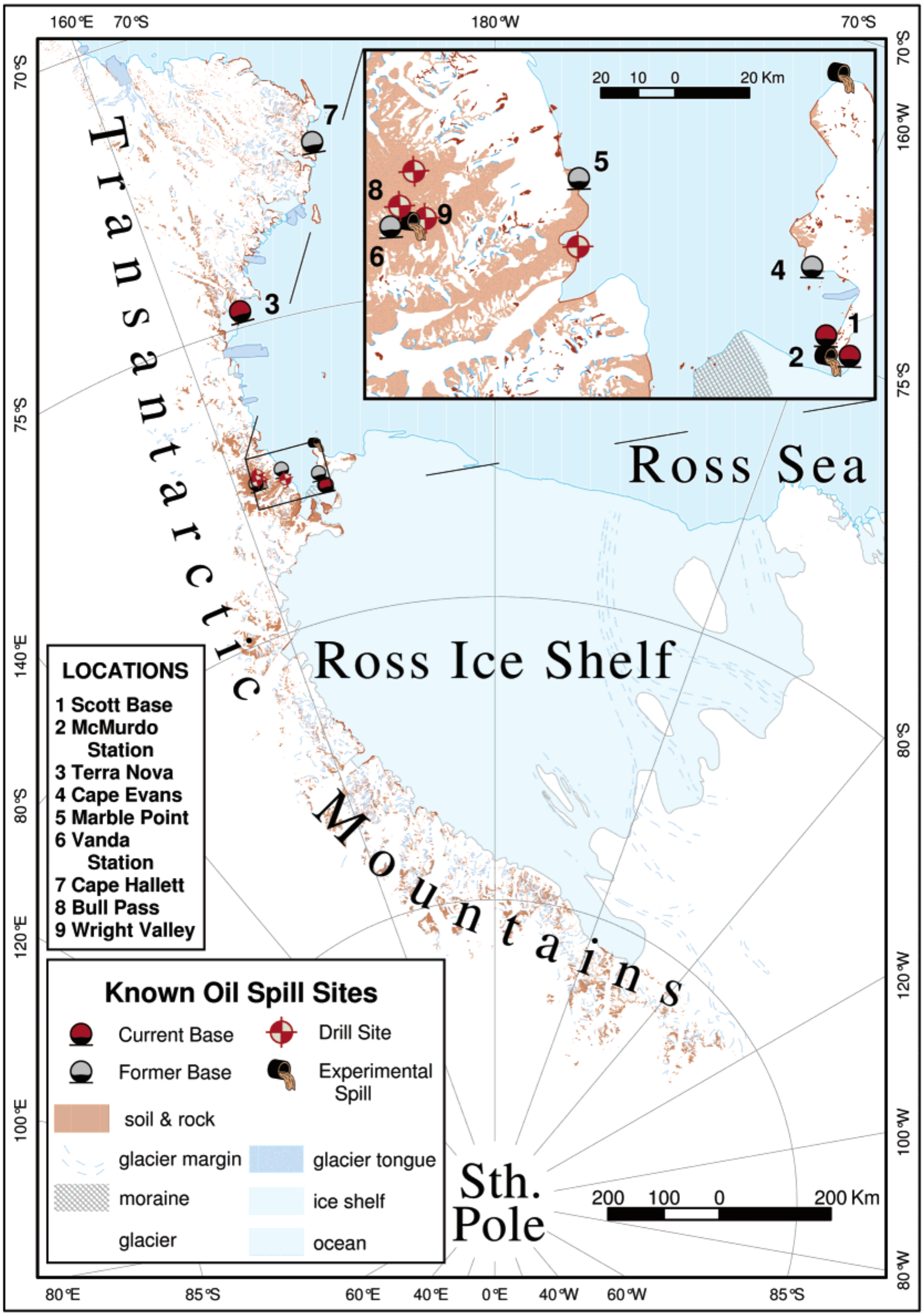

FIGURE 1. Map of the Ross Sea region highlighting soils and showing sites of known hydrocarbon spills, discriminating between current operating bases, former bases, drill sites, and experimental spills.

and to weathering differences (*11*). Beneath the surface pavement is the active layer with depths ranging from 17 to 55 cm (*12*). The soil texture in the active layer is highly variable, with most soils having a loamy sand or sand texture with abundant gravel, stones, and boulders (*13*). The soil material in the active layer, when not frozen and ice-cemented, is almost invariably loose and unconsolidated. The color of the subsurface soil varies according to the age of the soil and the parent materials (*11*).

Permafrost (defined as material that remains at temperatures <0 °C for 2 consecutive years) underlies all exposed ground surfaces except those heated by volcanic activity. Near the coast and along the polar plateau, Antarctic permafrost is usually ice-cemented (*10*). At some sites, particularly within the Dry Valleys, the water content of the permafrost (generally less than 5%) is insufficient to cement the soil particles together; the permafrost material is loose and is described as dry permafrost (*10*). In some areas,

TABLE 1. Chemical and Microbial Properties and Summer Moisture Contents of Hydrocarbon-Contaminated and Pristine Soils of the Ross Sea Region[a]

location depth (cm)	TPH[b] (mg/kg dry wt)	MPN[c] of hydrocarbon degraders (g^{-1} dry wt)	no. of culturable heterotrophs (g^{-1} dry wt)	% moisture	pH (water)	total C (%)	total P (%)	total N (%)	nitrate N (mg/kg dry wt)	EC[d,e] (mS/cm)
Scott Base										
pristine[f]										
0−1	<30	33	3.4×10^6	1.8	8.9	0.10	0.19	0.01	1.3	0.30
15−30	<30	13	2.5×10^3	6.2	8.3	0.06	0.18	0	0	0.07
contaminated[e]										
0−2	33700	1.3×10^5	4.2×10^6	1.6	7.8	5.14	0.15	0.02	0.8	0.22
20−30	1100	8.3×10^4	1.4×10^6	7.0	9.8	1.17	0.1	0.00	0.5	0.11
Marble Point										
pristine[f]										
0−3	<20	<10	3.7×10^5	2.4	9.6	0.28	0.07	0.02	2.2	0.65
15−32	<20	<10	2.4×10^4	5.9	7.9	0.50	0.07	0.01	7.4	0.99
contaminated[f]										
0−3	29100	1.1×10^7	5.3×10^7	1.9	8.3	5.33	0.06	0.02	0.5	0.18
12−27	200	8.8×10^4	6.6×10^6	11.4	9.5	0.20	0.06	0	0.5	0.20
Wright Valley										
pristine[f]										
0−2	<20	nd[g]	5.6×10^3	0.2	7.6	0.03	0.02	0.01	0	5.58
15−48	<30	nd	<100	2.0	7.1	0.02	0.03	0.04	103.8	7.25
contaminated[f]										
0−2	<30	nd	<100	0.4	7.4	0.02	0.03	0.01	24.5	0.62
16−35	960	nd	nd	4.8	7.3	0.07	0.02	0.05	116.6	11.86

[a] See Table 1a in the Supporting Information for additional data. [b] Total petroleum hydrocarbons. [c] Most probable number. [d] Electrical conductivity. [e] Unpublished data (Aislabie, J.). [f] Data taken from ref *40.* [g] Not detected.

permafrost below the active layer may consist almost entirely of ground ice believed to be up to several million years old (*11*).

There is an annual, cyclic pattern of soil temperature linked to solar radiation. In winter, with the absence of the sun, soil temperatures across the continent are continually below 0 °C. During summer there is a short period during which soil temperatures are above 0 °C with large daily fluctuations in near-surface soil temperatures and strong temperature gradients between the soil surface and the depth of freezing (*12*, *14*). The depth of thaw can vary markedly between seasons, depending on the air temperatures and snow and cloud cover. Summer soil surface temperatures of up to +18 °C have been reported for a range of sites in the Ross Sea region (*14*, *15*). In summer, surface albedo (the ratio of light reflected from, to light incident upon, a surface) is the major factor affecting the diurnal temperature regime of Antarctic soils as it determines the proportion of incoming solar radiation available to heat the soil (*15*). In winter, soil surface temperatures are generally linearly related to air temperature, although the soils may be insulated by winter snow cover (*12*).

In the coastal and northern regions, where temperatures and precipitation are relatively high, soil moisture values are greatest (*16*). For example, on the coast at Scott Base and Marble Point (Figure 1), gravimetric soil moisture contents are typically ca. 2% near the soil surface and up to 10% in the remainder of the active layer (Table 1). In the inland areas such the McMurdo Dry Valleys, where precipitation is reduced, gravimetric soil moisture values are lower with <1% moisture recorded throughout some soil profiles. Small areas of soil adjacent to streams, lakes, or thawing patches are moistened during summer by ephemeral water flows, with gravimetric moisture contents of up to 14% recorded (*16*). Much of the snowfall in the Ross Sea region is lost to sublimation, and increased soil moisture from snowmelt is often short-lived (*16*).

The soils typically have low levels of organic carbon and nitrogen, are low in clay (usually 1−2%; Table 1), and consequently have little pH buffering capacity. A notable exception are Ornithogenic soils formed under penguin rookeries, which have an organic carbon content around 20% and total nitrogen levels of about 16%. Soil pH may range from weakly acidic (pH 6) in inland soils at high elevation to highly alkaline (pH 9) in soils of coastal regions (*11*, *13*; Table 1). This reflects the dominant salts: in soils near the coast, chlorides dominate, whereas in more acidic, inland soils, sulfate and nitrate salts predominate (*11*). The salt content in the soils increases with dryness and surface age. The salts in older, drier soils commonly occur as a salty layer ca. 5−15 cm below the soil surface, and salt encrustations are common under surface pavement rocks (*13*).

Hydrocarbons in Antarctic Soils

Hydrocarbons are introduced into the Antarctic environment through natural and anthropogenic sources. Natural sources in soils include long-chain *n*-alkanes and/or *n*-alkenes most likely derived from cyanobacteria and green algae (*17*) and, less significantly, polyaromatic hydrocarbons associated with meteorites (*18*, *19*). Most hydrocarbons on land, however, are derived from human activity concentrated around current and past scientific research stations and field camps (*1*).

Anthropogenic Sources. Most human activities in the Antarctic require hydrocarbons for power generation, heating, and vehicle and aircraft operations. McMurdo Station on Ross Island (Figure 1), the largest scientific research station in the Antarctic, has storage capacity for approximately 34 million L of fuel, most of which is currently JP-5, a special mix of light petroleum distillate aviation turbine fuel with numerous additives (see section on Fuel Associated Non-Hydrocarbon Co-Contaminants) (*1*, *20*). In the past, jet fuel and diesel variants have included JP-8 and Diesel Fuel Arctic (DFA). Special Antarctic Blend (SAB) is the major fuel used at Australian bases in eastern Antarctica (*21*). Hydrocarbon mixes used in lesser quantities include mogas (a military grade of gasoline) and lubricating and engine oils. JP-5 fuel is distributed from McMurdo Station to airfields by above-ground pipelines and hoses and to Scott Base by road transport. At Marble Point, on the mainland, there is a refueling station (560 000 L storage capacity) for helicopters operating in the Dry Valleys, replenished by offshore pumping from refueling vessels.

Hydrocarbon contamination of soils is most often associated with accidental spillage during storage and distribution of fuels from storage tanks, drums, bladders, or pipelines (*1*, *20*, *22*). Other sources include leaks of lubricating oils and engine oils from vehicles and aircraft (*1*, *20*) and experimental oil spills (*23*−*26*), with minor contributions from the deposition of stack emissions from diesel generators and incinerators, or emissions from vehicles burning fuel (*20*, *27*). Another source of contamination in coastal areas is the release of diesel or aviation fuel into the sea from vessels grounding and/or sinking, as occurred in the Antarctic Peninsula following the grounding of the supply ship *Bahia Paraiso* (*28*). Hydrocarbon contamination of soils has also resulted from scientific drilling activities, most notably the Dry Valley Drilling Project where DFA was used as a drilling fluid at some sites including Lake Vida and New Harbor (*29*). The sites in the Ross Sea region where hydrocarbon spills have been reported are shown in Figure 1; however, it is likely that other sites have also been contaminated as formal documentation of oil spills is a relatively recent policy. McMurdo Station is the site of the most extensive contamination in the region. Widespread hydrocarbon contamination has been reported in McMurdo Station soils, with areas in the vicinity of fuel storage and distribution areas such as the helicopter pads most highly contaminated (*20*). Significant hydrocarbon contamination has also been reported at Old Casey Station (*22*) in East Antarctica.

Fate of Hydrocarbons. When spilled on Antarctic soils, hydrocarbons undergo naturally occurring processes that reduce the mass of the contaminants. Physical processes can cause the contaminants to disperse and become diluted and or/volatilize, whereas chemical and biological processes can transform contaminants to other compounds, possibly causing them to precipitate or sorb to soil. These mechanisms typically occur at all spill sites to varying degrees, depending on the type and concentration of the fuels spilled and on soil characteristics.

Light fuels with a high vapor pressure such as jet fuel and mogas readily volatilize from Antarctic soil (*24*−*26*, *30*). However, being of low viscosity, they are also mobile and thus able to migrate down through the unfrozen soil active layer (*25*, *26*, *30*). In comparison, heavier fuels such as lubricating and engine oil are less volatile and more viscous and do not appear to migrate far from the point of deposition (*14*, *22*, *30*). When the active layer is thawed, downward movement of hydrocarbons may be limited by the presence of an ice-saturated lens or layer that often occurs at the top of the permafrost (*31*). Fuel has been observed ponding at spill sites and spreading across a wider area on the ice-cemented permafrost surface than at the ground surface (*31*, *32*). While the ice-cemented layer is a seemingly impermeable barrier, recent studies in the Arctic have indicated that hydrocarbons move through this layer into frozen soil via cracks or fissures or unfrozen pore water (*33*).

Freeze−thaw processes may also influence hydrocarbon movement in soils. It has been demonstrated in sandy Arctic soils that oil moved ahead of the freezing front, implying that when soils are cooled from the surface down through the active layer, hydrocarbons may migrate toward the permafrost interface (*31*). Dissolved and particle-associated hydrocarbons in surface and subsurface soils can be mobilized with snowmelt during the thaw and may contribute to contamination of offshore marine environments (*3*, *20*, *22*, *34*).

The presence of hydrocarbon degraders in moist coastal soils indicates the potential for biodegradation of hydrocarbons under in situ conditions (Effect of Soil Biota). To our knowledge, there are no published reports on sorption of hydrocarbons to Antarctic soils.

Residual Hydrocarbon Contaminants in Soil. Total petroleum hydrocarbon (TPH) analysis of soil from a number of sites around current or former bases confirms the presence of hydrocarbon contamination in surface and subsurface soils (*21*, *22*, *24*, *30*, *35*−*41*; Table 1). Given the history of some sites, it is most likely that hydrocarbons have contaminated some of these soils for more than 40 yr. McMurdo Station and Scott Base, for example, were established for the International Geophysical Year in 1958, and hydrocarbons in soil at Cape Evans are presumed to originate from fuel depots laid by the Terra Nova Expedition of 1910 (*41*). Qualitative hydrocarbon analysis suggests that some sites have been contaminated with both heavy and light fuels (*3*). Furthermore, surface hydrocarbon contamination appears to have been modified through a combination of abiotic and biotic processes, whereas subsurface contamination in the same profile may be unchanged (*30*).

Chemical characterization of the hydrocarbon contaminants from some sites around Scott Base, Palmer Station, Casey Station, and Davis Station has revealed that *n*-alkanes predominate (*3*, *21*, *22*, *37*, *39*), with lesser concentrations of the more toxic monoaromatic and polyaromatic hydrocarbons (PAH). Typical PAH concentrations for Ross Sea region soils are summarized in Table 2. Highest levels of PAH were detected in McMurdo Station soils taken from an unpaved road and near gasoline pumps (*42*); naphthalene and/or methylnaphthalenes were the dominant PAHs detected (*3*, *42*, *43*). At some spill sites, residual hydrocarbons were detected predominantly as an unresolved complex mixture (UCM) (*3*). The chemically complex UCM is indicative of certain refined products such as lubricating oils (*44*), motor oils (*45*), and severely biodegraded (*46*) and weathered (*47*) oils.

Fuel Associated Non-Hydrocarbon Co-Contaminants. Other classes of compounds present in fuel oils used in the Antarctic include organic lead and anti-icing agents such as ethylene glycol monomethyl ether and diethylene glycol monomethyl ether. Military grade fuels, as used and supplied by the United States, also contain antistatic additives, antioxidants, and anticorrosive additives. Although elevated levels of organic lead have been detected in soil from a former gasoline storage area at Scott Base (*37*) and anti-icing agents presumptively identified in soils (*43*), the impact and significance of such fuel additives are not well understood.

Effects of Hydrocarbons on Soil Properties

Hydrocarbons in soil are of concern because of their potential for detrimental effects on soil properties. Understanding these effects is central to any attempt to manage or remediate contaminated soil.

Effects on Soil Temperature and Moisture Regimes. Comparisons between temperature profiles of hydrocarbon-contaminated and pristine sites at Scott Base and Marble Point (Figure 2) indicate that during sunny weather, when soils are snow-free, the daily maximum surface temperature of hydrocarbon-contaminated soils is often warmer (by up to ca. 10 °C) than adjacent pristine sites (*14*). The higher temperatures at the hydrocarbon-contaminated sites were attributed to decreased soil surface albedo due to surface darkening by hydrocarbons. In contrast, at a Bull Pass site where hydrocarbons contaminated the subsurface, no difference in soil temperature was detected between a pristine and hydrocarbon-contaminated soils (*14*).

There is potential for hydrocarbons to affect soil moisture regimes. Hydrocarbon-contaminated soils were weakly hydrophobic, whereas no evidence of hydrophobicity was detected at pristine sites. However, the small increase in

TABLE 2. PAH Contents of Hydrocarbon-Contaminated Soils of the Ross Sea Region

polyaromatic hydrocarbon (ng/g of dried soil)	Scott Base[a]	McMurdo Station[b]	Cape Evans[c]	Marble Point[a]	Vanda Station[a]
soil depths sampled (cm)	0–30	0–5	0–10	0–30	0–5
no. of soils analyzed from each site	5	20	7	4	2
naphthalene	235–6858	5–27 000	<300	<30–127	56–244
1-methylnaphthalene	125–2820	na[d]	na	<30	<30–299
2-methylnaphthalene	160–3015	na	na	<30–53	<30–436
acenaphthylene	<30–43	11–15 700	bdl[e]	<30	<30–137
acenaphthene	<30–203	30–17 800	bdl	<30	<30–69
fluorene	39–206	32–1590	1–250	<30	<30–286
phenanthrene	40–232	5–540	11–2460	<30	<30–1052
anthracene	<30	76–5000	2–160	<30	<30–121
fluoranthene	<30–161	2–13 300	18–770	<30	<30–482
pyrene	<30–416	3–132	11–1170	<30	<30–851
benz[*a*]anthracene	<30–38	4–1420	6–1230	<30	<30–58
chrysene	<30–60	5–1630	6–2950	<30	<30–96
benzo[*b*]fluoranthene	<30–60	na	6–340	<30	<30
benzo[*a*]pyrene	<30	na	3–370	<30	<30
indeno[1,2,3-*cd*]pyrene	<30	na	<70	<30	<30
dibenz[*ah*]anthracene	<30	na	<70	<30	<30
benzo[*ghi*]perylene	<30	na	<70	<30	<30

[a] Data taken from ref *43*. [b] Data presented for McMurdo Station are the range of averages taken from ref *42*. [c] Data taken from ref *41*. [d] Not analyzed. [e] Below detection limits.

hydrophobicity was considered unlikely to alter moisture penetration into the soil (*14*). No differences in moisture retention were found between hydrocarbon-contaminated and pristine soils at Scott Base, Marble Point, or Bull Pass (*14*).

Effects on Soil Chemical Properties. Some soil chemical properties may be impacted by hydrocarbon spills (*40*; Table 1). In particular, hydrocarbon spills on mineral soils of the Ross Sea region can lead to a substantial increase in soil carbon. While the carbon content of pristine soils was low (0.02 and 0.12%), following contamination with hydrocarbons the soil carbon content exceeded 5%. Levels of nitrate in hydrocarbon-contaminated soils from Scott Base and Marble Point were depleted compared with pristine soils, a possible consequence of microbial activity in the contaminated soils. Total P levels, however, appeared unaffected by hydrocarbon contamination. The bulk soil pH values of the surface hydrocarbon-contaminated soils from Scott Base, Marble Point, and Cape Evans were lower than the corresponding pristine sites, possibly indicating the accumulation of acidic microbial metabolites derived from hydrocarbons.

Effects on Soil Biota. The prevailing low temperatures, low humidity, freeze–thaw cycles, and salinity of Antarctic soils combine to create a harsh environment for soil biota. Few plants and animals have managed to colonize and survive in the terrestrial environment. One report speculates on possible effects of hydrocarbons on moss and collembola (*23*) and another reports the observation of oiled penguin chicks in melt pools on land at Cape Hallett (*48*). Microbes, however, are distributed throughout Antarctic soils. Investigations of the effects of hydrocarbons on Antarctic soil biota have therefore focused on microbes.

Studies of the impacts of hydrocarbon spills on soil microbial populations were originally initiated as part of the environmental monitoring program for the Dry Valley Drilling Project (*49*); more recent investigations derive from interest in the potential application of bioremediation for cleanup of hydrocarbon-contaminated Antarctic soils (*37, 38, 50, 51*).

Numbers of Microbes. Spillage of hydrocarbons on Antarctic soils can result in enrichment of hydrocarbon-degrading microbes (*36–38, 40, 49, 52, 53*; Table 1) so that they become a significant proportion of the total culturable microbiota. Numbers of hydrocarbon degraders are often low or below detection limits in pristine soils (*37*, *38*, *40*) (although ornithogenic soils may be an exception; *52*, *53*), whereas $>10^5$ hydrocarbon degraders g^{-1} have been cultivated from contaminated soils (*37, 38, 40, 52, 53*). In contrast, culturable heterotrophic bacteria were only 1–2 orders of magnitude higher in hydrocarbon-contaminated than pristine coastal soils (*37*, *38*, *40*). Culturable yeasts were not detected in pristine coastal soils, yet reached $>10^5$ colony forming units g^{-1} dry wt in contaminated soils (*40*). These results indicate that hydrocarbon contaminants in Antarctic soils can serve as substrates for microbial growth and result in an enhanced number of culturable bacteria and increased proportions of hydrocarbon-degrading bacteria. A notable exception was a site near Scott Base, where reduced numbers of culturable heterotrophic bacteria and the absence of detectable hydrocarbon degraders were attributed to the presence of residual toxic leaded fuels (*37*). Organic lead levels at the site were 25-fold higher than those detected in soils from pristine sites.

Significant rates of mineralization of radiolabeled dodecane and naphthalene have been measured in microcosms containing contaminated soils from Scott Base but not in nearby pristine soils. This indicates that hydrocarbon degraders can be active in the soils (*37*) under conditions similar to those in situ. The observed persistence of hydrocarbons in soils over decades however, indicates that in situ biodegradation rates must be very slow.

Hydrocarbon-Degrading Bacteria. Hydrocarbon-degrading bacteria isolated from contaminated Antarctic soils have been assigned to a number of genera including *Rhodococcus*, *Acinetobacter*, *Pseudomonas*, and *Sphingomonas* (*54–60*). All the hydrocarbon-degrading bacteria reported thus far are psychrotolerant rather than psychrophilic: while they could grow at low temperatures, their optimum temperature for growth was greater than 15 °C. Given the temperatures that surface soils can reach in summer (ca. 20 °C), the paucity of psychrophiles restricted to low temperatures is not surprising.

Rhodococcus spp. were isolated directly from contaminated soil when provided with JP-8 jet fuel as sole source of carbon (*58*). These bacteria degraded *n*-alkanes with chain lengths from C6 to C20 and the branched alkane pristane but not aromatic compounds. Phylogenetic analyses have revealed that cultivated *Rhodococcus* spp. group with either *R. fascians* or *R. erythropolis* and are similar to alkane-degrading bacteria isolated from other cold environments (*58*), such as *Rhodococcus* sp. Q15 from Lake Ontario, Canada (*61*).

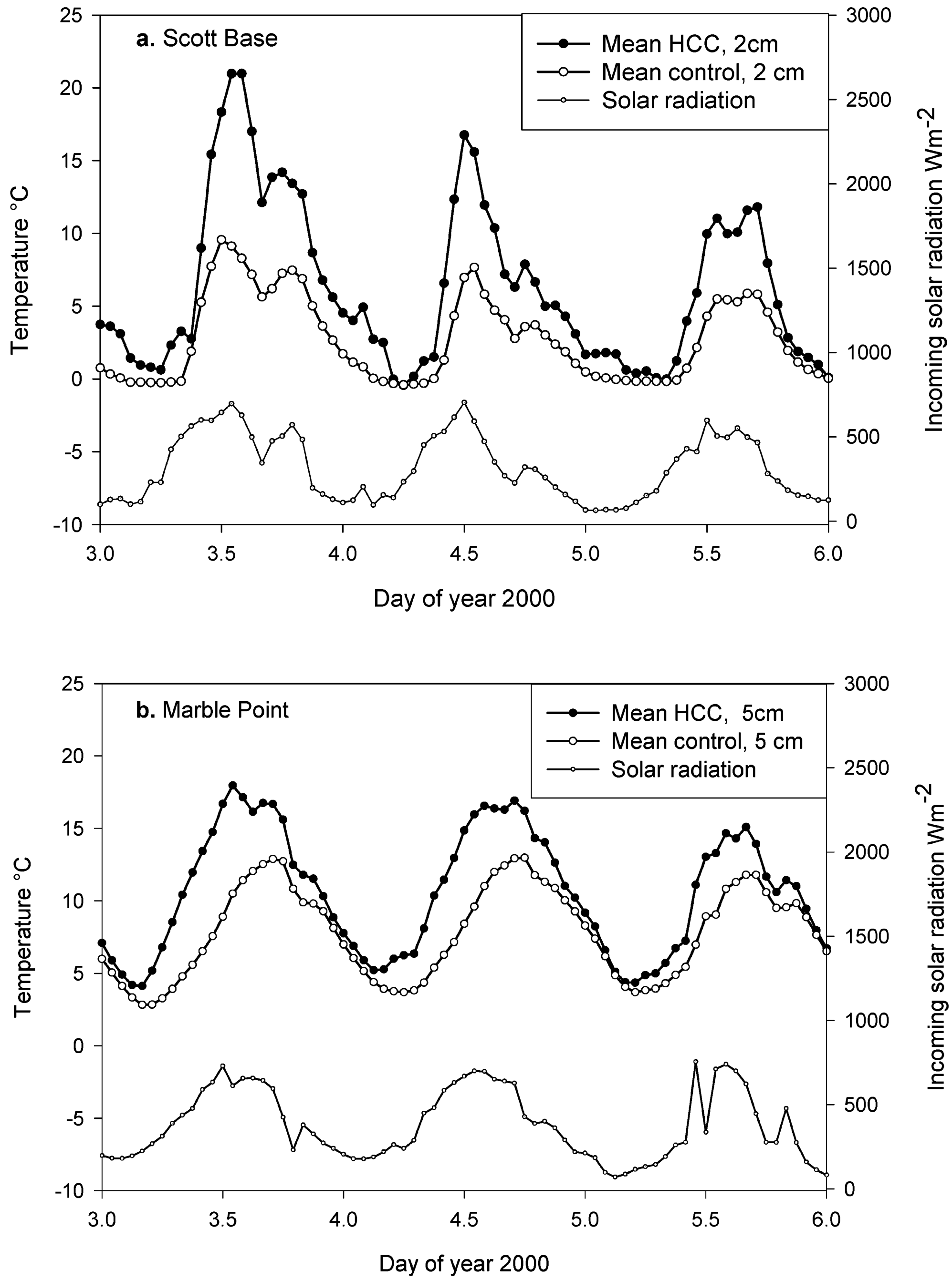

FIGURE 2. Incoming solar radiation and soil temperature for hydrocarbon-contaminated (HCC) and pristine soils for January 3−5, 2000, at (a) Scott Base at 2-cm soil depth and (b) Marble Point at 5-cm depth.

Detailed studies of alkane degradation (*alk*) genes in the psychrotolerant strains *Rhodococcus* sp. Q15 and *R. erythropolis* NRRL B-16531 revealed the presence of multiple alkane hydroxylase systems (*61*). This may be a common feature of hydrocarbon-degrading *Rhodococcus* spp., conferring on them a broad alkane substrate range for growth. Complementary investigations with *alk* genes from Gram-positive and Gram-negative bacteria determined that homologues of two *Rhodococcus alk* genes were common in contaminated and pristine soils from the Antarctic Peninsula (*62*) and that gene Rh *alkB1* was more prevalent in culturable cold-adapted bacteria. This suggests that *Rhodococcus* is a predominant alkane degrader in pristine and contaminated polar soils.

Pseudomonas and *Sphingomonas* spp. were isolated when soil samples were provided with aromatic substrates, such as *m*-toluate or naphthalene, as the sole source of carbon (*59*). These bacteria were able to use more than one aromatic hydrocarbon for growth. Phylogenetic analysis of the *Pseudomonas* isolates revealed that they grouped with *P. syringae* (*59*). This cluster also contains *Pseudomonas* spp. BI7 and BI8, aromatic hydrocarbon-degrading bacteria isolated from Arctic soil (*63*).

The genus *Sphingomonas* contains a number of PAH-degrading strains. Phylogenetic analysis indicated that the aromatic-degrading *Sphingomonas* spp. fell into two groups: *Sphingomonas* sp. Ant 17 clustered with known PAH degraders (*59*), whereas *Sphingomonas* sp. Ant 20 was recently assigned to the new species *S. aerolata* (*64*). *Sphingomonas* sp. Ant 17 degrades the aromatic fraction of several different crude oils, jet fuel, and diesel fuel at low temperatures and without nutrient amendment. It utilizes or transforms a broad range of pure aromatic substrates, including hydrocarbons, heterocycles, aromatic acids, and alcohols (*65*). Study of catabolic genes in psychrotolerant aromatic degrading *Pseudomonas* isolates from Antarctic and Arctic soils indicates that the genes are analogous to those originally described in mesophiles (*63*, *66*).

Recently, heterotrophic nitrogen-fixing bacteria isolated from Marble Point soil were also shown to degrade jet fuel (*67*). One of the isolates, *Pseudomonas stutzeri* 5A, grew on the aromatic compounds toluene, benzene, and *m*-xylene, whereas *Pseudomonas* sp. 5B utilized hexane and dodecane vapors. These results suggest that such bacteria may contribute both to hydrocarbon degradation and nutrient cycling in situ.

Effects on Microbial Community Diversity. Whereas the presence of hydrocarbons in Antarctic soils can result in increased abundance of culturable microbes, a concomitant decrease is typically observed in overall microbial community diversity (*29*, *40*). At drilling sites where diesel fuel has been spilled, ammonifiers and hydrocarbon-degrading microbes may become predominant (*29*). Furthermore, shifts in the predominant fungal species of soils have been noted. Specifically, *Phialophora* spp. were more abundant in hydrocarbon-contaminated soils, whereas *Geotrichum* and *Chrysosporium* dominated pristine soils, and yeasts were isolated only from contaminated soil (*40*, *54*).

To determine the impacts of hydrocarbon contamination on the diversity of bacterial communities in Ross Sea region coastal soils, a culture-independent phylogenetic survey and traditional culturing methods were combined (*68*). Soil samples were taken from two soil depths at a hydrocarbon-contaminated site and nearby pristine site at Scott Base. Small subunit rRNA genes were amplified directly from extracted soil DNA or from purified bacterial isolates using universal *Bacteria*-specific primers. Proteobacteria, specifically members of the genera *Pseudomonas*, *Sphingomonas*, and *Variovorax*, dominated the contaminated soils. In contrast, the pristine soil population was more diverse, comprising members of the divisions *Cytophaga*/*Flavobacterium*/*Bacteroides*, *Deinococcus*/*Thermus*, *Fibrobacter*/*Acidobacterium*, and Low G+C Gram-positive bacteria that were detected almost exclusively in pristine soil. However, the significance of this shift is unknown, as is the time required to re-establish the initial microbial population profile.

Management of Oil Spill Sites

Antarctic managers have a responsibility to avoid, remedy, or mitigate the adverse impacts of oil spills in Antarctic soils. In 1998, the Antarctic Treaty Consultative Meeting agreed upon a resolution recommending the adoption of guidelines related to fuel oil handling at research stations, spill prevention, and containment of fuel oils, oil spill contingency planning, and reporting of oil spills (*69*). National operators have made considerable improvements in fuel management, particularly at permanent stations. All national programs have fuel spill contingency plans in place, and recent upgrades to fuel transport and storage systems at McMurdo Station and Scott Base have provided double containment for most bulk fuel supplies and improvements to fuel transfer systems (*1*, *20*). Training is provided to station personnel, and response exercises are carried out routinely. Fuel spills still occur, although one might expect their frequency and size to decrease with infrastructure and procedural improvements.

Common practice in response to a fuel spill is to recover mechanically as much contaminated soil as possible, including any overlying contaminated snow or ice. This material is then shipped back to the home country and disposed of, usually at considerable expense. This procedure is still the dominant means of spill site management, but it is not based on sound scientific information about either the fate of spilled fuel or the effects of mitigation measures on terrestrial ecosystems. In some cases, this approach may cause more damage to the environment. For example, soil excavation can cause permafrost melt, which may lead to severe environmental impacts such as altered streamflows, soil shrinkage, land slumping, salinization, and mobilization of contaminants (*6*, *39*). The Environmental Protocol requires that remediation and cleanup activities should not result in greater adverse environmental impact than the "do nothing" approach. To achieve this goal, more sophisticated response options are needed that take full account of the type and quantity of fuel spilled and of local environmental conditions and associated values. Managers need relatively simple decision tools, underpinned by good science, that will allow them to make quick decisions and to implement appropriate responses. This approach is particularly relevant in Antarctica where there is a short operating season and therefore a limited opportunity to take action, logistics are often constrained, and there are high costs associated with any cleanup effort. Any management approach must also be backed by comprehensive reporting and evaluation systems that allow the performance of any changes to current practice to be assessed and, if necessary, revised in future years. With advancing technology, geographic information systems are now proving useful to document and manage information on fuel spills (*70*), whereas noninvasive techniques such as remote sensing (*71*), ground penetrating radar, and electromagnetic induction (*72*) are now being trialed as tools for mapping fuel spills in Antarctica and other permafrost regions.

Alternatives to the "dig it up and ship it out" approach are only just beginning to be discussed in the Antarctic context. For example, doing nothing may be just as effective as digging up obviously contaminated soil where very small spills occur in certain environments that aid evaporative processes, such as the Dry Valleys (*26*). In contrast, where there is surface contamination by less volatile fuels, the traditional excavation approach may remain valid. Alternative remediation technologies such as permeable reactive barriers (*34*) and bioremediation (*51*, *74*) are currently being developed for the Antarctic. Vapor extraction (*75*) and in situ chemical oxidation (*76*) could also prove useful.

Permeable reactive barriers have been proposed for removal of hydrocarbons contaminants from flowing water (*34*). Several small experimental field plots using granular activated carbon were established to assess material performance and conceptual designs on-site at Casey Station in East Antarctica. However, further research is required to quantify reaction/adsorption rates at low temperatures for different fill material and to establish breakthrough curves for promising material.

Bioremediation is increasingly viewed as an appropriate remediation technology for cold climate soils. As for all soils, the successful application of bioremediation is dependent on appropriate biodegradative microbes and environmental conditions. As the Antarctic Treaty precludes importation of foreign organisms into the Antarctic, indigenous microbes are required. Fortunately, high numbers of hydrocarbon-degrading microbes have been detected in contaminated coastal soils, although bioaugmentation may be required for inland soils (*40*). Furthermore, laboratory studies have confirmed that bacteria isolated from contaminated soil have the ability to degrade the most common hydrocarbon contaminants in the soils, specifically *n*-alkanes, monoaromatics, and naphthalenes (*58*−*60*). The environmental conditions that limit hydrocarbon degradation in situ include low soil temperatures, particularly in subsurface soils, low levels of nutrients and moisture, and possibly alkalinity (*37*, *38*). As the soils are highly permeable, oxygen availability is most likely not a limiting factor in situ, and the low levels of soil organic matter indicate that contaminants, especially low molecular weight hydrocarbons, should be bioavailable. However, as indicated by the persistence of spilled hydrocarbons in situ, it is likely that the method of choice will be "assisted bioremediation", through amelioration of the factors limiting biodegradation such as nutrient limitation. Care must be taken when adding nitrogen to Antarctic soil as excess levels can inhibit hydrocarbon biodegradation by decreasing soil water potentials in low organic carbon soils (*51*, *77*). Bioremediation experiments conducted in situ indicated that, while nutrient and water addition to mineral soil enhanced hydrocarbon degradation in surface mineral soils (*73*, *74*), slow release fertilizer or fish compost did not enhance numbers of hydrocarbon degraders in ornithogenic soils (*53*).

Given the low temperatures in subsurface soils, the short season during which soils are thawed (ca. 6–12 weeks), and the need to control temperature, nutrient levels and moisture to increase degradation rates, ex situ bioremediation is likely to be the strategy of choice for remediation. Such an approach has proven successful when applied to Arctic soils. For example, ex situ biopiles constructed to treat diesel-contaminated soils have used combinations of biostimulation (heating, nutrients, and aeration) and bioaugmentation to achieve hydrocarbon degradation. Active heating (*78*) and passive heating (*79*) increased hydrocarbon biodegradation rates, but importantly, biodegradation has also been demonstrated to occur at or below 0 °C (*80*). Bioaugmentation of biopiles with enrichments of cold-adapted microbes has yielded variable results in the Arctic (*79*, *81*), but nutrient amendment consistently improved bioremediation (*78*, *79*, *81*). Some studies have shown that the integration of nutrient amendment and heating regimes is important for optimum bioremediation in Arctic soils (*78*, *82*), and this is likely also true for Antarctic soils.

Any remediation technologies developed for the Antarctic must operate under challenging environmental conditions, be easy to install and operate, have low energy and infrastructure requirements, and have minimal permanent impact on the environment.

Gaps in Current Knowledge

The area affected by hydrocarbons in Antarctica is not large, yet significant hydrocarbon contamination can be detected in soil around current and former scientific research stations more than 30 yr post-spill. Understanding the fate of spilled fuel in different environments, including the attendant risks to soil biota and soil processes, is critical to devising appropriate pro-active and reactive response strategies. This is particularly true for Antarctic soils, for which simple extrapolation from temperate environment experience is surely inappropriate.

Our current understanding of both the abiotic and biotic effects of hydrocarbon spills on Antarctic soils is incomplete and requires scientific investigation in several disciplines. For example, additional information about the chemical composition of contaminants and co-contaminants (both in spilled products and post-weathering), would improve prediction of spill impacts. Their abiotic fates (including volatilization, adsorption, and dissolution) are only partially known: for example, where hydrocarbons darken the soil surface, they contribute to increased soil temperatures during sunny periods, but possible effects on soil moisture and wettability are poorly known. Despite known parallels between Arctic and Antarctic conditions, it is not clear whether models specific to Antarctic soils are required for hydrocarbon fate and transport mechanisms such as penetration into permafrost (*31*, *33*) and the effects of freeze–thaw cycles on hydrocarbon dispersion.

Because spilled oil persists for long periods in Antarctic soils, questions also arise about whether the long-term residues are comparable to those in temperate soils or whether abiotic factors, particularly sorption and abiotic oxidation, exert a disproportionate influence on the fate of spilled oils in Antarctica. As oils weather and biodegrade, the fraction detected as the UCM increases. However, the toxicity to Antarctic microbiota of the different UCMs arising from fuels and lubricating oils is unknown, as is the mobility of this fraction.

The long-term effects of hydrocarbons on soil biota, including cyanobacteria and microalgae, and effects on nutrient cycling have yet to be studied. This information could be used to develop soil ecotoxicity tests appropriate for Antarctic soils. Although risks to human health and impacts to biota are the most widely accepted criteria for environmental guidelines, it may be that other criteria designed to protect specific values of the region, such as wilderness values, are also appropriate for the Antarctic (*83*).

The potential for assisted bioremediation of Antarctic fuel spills has yet to be comprehensively examined. In particular, measured rates of hydrocarbon biodegradation in situ in different soil types are lacking. Fundamental questions relevant to this area include: the rates of microbial biodegradative activity in situ and the relative contributions of fungi compared to bacteria; the magnitude of microbial contributions to nutrient cycling; microbial adaptations to cold temperature, nutrient limitation, and resistance to desiccation, ultraviolet irradiation, freeze–thaw cycles, and contaminant toxicity. Localized changes in soil microbial communities have been attributed to contamination effects and include reduction in bacterial diversity and increased dominance of a few resilient or opportunistic hydrocarbon-degrading bacterial species. With current molecular techniques, we are just beginning to address questions about the distribution of microbes and their catabolic genes in soil profiles and in different Antarctic soils; the potential for lateral transfer of catabolic genes and their persistence in the absence of hydrocarbons; and the significance and duration of population diversity shifts after hydrocarbon impact. Superimposed on the primary effects of oil spillage on Antarctic microbiota are the unknown potential effects of subsequent physical and chemical remediation efforts.

Addressing these areas of essential research will lead to rational selection of cleanup standards and remediation expectations appropriate to Antarctic soils. To date, no consensus has been reached on remediation guidelines for hydrocarbon contamination or cleanup protocols for the Antarctic. While we could apply target values for cleanup applied in higher latitudes, we have insufficient data to predict whether it is reasonable to use such target values to indicate risks in Antarctic soils, or whether these levels can be achieved. As our environmental management approaches become more refined, we will demand a more sophisticated understanding of the systems we aim to protect, presented in a manner that is targeted and comprehensible. An enlightened approach to fuel spill management, in particular, should lead not only to real savings in resources and other costs but also to an overall reduction in the extent and severity of human impacts on the Antarctic environment.

Acknowledgments

Dr. Ron Paetzold, U.S. Department of Agriculture, supplied soil climate data. Mr. Robert Gibb, Landcare Research, prepared Figure 1. This work was supported by funding from the Foundation for Research, Science and Technology, New Zealand (C09X0218). Antarctica New Zealand provided logistic support.

Supporting Information Available

Table 1a contains additional data on the chemical and microbial properties and summer moisture contents for hydrocarbon-contaminated and pristine soils of the Ross Sea region. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Waterhouse, E. J., Ed. *Ross Sea Region 2001. A State of the Environment Report for the Ross Sea Region of Antarctica*; New Zealand Antarctic Institute: Christchurch, New Zealand, 2001.
(2) Fox, A. J.; Cooper, P. R. *Polar Rec.* **1994**, *30*, 201.
(3) Kennicutt, M. C.; McDonald, T. J.; Denoux G. J.; McDonald S. J. *Mar. Pollut. Bull.* **1992**, *24*, 499.
(4) Cripps, G. C. *Mar. Pollut. Bull.* **1992**, *25*, 288.
(5) Suttie, E. D.; Wolff, E. W. *Atmos. Environ. Part A* **1993**, *27*, 1833.
(6) Campbell, I. B.; Claridge, G. G. C.; Balks, M. R. *Antarct. Sci.* **1994**, *6*, 307.
(7) Gardner, H.; Kerry, K.; Riddle, M.; Brouwer, S.; Gleeson, L. *Nature* **1997**, *387*, 245.
(8) Giese, M.; Riddle, M. *Polar Biol.* **1999**, *22*, 366.
(9) Cripps, G. C.; Priddle, J. *Antarct. Sci.* **1991**, *3*, 233.
(10) Bockheim, J. G. *Arct. Antarct. Alp. Res.* **2002**, *34*, 308.
(11) Campbell, I. B.; Claridge, G. G. C. *Antarctica*: *Soils, Weathering Processes and Environment*; Elsevier: New York, 1987; 368 pp.
(12) Guglielmin, M.; Balks, M. R.; Paetzold, R. F. In *Proceedings 8th International Permafrost Conference*; Vol. 1; Phillips, M., Springham, S. M., Arenson, L. U., Eds.; Balkema: Rotterdam, 2003; pp 337−341.
(13) Bockheim, J. G. *Soil Sci. Soc. Am. J.* **1997**, *61*, 224.
(14) Balks, M. R.; Paetzold, R. F.; Kimble, J. M.; Aislabie, J.; Campbell, I. B. *Antarct. Sci.* **2002**, *14*, 319.
(15) Campbell, D. I.; MacCulloch, R. J. L.; Campbell, I. B. In *Ecosystem Processes in Antarctic Ice-Free Landscapes*; Lyons, W. B., Howard-Williams, C., Hawes, I., Eds.; Balkema: Rotterdam, 1997; pp 45−55.
(16) Campbell, I. B.; Claridge, G. G. C.; Balks, M. R.; Campbell, D. I. In *Ecosystem Processes in Antarctic Ice-Free Landscapes*; Lyons, W. B., Howard-Williams, C., Hawes, I., Eds.; Balkema: Rotterdam, 1997; pp 61−76.
(17) Matsumoto, G. I.; Yamada, S.; Ohtani, S.; Broady, P.; Nagashima, H. *Proc. NIPR Symp. Polar Biol.* **1996**, *9*, 275.
(18) Clemett, S. J.; Chillier, X. D. F.; Gillette, S.; Zare, R. N.; Maurette, M.; Engrand, C.; Kurat, G. *Origins Life Evol. Biosphere* **1998**, *28*, 425.
(19) Naraoka, H.; Shimoyama, A.; Harada, K. *Earth Planet. Sci. Lett.* **2000**, *184*, 1.
(20) Kennicutt, M. C.; Wylie, D. J.; Wolff, G. A. *Summary of Existing Environmental Data, McMurdo Station, Antarctica*; Geochemical and Environmental Research Group, Texas A&M University: College Station, TX, 1998.
(21) Green, G.; Nichols, P. D. *Antarct. Sci.* **1995**, *7*, 137.
(22) Deprez, P. D.; Arens, M.; Locher, H. *Polar Rec.* **1999**, *35*, 299.
(23) Konlechner, J. *N. Z. Antarct. Rec.* **1985**, *6*, 40.
(24) Green, G.; Skerratt J. H.; Leeming, R.; Nichols, P. D. *Mar. Pollut. Bull.* **1992**, *25*, 293.
(25) Balks, M. R.; Holmes, D. J.; Aislabie, J. In *Transactions of the 17th World Congress of Soil Science*; Kheoruenromne, I., Ed.; International Union of Soil Sciences: Bangkok, Thailand, 2002; pp 320-1−320-9.
(26) Webster, J.; Webster, K.; Nelson, P.; Waterhouse, E. *Environ. Pollut.* **2003**, *123*, 163.
(27) Caricchia, A. M.; Chiavarini, S.; Cremisini, C.; Fantini, M.; Morabito, R.; Perini, A.; Pezza, M. *Water Sci. Technol.* **1993**, *27*, 235.
(28) Kennicutt, M. C. *Environ. Sci. Technol.* **1990**, *24*, 620.
(29) Cameron, R. E.; Honour, R. C.; Morelli, F. A. In *Adaptations within Antarctic Ecosystems, Proceedings of the Third SCAR Symposium on Antarctic Biology*; Llano G. A., Ed.; Gulf Publishing: Houston, TX, 1977; pp 1157−76.
(30) Gore, D. B.; Revill, A. T., Guille D. *Antarct. Sci.* **1999**, *11*, 427.
(31) Chuvilin, E. M.; Naletova, N. S.; Miklyaeva, E. C.; Kozlova, E. V.; Instanes, A. *Polar Rec.* **2001**, *37*, 229.
(32) Balks, M. R.; Campbell, I. B. *N. Z. Soil News* **1995**, *43*, 236.
(33) Biggar, K. W.; Haidar, S.; Nahir, M.; Jarrett, P. M. *J. Cold Reg. Eng.* **1998**, *12*, 84.
(34) Snape, I.; Morris C. E.; Cole C. M. *Cold Reg. Sci. Technol.* **2001**, *32*, 157.
(35) Krzyszowska, A. *Pol. Arch. Hydrobiol.* **1990**, *37*, 313.
(36) Tumeo, M. A.; Wolks, A. E. *Antarct. J.* **1994**, *29*, 375.
(37) Aislabie, J.; McLeod, M.; Fraser, R. *Appl. Microbiol. Biotechnol.* **1998**, *49*, 210.
(38) Balks, M. R.; Aislabie, J.; Foght, J. M. In *Proceedings of the 16th World Congress of Soil Science*; International Union of Soil Sciences: Montpelier, France, 1998; CD-ROM.
(39) Snape, I.; Riddle, M. J.; Cole, C. M.; Stark, J. S. *Polar Rec.* **2001**, *37*, 99.
(40) Aislabie, J.; Fraser, R.; Duncan, S.; Farrell, R. L. *Polar Biol.* **2001**, *24*, 308.
(41) Blanchette, R. A.; Held, B. W.; Jurgens, J. A.; Aislabie, J.; Duncan, S.; Farrell, R. L. *Polar Rec.* **2004**, *40*, 1.
(42) Mazzera, D.; Hayes, T.; Lowenthal, D.; Zielinska, B. *Sci. Total Environ.* **1999**, *229*, 65.
(43) Aislabie, J.; Balks, M.; Astori, N.; Stevenson, G.; Symons, R. *Chemosphere* **1999**, *39*, 2201.
(44) Gough, M. A.; Rhead, M. M.; Rowland, S. J. *Org. Geochem.* **1992**, *18*, 17.
(45) Draper, W. M.; Dhaliwal, J. S.; Perera, S. K.; Baumann, F. J. *J. AOAC Int.* **1996**, *79*, 508.
(46) Killops, S. D.; Al-Juboori, M. A. H. A. *Org. Geochem.* **1990**, *15*, 147.
(47) Barakat, A. O.; Qian, Y. R.; Kim, M.; Kennicutt, M. C. *Environ. Int.* **2001** *27*, 291.
(48) Anonymous. *Mar. Pollut. Bull.* **2001**, *42*, 255.
(49) Parker, B. C.; Howard, R. V. *Biol. Conserv.* **1977**, *12*, 163.
(50) Wardell, L. J. *J. Soil Contam.* **1995**, *4*, 111.
(51) Ruberto, L.; Vazquez, S. C.; MacCormack W. P. *Int. Biodeterior. Biodegrad.* **2003**, *52*, 115.
(52) Delille, D. *Microb. Ecol.* **2000**, *40*, 159.
(53) Delille, D.; Pelletier, E.; Delille, B.; Coulon, F. *Polar Rec.* **2003**, *39*, 1.
(54) Kerry, E. *Polar Biol.* **1990**, *10*, 423.
(55) Pruthi, V.; Cameotra, S. S. *World J. Microbiol. Biotechnol.* **1997**, *13*, 137.
(56) MacCormack, W. P.; Fraile, E. R. *Antarct. Sci.* 1**997**, *9*, 150.
(57) Cavanagh, J. E.; Nichols, P. D.; Franzmann, P. D.; McMeekin, T. A. *Antarct. Sci.* **1998**, *10*, 386.
(58) Bej, A. K.; Saul, D. J.; Aislabie, J. *Polar Biol.* **2000**, *23*, 100.
(59) Aislabie, J.; Foght, J.; Saul, D. *Polar Biol.* **2000**, *23*, 183.
(60) Panicker, G.; Aislabie, J.; Saul, D.; Bej, A. K. *Polar Biol.* **2002**, *25*, 5.
(61) Whyte, L. G.; Smits, T. M. H.; Labbé, D.; Witholt, B.; Greer, C. W.; van Beilen, J. B. *Appl. Environ. Microbiol.* **2002**, *68*, 5933.
(62) Whyte, L. G.; Schultz, A.; van Beilen, J. B.; Luz, A. P.; Pellizari, V.; Labbé, D.; Greer, C. W. *FEMS Microbiol. Ecol.* **2002**, *41*, 141.
(63) Whyte, L. G.; Bourbonnière, L.; Greer, C. W. *Appl. Environ. Microbiol.* **1997**, *63*, 3719.
(64) Busse, H.-J.; Denner, E. B. M.; Buczolitis, S.; Salkinoja-Salonen, M.; Bennasar, A.; Kampfer, P. *Int. J. Evol. Syst. Bacteriol.* **2003**, *53*, 1253.
(65) Baraniecki, C. A.; Aislabie, J.; Foght, J. M. *Microb. Ecol.* **2002**, *43*, 44.
(66) Farrell, R. L.; Rhodes, P. L.; Aislabie, J. *Biochem. Biophys. Res. Commun.* **2003**, *312*, 235.
(67) Eckford, R.; Cook, F. D.; Saul, D.; Aislabie, J.; Foght, J. *Appl. Environ. Microbiol.* **2002**, *68*, 5181.
(68) Saul, D. (manuscript in preparation).
(69) *Final report of the twenty-second Antarctic Treaty Consultative Meeting*; Antarctic Treaty Consultative Meeting: Tromso, Norway, 1998.
(70) Babicka, N. A.; Goldsworthy, P. M. In *Proceedings, Contaminated Site Remediation*: *From Source Zones to Ecosystems*; Johnston, C. D., Ed.; Centre for Groundwater Studies: Melbourne, Australia, 2000; pp 261−265.
(71) Rees, W. G. *Polar Rec.* **1999**, *35*, 19.
(72) Pettersen J. K., Nobes. D. C. *Cold Reg. Sci. Technol.* **2003**, *37*, 187.
(73) Kerry E. *Polar Biol.* **1993**, *13*, 163.
(74) Snape, I.; Ferguson, S.; Revill, A. In *Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates* (*ARCSACC*); Nahir, M., Biggar, K., Cotta, G., Eds.; St. Joseph's Print Group: Edmonton, AB, Canada, 2003; pp 257−261.
(75) Filler, D. M.; Barnes, D. L. In *Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates* (*ARCSACC*); Nahir, M., Biggar, K., Cotta, G., Eds.; St. Joseph's Print Group: Edmonton, AB, Canada, 2003; pp 343−348.
(76) Watts, R. J.; Haller, D. R.; Jones, A. P.; Teel, A. L. *J. Hazard. Mater.* **2000**, *B76*, 73.
(77) Ferguson, S. H.; Franzmann, P. D.; Revill, A. T.; Snape, I.; Rayner, J. L. *Cold Reg. Sci. Technol.* **2003**, *37*, 197.

(78) Filler, D. M.; Lindstrom, J. E.; Braddock, J. F.; Johnson, R. A.; Nickalaski, R. *Cold Reg. Sci. Technol.* **2001**, *32*, 143.
(79) Mohn, W. W.; Radziminski, C. Z.; Fortin, M.-C.; Reimer, K. J. *Appl. Microbiol. Biotechnol.* **2001**, *57*, 242.
(80) Rike, A. G.; Haugen, K. B.; Børresen, M.; Engene, B.; Kolstad, P. *Cold Reg. Sci. Technol.* **2003**, *37*, 97.
(81) Thomassin-Lacroix, E. J. M.; Eriksson, M.; Reimer, K. J.; Mohn, W. W. *Appl. Microbiol. Biotechnol.* **2002**, *59*, 551.
(82) Walworth, J.; Braddock, J.; Woolard, C. *Cold Reg. Sci. Technol.* **2001**, *32*, 85.
(83) Riddle, M. J.; Poland, J. S.; Zeeb, B. In *Proceedings of the Third International Conference on Contaminants in Freezing Ground*; Snape, I., Warren, R., Eds.; CSIRO Marine Laboratories: Hobart, Australia, 2002; pp 8−10.

Received for review September 1, 2003. Revised manuscript received November 18, 2003. Accepted November 20, 2003.

ES0305149