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Microbial Ecology of Terrestrial Antarctica: Are Microbial Systems at Risk From Human Activities?

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ABSTRACT

Many of the ecological systems found in continental Antarctica are comprised entirely of microbial species. Concerns have arisen that these microbial systems might be at risk either directly through the actions of humans or indirectly through increased competition from introduced species. Although protection of native biota is covered by the Protocol on Environmental Protection to the Antarctic Treaty, strict measures for preventing the introduction of non-native species or for protecting microbial habitats may be impractical.

This report summarizes the research conducted to date on microbial ecosystems in continental Antarctica and discusses the need for protecting these ecosystems. The focus is on communities inhabiting soil and rock surfaces in non-coastal areas of continental Antarctica. Although current policies regarding waste management and other operations at Antarctic research stations serve to reduce the introduction of non-native microbial species, importation cannot be eliminated entirely. Increased awareness of microbial habitats by field personnel and protection of certain unique habitats from physical destruction by humans may be necessary. At present, small-scale impacts from human activities are occurring in certain areas both in terms of introduced species and destruction of habitat. On a large scale, however, it is questionable whether the introduction of non-native microbial species to terrestrial Antarctica merits concern.

Key Words: Antarctica, bacteria, microbial ecology, dry valleys, soil, human impacts.

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1. INTRODUCTION AND BACKGROUND

The Antarctic Treaty nations agreed to the Protocol on Environmental Protection to the Antarctic Treaty in 1991. Annex II of the Protocol describes measures intended to ensure the protection of native flora and fauna. Although the primary focus of these measures is on preventing the introduction of macroscopic animals and plants to Antarctica, Appendix C of Annex II describes steps that should be taken to prevent the introduction of microorganisms not present in the environment. Although not implemented for this purpose, implementation of Annex III of the Protocol may also help to substantially reduce the introduction of non-native microbes by limiting the amounts and types of waste materials disposed of in Antarctica. It is recognized, however, that measures to ensure the complete exclusion of non-native microorganisms are impractical, short of preventing all human activities in Antarctica (Draggan 1993).

One issue not adequately addressed in Annex II is the protection of unique microbial habitats in Antarctica. Many of the Sites of Special Scientific Interest designated by the Antarctic Treaty were established at least in part for reasons related to the protection of microbial research (Draggan 1993). The degradation of microbial habitats in these and other areas, in combination with the introduction of exogenous microbes, may directly or indirectly interfere with scientific research conducted in Antarctica (Wynn-Williams 1985).

Historical interest in the microbiota of Antarctica may be categorized according to basic research emphasis, as modified from Wynn-Williams (1990):

- Examination of Surrogates for the Study of Extraterrestrial Environments: A series of investigations was initiated in the early 1970s as part of the Viking exploration program using the Dry Valleys (Victoria Land) as a surrogate for environments anticipated on Mars (Horowitz et al. 1972; Vishniac and Mainzer 1972; 1973; Cameron 1975; Cameron et al. 1976).

- Environmental Impact Studies: Several studies were conducted to examine the effects of research and logistical activities on microbial ecosystems, with special attention given to activities associated with the Dry Valley Drilling Project (DVDP) during the early 1970s (Cameron 1972a; Cameron et al. 1977; Parker 1978; Parker et al. 1978a; 1978b). Other assessments of microbial contamination were associated with the construction of research stations (Wynn-Williams 1985) and the potential exploration for oil resources (Konlechner 1985).

- Degradation of Research Conditions: Several studies were conducted on the survival and distribution of introduced bacteria, yeasts, and fungi associated with humans in the Dry Valleys and other inland sites (Cameron 1971; 1972b; Cameron et al. 1971a;

Cameron and Ford 1974). These studies were designed to determine whether introductions of non-native species were impacting research activities. More recently, problems encountered while conducting microbial research in terrestrial Antarctica due to the overwhelming effects of the presence of humans have been reported (Wynn-Williams 1985; Toyoda et al. 1985; Kerry 1990).

- Basic Research on Cold Adaptation: Considerable research has been conducted on the fundamental physiological principles associated with cold adaptation, including freezing tolerance, cryopreservation, anhydrobiosis, and psychrophily in microorganisms (Morita et al. 1977; Vishniac and Hempfling 1979a; Herbert 1986).

- Examination of Unique Microbial Habitats: Unique endolithic microbial ecosystems found within the shelter of porous sandstones and other rocks in the Dry Valleys (Victoria Land) have been examined (Friedmann 1977; 1982; 1985; Friedmann and Ocampo-Friedmann 1984; Nienow and Friedmann 1993). Research has also been conducted on unique, thermophilic microbes found in geothermal soil (Nicolaus et al. 1991; 1995; 1996).

The objective of this paper is to provide the National Science Foundation, Office of Polar Programs with a review of the information available on microbial ecosystems of continental Antarctica and how research and logistical support activities might be impacting these systems. Cold adaptation is discussed only as it relates to the development of microbial communities in the region and to the failure (or success) of exogenous microbes to survive once introduced. The focus is on bacteria, although other microbial forms are discussed as well. Conclusions regarding the efficacy of current policies and requirements on the protection of microbial ecosystems are also provided.

2. MICROBIAL ECOLOGY OF TERRESTRIAL ANTARCTICA

In contrast with marine systems, microbial systems in terrestrial Antarctica are characterized by relatively low levels of nutrients and primary productivity. These systems generally fall into two categories: those associated with macroscopic vegetation and those found primarily in areas essentially devoid of macroscopic vegetation. Microbial systems associated with moss and lichen communities in Antarctica are often complex (Baker and Smith 1972) and may resemble those found in similar associations in more temperate climates (Vishniac 1993). The geographic range of these communities is limited by the range of the associated moss and lichen communities, which are generally restricted to the Antarctic peninsula and a few coastal areas elsewhere.

In contrast, the distribution and abundance of terrestrial microbiota in non-vegetated areas of Antarctica is severely restricted by unfavorable environmental conditions and discontinuous inputs of nutrients and energy to the system (Draggan 1993). Microbiota living at or near the substrate surface in continental Antarctica are subjected to prolonged periods of sub-freezing temperatures, desiccation, hypersalinity, and transient and diurnal freeze-thaw cycles (Wynn-Williams 1990). In most areas, liquid water necessary to support the microbial growth required to stabilize the soil surface is inadequate (Cameron and Benoit 1970). The high velocity of katabatic winds common on the Antarctic continent also tend to substantially disrupt the soil surface. Such environmental conditions severely restrict the ability of microorganisms to colonize many areas within the region.

Research has attempted to evaluate the distribution of microbes in the Dry Valleys based on key environmental parameters (Cameron 1972c; Horowitz et al. 1972). These studies emphasized the importance of temperature and relative humidity in determining the survival and growth of microorganisms in terrestrial Antarctica. Other environmental parameters were not found to be well correlated with abundance, distribution, or the types of microorganisms found in the area.

Temperatures commonly fluctuate widely over relatively short time periods in the soils of continental Antarctica, and influence microorganisms directly or indirectly (Herbert 1986). Direct effects may influence growth rate, enzyme activity, cell composition, and nutritional requirements, whereas indirect effects may occur through the influence of temperature on properties such as the solubility of compounds, ion transport and diffusion, and osmotic effects on membranes (Oppenheimer 1970).

Several authors have claimed that microbial species isolated from terrestrial Antarctica do not generally possess special adaptations for coping with the extreme environmental conditions, as most isolated to date are cold- and desiccation-tolerant species that are also found in more temperate zones (Vincent 1988). However, other authors have indicated that Antarctic isolates of some species are capable of growing at lower temperatures than those of the same species collected in more temperate locations (Latter and Heal 1971; Line 1988).

The presence of suitable substrate may be of greater significance than climatic conditions in defining the presence and/or diversity of soil microorganisms in Antarctica (Boyd et al. 1966; Cameron and Benoit 1970; Cameron 1972b; Cameron et al. 1971a; Cameron and Ford 1974). Cameron et al. (1970a) reported greater density and diversity of microorganisms in younger soils with northern (sunny) exposures in comparison with older, better developed soils on southern with northern (sunny) exposures in comparison with older, better developed soils on southern exposures found nearby, and concluded that the development of microbial ecosystems in terrestrial Antarctica requires a favorable complex of interacting microclimatic and edaphic factors. Hirsch et al. (1985) reported relatively rich microflora in uncontaminated soils collected near rock boulders that had fairly narrow ranges of optimum growth for pH and temperature. In addition to climate and edaphic factors, other contributing factors may include the presence of penguin rookeries and camp-scavenging birds (Zunino et al. 1985) and the increased accumulation of organic matter (Boyd et al. 1970). Cameron et al. (1977) identified a gradient of microbial abundance decreasing from the coast of south Victoria Land to Mt. Howe at 87°21'S. This gradient was primarily attributed to the decreasingly favorable habitat from north to south, although "chemical and microbiological contamination brought about by human activity" was also identified as a contributing factor.

Many of the microbial studies conducted in pristine areas of terrestrial Antarctica have yielded very low viable cell counts and low species diversity. Parker et al. (1977) reported that soil samples collected from relatively pristine areas likely represent endemic populations characterized by the presence of low numbers of organisms of only a few species. These "systems" more closely resemble loose assemblages of species rather than true communities of multiple populations. Aside from indicating exceptionally low microbial populations, this also implies a general lack of community development in most of the habitats evaluated other than those that appear to be influenced by human activities.

Most of the early studies of Antarctic microbial ecology involved the use of methods such as cell counts to determine the presence and abundance of species. Frequently, species reported in these studies were found to be viable only under laboratory conditions. It is therefore likely that many of these organisms were transported into the area as dormant cells incapable of completing their life cycles under the harsh ambient conditions. As survival in a dormant state is far less demanding than growth and reproduction, this leads to difficulties in assessing the results of these studies. As stated by Vishniac (1993), cell viability under laboratory conditions is "not synonymous with membership in the microbial community." However, other microbes found in terrestrial Antarctica such as the endolithic species communities found living inside the surfaces of sandstones and other rocks (Friedmann 1977; 1982; 1985; Friedmann and Ocampo-Friedmann 1976; 1984) clearly represent constituents of "true" microbial communities (Wynn-Williams 1990).

3. INTRODUCTION PATHWAYS

Many of the microbial species isolated from soil and air samples in Antarctica are considered indigenous in that they are thought to have arrived on the continent without the assistance of humans. A variety of natural pathways have been identified by which microbes may be introduced to Antarctica. For areas located near marine systems, microbes may be dispersed via the action of sea spray or the movement and activities of animal vectors such as penguins and other birds and seals. In more isolated, non-marine systems such as the Dry Valleys, a more likely route for introduction is via high altitude air-streams.

That non-marine microbial species may have entered Antarctica via the atmosphere is by no means a new concept (McLean 1918), and many microorganisms have been shown to retain their viability for long periods of time despite the freezing and desiccating conditions found in Antarctica (Vincent 1988). This capability also enables propagules to survive in the upper airstream for the extended time period necessary for long-range, intercontinental transport to occur. This ability to survive in extreme environments likely explains why viable cells are found in virtually all continental soils other than those containing high levels of toxic substances (Vishniac 1993). However, questions regarding survival times and adaptive success of microorganisms introduced to Antarctica remain (Cameron et al. 1977). Long-distance transport of lichen spores and vegetative propagules to Antarctica has also been reported (Kappen 1993; Kappen and Straka 1988), although successful establishment of lichens is somewhat more complex in that both the fungal and algal symbionts must be present together.

The activities of humans in Antarctica have greatly enhanced the rate at which microbes are introduced to the continent. Such introduction may occur via a variety of materials including food, field gear, and wastes (Lipps 1978). Horses and dogs brought into Antarctica in the past served as another important source of microbial contamination. Meyer et al. (1962; 1963) reported the presence of viable exogenous microbiota at sites on Ross Island that were introduced during early expeditions of Shackleton (Cape Royds) and Scott (Cape Evans) in such diverse media as baker's yeast and hay. Rusted cans, bottles, pony manure, and other debris left by Shackleton's party at Cape Royds were also contaminated with viable microbiota (Boyd and Boyd 1963a). The long-term survival of these organisms underscores the need for minimizing wastes left in Antarctica.

4. SPECIFIC OBSERVATIONS AND RESULTS

As the level of human activities in Antarctica has increased, the relative importance of humans as vectors for the introduction of exogenous microbiota to the region has also increased. Assessment of microbial contamination in and around McMurdo station and other areas on Ross Island was initiated in the early 1960s. Boyd and Boyd (1963a) reported substantial seasonal variability in the populations of microorganisms in soils from Ross Island and the adjacent mainland, and observed that cell counts were generally higher in areas where humans and other animals had been present. They identified several species common to temperate regions from soil samples collected at Hut Point, Cape Royds (at the site of a penguin rookery), and around McMurdo Station. The presence and viability of coliform bacteria was also assessed in soils from the Ross Island area, including a site at McMurdo Station that had recently been contaminated by human sewage, and several penguin rookery sites (Boyd and Boyd 1963b). The few viable coliforms that were found remained viable for only a short time following introduction to Antarctic soils.

Hirsch et al. (1985) reported different results from soil samples collected from an area known to be contaminated with human urine and a nearby uncontaminated area, with the organisms isolated from the contaminated area showing optimum growth at higher pH and higher temperature. Other assessments of microbial contamination around permanent bases such as McMurdo Station and outlying field camps were subsequently conducted (Cameron 1972a).

Species of *Clostridium*, a potential public health concern, were observed in the soil in the vicinity of a Japanese facility, Syowa Station (Miwa 1975a; 1975b; 1976). Subsequent investigations conducted at the same site identified other exogenous bacteria, actinomycetes, and fungi, with the number of each type increasing with proximity to the station (Toyoda et al. 1985). Soil and snow samples in the vicinity of the Soviet Mirnyy Station were also reported to contain exogenous microbial contamination (Abyzov et al. 1986).

Several baseline microbial studies were initiated during the 1970s to determine the distribution of endemic species in relatively undisturbed areas of Antarctica. Much of this work was conducted in the Dry Valley region of Victoria Land, including a Site of Special Scientific Interest for microbiology in the Barwick Valley (Parker et al. 1978b), and other sites in the Transantarctic Mountains (Cameron et al. 1970a; Cameron and Ford 1974; Parker and Howard 1977; Parker et al. 1977; 1982). Small numbers of viable soil-borne microbes were found as far south as 87°21'S, the southernmost site examined, indicating that the potential geographic distribution of soil-borne microbes in Antarctica is limited only by the distribution of soil (Cameron 1972b). Laboratory analysis of air samples collected as part of these studies provided evidence that microorganisms found were adapted to higher temperatures, thereby implying exogenous origin (Cameron et al. 1970a; Lacy et al. 1970; Cameron et al. 1971b).

One of the more comprehensive evaluations of Antarctic terrestrial microbiology occurred in conjunction with the DVDP (Block 1984). Microbial contaminants observed at DVDP sites included molds (*Penicillium* spp.) and spore-forming bacteria (*Bacillus* spp.) that had been previously undetected in terrestrial Antarctica, as well as non-indigenous coryneform bacteria (Cameron et al. 1977). Considerable contamination of DVDP drilling sites and camps with exogenous microbes of human origin were identified during these efforts (Morelli et al. 1972; Cameron 1972a). Some of the bacteria cultured were found to remain viable (but not grow) following 24 hours of incubation at 55°C, indicating tremendous ranges of tolerance to temperature extremes. The DVDP monitoring program also included an evaluation of the microbiological history of the Antarctic ice sheet and the long-term survival of viable microbes (Cameron and Morelli 1974). Summaries of the distribution of microbial genera reported from soil samples collected in the Dry Valleys and on Ross Island during the 1960s and 1970s are provided elsewhere (Johnson et al. 1978; Wynn-Williams 1990).

Air samples collected as part of the DVDP monitoring program indicated that nearly all pre-season air samples collected resulted in lower bacterial counts than did post-drilling samples, again providing evidence that human activities at the study sites were largely responsible for the presence of these microorganisms. Cameron et al. (1974) subsequently concluded that although the density of bacteria increased with human activity, such aerial contamination was localized and unlikely to have a major effect on the ecosystem.

Among the other microbial groups studied in air and soil from continental Antarctica are fungi (Sun et al. 1978); and yeasts (Atlas et al. 1978). In describing the yeasts, Atlas et al. (1978) reported that members of the universally distributed genera *Cryptococcus* and *Aureobasidium* were common in Dry Valley soils. Although these yeast species were found to possess adaptive features necessary for growth and survival under the harsh environmental conditions found in the region, they were not unique to the continent. Subsequent studies, however, have identified several species of *Cryptococcus* from soils in the Dry Valleys that have not been found elsewhere (Vishniac 1985; Baharaeen and Vishniac 1982; Vishniac and Baharaeen 1982; Vishniac and Hempfling 1979b). This includes a unique complex that appears to have evolved there (Baharaeen et al. 1982).

With the exceptions of certain unusual soils (saline or thermophilic conditions), particular microbial genera or species do not seem to characterize certain soil types or locations. Rather, the same cosmopolitan species have been reported from a wide variety of sites. As pointed out by Vishniac (1993), however, it would be surprising if Antarctic environments had failed over the long term to select microbes that were specially adapted to the rigors of the ambient environment, resulting eventually in speciation. Indications of such adaptation have been noted in the literature (Latter and Heal 1971; Line 1988.

During the mid-1980s, Friedmann and his associates began to publish results of their studies on cryptoendolithic microorganisms (Friedmann and Ocampo-Friedmann 1976; 1984; Friedmann 1977; 1982; 1985; Friedmann and McKay 1985; Friedmann and Meyer 1987; Meyer et al. 1988; Nienow and Friedmann 1993). These organisms have adapted to the extreme environmental conditions found in the interior of Antarctica by occupying a unique niche within the interstitial spaces beneath the surface of sandstones and other porous rocks. Because endolithic communities require photosynthesis, colonization is restricted to rocks that exhibit some degree of translucence, and colonization is limited to depths of only a few mm below the rock surface. To date, five cryptoendolithic communities inhabiting sandstone have been described in the Dry Valley region (Friedmann et al. 1988). Because of their habitat, these organisms are considered endemic and are unlikely to be displaced by microorganisms imported by humans.

5. METHODS USED

Retrospective examination of many of the early investigations of Antarctic microbiology has indicated a number of methodological problems with both the techniques employed and the conclusions drawn, as summarized here. A more comprehensive review of the technical problems associated with field microbiology in Antarctica is provided by Wynn-Williams (1979), while problems with some of the culture techniques used during the earlier studies are described in greater detail by Vishniac (1993).

Cell counts varying by an order of magnitude or more have been reported for Antarctic soils using different growth media (Line 1988; Parker et al. 1977; 1982). Vishniac (1993) suggests that early observations of sterile soil samples (Boyd et al. 1966; Horowitz et al. 1972) resulted from the use of inappropriate growth media (Vishniac 1993). The counting techniques used were also variable, and differences of five to six orders of magnitude were reported between direct counts and plate counts (Smith and Tearle 1985; Ramsay and Stannard 1986). Vishniac (1983) suggested that nonclassical methods involving techniques other than cell cultures may be required to isolate microbes from extreme environments.

The temperature at which samples are cultured are also important, as cells that were incapable of growth at the low temperatures were considered to be of exogenous origin. Many researchers selected 37°C, or human body temperature, as a high temperature for culturing samples (Cameron et al. 1970b; Lacy et al. 1970; Toyoda et al. 1985; Miwa 1975a). Most studies failed to consider that even if culture temperatures are regulated, laboratory conditions do not adequately replicate ambient conditions found in Antarctica, which include rapid temperature fluctuations, high potential for desiccation, low light levels, and low nutrient availability.

Some studies (Horowitz et al. 1972) used very small quantities of soil in their cultures, which may dramatically influence culture results. Other studies failed to consider other factors that may influence microbial abundance in soils, such as altitude and soil depth. Human activities, both past and present, have also been cited as dramatically complicating viable cell counts (Wynn-Williams 1985; Toyoda et al. 1985; Kerry 1990).

Finally, most of the early studies of microbial assemblages in Antarctica failed to consider the high variability of chemical and physical properties common over small spatial scales in the soils of continental Antarctica. This is in direct contrast to soils of most temperate regions, where the flow of water through the soil system prevents the development of physicochemical variability. Klingler and Vishniac (1988), for example, found an order of magnitude difference in the mineral content of soil samples collected from within the same general area. Wynn-Williams (1990) published a survey of physical and chemical characteristics of inland Antarctic soils, which indicated that substantial variability in microbial abundance occurred at sites reported to be the same (Boyd and Boyd 1963a; Cameron 1969; Allen et al. 1974; Vishniac and Hempfling 1979a; Parker et al. 1982).

Despite the problems associated with the early microbial studies in continental Antarctica, two general conclusions may be drawn (Vishniac 1993):

1. Although microbial populations of soils in continental Antarctica are small, these soils are not sterile.
2. Data collected during studies conducted to date should generally not be extrapolated to other geographic areas, even over small spatial scales.

6. IMPACTS TO MICROBIAL ECOSYSTEMS: ARE THEY OCCURRING?

That microbes have been and are continuing to be introduced into Antarctica via human activities is undeniable. A list of microbial species considered by Cameron and his coworkers to have been introduced during the DVDP is provided in Table 1 (Cameron et al. 1977). Similar lists have been provided in other studies, and other species not yet recognized are assuredly present as well. Despite this information, however, recognition and assessment of environmental impacts on microbial ecosystems in continental Antarctica is problematic due to the paucity of information on endemic microbial species. Important questions remain regarding which species are truly endemic, the geographic distribution of these species, and the long-term viability of exogenous species under environmental conditions found in terrestrial Antarctica.

Although microbes originating from temperate areas have been introduced by humans on a regular basis since Antarctic exploration began, it remains uncertain whether these species have the capacity to displace or to modify existing microbial assemblages on anything but a very localized scale (Vincent 1988). In a series of articles, Cameron and his associates concluded that human activities have altered microbial ecosystems in the region at least on a small-scale, site-specific basis. Their conclusions were based on observations of areas such as the Dry Valleys, where alterations to the endemic microbial communities were thought to result from the establishment of semipermanent field camps, the use of motorized vehicles and helicopters, and the establishment of designated storage sites for materials and supplies at former field camps (Cameron et al. 1972).

Subsequently, Cameron et al. (1974; 1976) reported that indigenous populations of bacteria, fungi, and algae at McMurdo Station were completely eliminated and replaced by a different set of hydrocarbon-decomposing species. During this time frame, increased numbers and types of bacteria and fungi were reported for many areas impacted by humans. Although it was recognized that some introductions were inevitable, they ultimately recommended continued monitoring of the microbial communities in areas of high potential for human influence:

> "Microbial changes in the ecosystem can and do occur at the various sites, some to a more serious degree than others. Some taxa, such as *Penicillium* spp., appear to be notorious camp followers. Shifts, enhancement, or elimination of microbial population can be expected to occur at sites that were inhabited in the past as well as at sites likely to be occupied in the future" (Cameron et al. 1977, p. 1169).

Cameron (1972c) described human-induced perturbations to the microbial ecology of Antarctica as falling into three distinct categories:

1. Disruption of Competitive Interactions: As discussed above, many of the microbial species found in Antarctica do not possess special adaptations to the environmental conditions, but simply represent cold- and desiccation-tolerant species that may also be found in temperate environments (Vincent 1988). Over the long term, introduction of such hardy species may result in the alteration of competitive interactions between microbial species. The extent to which human activities has contributed to the introduction and/or distribution of such organisms to date is unknown.

Table 1. Possible introduced species encountered during the DVDP (Cameron et al. 1977).

- Actinomycetales
  - Actinomycetaceae
    - Streptomyces exfoliatus
    - S. parvus
- Eubacteriales
  - Achromobacteraceae
    - Achromobacter butyri
    - A. liquefaciens
    - A. parvulus
    - A. stenohalis
    - A. superficialis
    - A. xerosis
    - Flavobacterium diffusum
    - F. solare
  - Bacillaceae
    - Bacillus
    - B. cereus
    - B. circulans
    - B. coagulans
    - B. firmus
    - B. lentus
    - B. megaterium
    - B. pergrinosus
    - B. pumilis
    - B. sp.
  - Brevibacteriaceae
    - Brevibacterium ammoniagenes
    - B. fulvum
    - B. incertum
    - B. imperiale
    - B. maris
    - B. sulfureum
    - B. tegumenticola
  - Corynebacteriaceae
    - Arthrobacter globiformis
    - A. ureafaciens
    - Corynebacterium bovis
    - C. capitovale
    - C. equi
    - C. hoagii
    - C. hypertrophicans
    - C. peregrinum
    - C. pseudodiphthericum
    - C. rathayi
    - C. sepedonicum
    - C. striatum
  - Micrococcaceae
    - Micrococcus albus var. albidus
    - M. candidus
    - M. conglomeratus
    - M. flavus
    - M. freudenreichii
    - M. rubens
    - M. ureae
    - Sarcinia flava
    - Staphylococcus epidermidis
    - S. pyrogenes
- Pseudomonadales
  - Pseudomonadaceae
    - Pseudomonas fragi

2. Microbial Enhancement: Human activities may serve to enhance microbial communities in terms of both the number and diversity of species present. For example, nutrients associated with sewage discharge may stimulate the growth of certain microbial species, possibly at the expense of the original microbial community. Physical disruption of substrate may also enhance microbial communities by releasing nutrients and/or dormant organisms from lower substrate depths (Cameron and Morelli 1974) or by locally interfering with thermal balance and/or light regimes (Wynn-Williams 1990). For example, although decomposition is an extremely slow process in continental Antarctica, the organisms responsible for mediating decomposition are generally introduced along with foreign materials.

3. Habitat Destruction: Human activities may also result in the inadvertent inhibition or elimination of certain microbial habitats. This may occur through physical destruction of the habitat, introduction of toxic contaminants, or increased competition from exogenous species. Physical destruction of habitat by humans is of potential importance in at least two microbial community types: moss/lichen communities and cryptoendolithic communities. Because of their slow growth rates, recovery of mosses and lichens damaged by humans or vehicles can be an extremely slow process. With respect to the cryptoendolithic communities, the physical structures in the surfaces of sandstones and other rocks in which these organisms live are extremely fragile. Increased human activity in the Dry Valleys and other areas where these organisms exist may result in destruction of this habitat.

   On a localized scale, spills of toxic materials such as fuels or drilling fluids may cause dramatic shifts in the distribution and/or abundance of native microbiota (Vincent 1988). Contamination of soils in the Dry Valleys with Arctic-grade diesel fuel (DFA), for example, has been observed to persist for many years, and has reportedly resulted in replacement of local microbial assemblages with other native or introduced species that are capable of tolerating or possibly even degrading the spilled hydrocarbons (Vincent 1988). Soils contaminated with calcium chloride drilling muds near Lake Fryxel in the Dry Valleys exhibited a large decrease in the number of colony-forming microbes as well as a drastic reduction in species diversity (Parker and Howard 1977). Experimental applications of crude oil to a small area of soil at Cape Bird, Ross Island, similarly resulted in a reduction in the diversity of the microbial assemblage, and a marked drop in microbial species diversity (Konlechner 1985).

To these categories compiled by Cameron, a fourth may be added:

4. Altered gene pool: Alteration of the microbial gene pool through interchange of bacterial plasmids between indigenous microbes and those introduced by humans may occur. This phenomenon has been observed with Antarctic microbes in experimental settings (Kobori et al. 1984; Siebert and Hirsch 1988).

7. CONCLUSION AND RECOMMENDATIONS

Historically, concerns regarding human impacts to microbial systems in terrestrial Antarctica have focused on the introduction of non-native biota and the potential for disrupting native microbial assemblages through competition from introduced species. Small-scale impacts from human activities appear to be occurring in certain areas both in terms of introduced species and destruction of habitat, and the extent of future impacts to these systems are largely unknown. On a large scale, however, it is questionable whether the introduction of non-native microbial species to terrestrial Antarctica merits concern.

Many microbes enter continental sites in Antarctica via the airstream, and as such they are exposed to extreme climatic conditions prior to their arrival on the continent. Although organisms imported in this manner may theoretically retain their viability for many years following introduction, many (if not most) are incapable of completing their life cycles under ambient environmental conditions. Even those species that are capable of growing and reproducing in Antarctica would likely suffer from severe competitive disadvantage relative to indigenous species. As indicated by Vishniac (1993), the presence of viable, exotic microorganisms in laboratory cultures of Antarctic soils does not necessarily indicate that these organisms have become part of the local microbial ecosystem.

Accurate assessments of the impact of human activities on microbial communities should take into consideration rates of change and long-term cycles rather than relying solely on standing crops and short-term changes in population or community structure (Wynn-Williams 1990). Short-term studies are not likely to be capable of accurately determining the level of background variation present within the indigenous microbial community. Yet most microbial studies conducted in Antarctica to date have been of limited duration, and the few that involved repeat sampling often yielded substantially different results due to high spatial variability in organism numbers (Wynn-Williams 1990).

Exotic species are most likely to survive in the Antarctic if they are introduced along with substrates from temperate locations. Materials brought to the continent, for example, can contain large quantities of a wide variety of temperate-zone microbes, including those capable of decomposing the material. The influx of large quantities of organic materials over the past century coupled with uncertainties regarding the long-term viability of dormant cells underscores the lack of information on the potential impacts of changing climatic conditions on the microbial ecology of terrestrial Antarctica. Decomposition and nutrient cycling rates may increase dramatically should climatic conditions change.

The Protocol on Environmental Protection to the Antarctic Treaty contains provisions that may help to limit the impacts to native microbial systems. Annex II of the Protocol, for example, describes measures intended to ensure the protection of native flora and fauna. Although the primary focus of Annex II is on preventing the introduction of macroscopic animals and plants to Antarctica, Appendix C of Annex II specifically describes steps that should be taken to prevent the introduction of microorganisms not present in the native environment.

Measures described in Annex III of the Protocol may also substantially decrease the potential for entry of temperate zone microbes to U.S. research stations. Annex III describes measures designed to limit the accumulation and disposal of waste materials in Antarctica by requiring that most wastes be removed from the continent. Human wastes are also routinely removed from field camps. With the establishment of large research bases over the past few decades, substantial quantities of waste materials were left in Antarctica. Annex III also requires that abandoned waste sites and work areas be cleaned up.

Treaty provisions imposed during recent years ban the import of animals such as horses and dogs, which should also help to decrease the rates at which microbes are introduced and dispersed. Despite these policies, however, the mere presence of permanent research and logistical support bases such as McMurdo Station will continue to provide persistent sources of inocula for a variety of exotic species. Field camps and transportation also provide sources of inocula that may influence community structure on a small scale.

Given the geographic extent of the Antarctic continent, the impacts of research activities on microbial communities and assemblages remain small, although these impacts may be significant on a local scale (Cameron 1972a; Fifield 1985). Furthermore, since strict prevention of microbial introductions is impractical, perhaps the best recommendation is that made by Cameron et al. (1977), who proposed that continued monitoring of the microbial communities be conducted in areas where the potential for human influence is relatively high. This would necessitate the application of better, more standardized techniques and the accurate establishment of baseline conditions and natural variability. Special attention might be given to areas such as the Sites of Special Scientific Interest that are dedicated to the study of microbial ecology.

There is also considerable uncertainty regarding the degree to which special habitats are being destroyed by human activities. For example, the extent to which the minute physical structures on the surfaces of rocks that provide habitat for cryptoendolithic communities in the Dry Valley area are being destroyed by human activities is not known. Furthermore, information is needed regarding the length of time required for these communities to recover following damage by humans. Issues such as these should be addressed before the extent of human intervention into the microbial ecology of continental Antarctica can be understood. Increased awareness of microbial habitats by field personnel and protection of certain unique habitats from physical destruction by humans may be necessary.

Finally, assessment of the potential for human influence on the microbial ecology of Antarctica cannot fail to consider the issue of tourism. If projected increases in the levels of tourism in Antarctica prove to be accurate, the potential exists for increased microbial contamination of antarctic sites, destruction of microbial habitat, and increased importation of organic materials. At present, controls on international tourism are virtually nonexistent. However, the International Association of Antarctic Tour Operators (IAATO) has established strict guidelines for preventing the introduction of non-native species. If microbial monitoring is to be conducted in Antarctica in the future, it would be advisable to attempt to determine baseline levels for areas that will likely receive increased tourism pressure.

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