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Temporal and spatial patterns of anthropogenic disturbance at McMurdo Station, Antarctica

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Abstract
Human visitations to Antarctica have increased in recent decades, raising concerns about preserving the continent's environmental quality. To understand the spatial and temporal patterns of anthropogenic disturbances at the largest scientific station in Antarctica, McMurdo Station, a long-term monitoring program has been implemented. Results from the first nine years (1999–2007) of monitoring are reported. Most physical disturbance of land surfaces occurred prior to 1970 during initial establishment of the station. Hydrocarbons from fuel and anthropogenic metals occur in patches of tens to hundreds of square meters in areas of fuel usage and storage. Most soil contaminant concentrations are not expected to elicit biological responses. Past disposal practices have contaminated marine sediments with polychlorinated biphenyls (PCBs), petroleum hydrocarbons, and metals in close proximity to the station that often exceed concentrations expected to elicit biological responses. Chemical contamination and organic enrichment reduced marine benthic ecological integrity within a few hundred meters offshore of the station. Contaminants were detected in marine benthic organisms confirming bioavailability and uptake. PCBs in sediments are similar to suspected source materials, indicating minimal microbial degradation decades after release. Anthropogenic disturbance of the marine environment is likely to persist for decades. A number of monitoring design elements, indicators and methodologies used in temperate climates were effective and provide guidance for monitoring programs elsewhere in Antarctica.

Keywords: environmental monitoring, human impacts, pollutants, Antarctica

The research team dedicates this article to the memory of Guy Denoux, a colleague and friend.

1. Introduction

Antarctica, once known as *Terra Incognita* (the unknown land), is an international focus of science, exploration and public interest. Once a remote, isolated and uninhabited continent, Antarctica is now visited by several thousand people each year [1]. The continent is affected by the activities and facilities that support the geopolitical aspirations of Antarctic Treaty nations and scientific investigations as well as tourism [2–7]. Environmental protection of Antarctica is provided by the Antarctic Treaty [8, 9]. The Treaty and its annexes set forth national responsibilities to protect the environment and these obligations are enacted through national legislation that regulates each country's nationals while in Antarctica. The Treaty's environmental protection practices were clarified and enhanced by the Protocol on Environmental Protection which came into force in 1998 [10]. The Protocol recognized that managing the impact of humans in Antarctica requires that disturbances be quantified through long-term, sustained observations—i.e., monitoring. The Antarctic environment is highly variable and this variability is the backdrop against which human-induced stresses occur [5–7]. A warming climate adds an additional complexity to discerning local anthropogenic change from natural variability [11–14]. Standardization of Antarctic environmental monitoring programs has been encouraged for more than a decade and has witnessed broader international implementation in recent years. This study is one of the first comprehensive, systematic environmental monitoring studies in Antarctica. The remote and severe conditions of Antarctica challenge those tasked with implementing monitoring programs and experiences in other regions may not be applicable or feasible in Antarctica. The flora and fauna of Antarctica, much of it still undescribed, have been isolated and independently evolving for millennia and it remains unclear how these ecosystems will respond to human-induced stress experienced over the last half-century or so [15, 30].

Despite a perception that the Antarctic environment is pristine, it is subject to diverse human impacts on local, regional and global scales and this has recently been at the forefront of research interest as well as public and political concerns. Some of these impacts are potentially significant in terms of ecosystem stability and function as well as providing challenges to environmental management in Antarctica. The Antarctic environment remains sufficiently unimpacted to allow identification of responses that are subject to confounding factors in temperate climates where stressors can be much greater and diverse. This study documents human impacts at one of the most concentrated locations of human activity in Antarctica—McMurdo Station. The area of McMurdo Station is small (a few square kilometers) but the impact of human activities is important due to the limited ice-free areas available to indigenous flora and fauna (figure 1).

Humans have occupied the McMurdo Sound area for over a hundred years (figure 1) [16]. While early habitation was modest in number and duration, this changed fifty years ago during the International Geophysical Year (IGY) 1957–58 [17, 18]. As part of the IGY, year-round, permanent facilities were established at McMurdo Station and other locations around the continent. During the IGY, populations at McMurdo Station exceeded 3000 people, but summer populations dropped to approximately 1200–1400 in the late 1950s and remained relatively stable until the early 1980s when summer populations began to increase. In the mid-1990s US Antarctic Program summer populations, while variable, rose averaging approximately 1700 each year in the Ross Sea Region. Over the years, humans have altered landscapes and introduced foreign materials, alien species, and contaminants. A nuclear reactor was removed from the station and the area remediated in the 1970s and it was determined that there was minimal risk due to radioactive material remaining on the site [19]. The decommissioning was declared complete concluding that the site had been remediated to levels as low as reasonably achievable.

Human impacts at McMurdo Station have been monitored by the United States Antarctic Program for many years [20–28]. The scale of McMurdo Station in terms of the area of ice-free ground, the buildings, roads, and storage areas occupies a significant percentage of the land in the area. Anthropogenic disturbance and impact in Antarctic terrestrial habitats can be important since ice-free areas are only 0.3% of the continent and only a portion of that is at low altitude and near the coast where most stations and tourist activities occur [7, 30]. Early studies of human impact at McMurdo Station were directed at construction projects, remediation of spills, and environmental impact assessments. Most studies were restricted in spatial extent and few time-series datasets were collected. Studies of the marine environment adjacent to the station identified chemical contamination and benthic community disturbances caused by past disposal practices. The current study quantifies the spatial and temporal patterns of human impact at McMurdo Station. In 1999, a coordinated program to monitor environmental quality at McMurdo Station was initiated based on best available practices, monitoring experiences in temperate climates (where applicable), recommendations of international workshops, and previous studies. The program was conducted in two stages. A three-year pilot study was conducted (1999–2002) to establish the basic elements of a monitoring program and a long-term monitoring program was implemented that continues today.

2. Experimental section

The pilot study collected data in the marine and terrestrial environments in and adjacent to McMurdo Station (figures 1 and 2). Based on knowledge of human occupation at McMurdo Station; a suite of physical, chemical, and biological indicators were initially chosen for measurement. On land, more than 2000 samples were collected and analyzed during the pilot project (1999–2002) to test monitoring design elements. Probabilistic and fixed-point datasets demonstrated that a combination of designs provided the most robust representation of disturbance in the terrestrial setting. Power analysis indicated a doubling of chemical concentrations from one year to the next could be detected with a minimum of 17 random samples collected across the station [29].

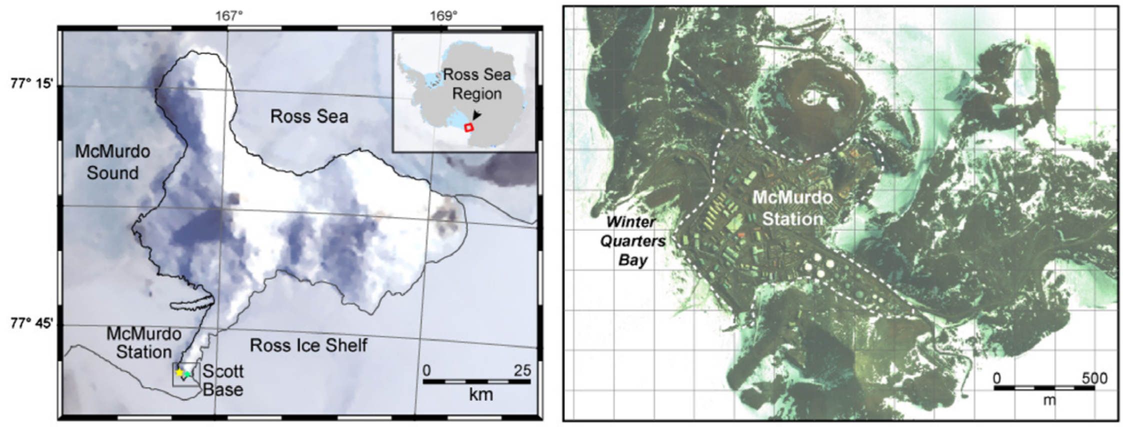

Figure 1. McMurdo Station, Antarctica and the surrounding environs. Scott Base is off just off the satellite image. The background Quickbird satellite image is copyrighted by DigitalGlobe, Inc.

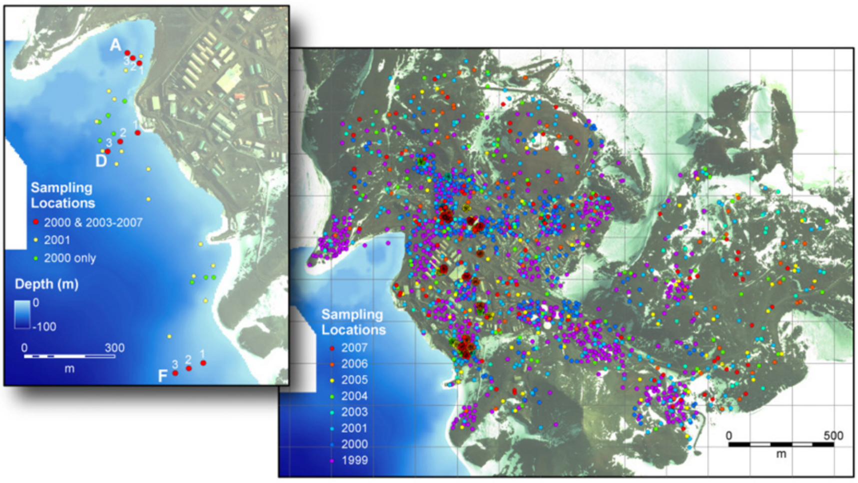

Figure 2. Long-term monitoring sites at McMurdo Station, Antarctica from 1999 to 2007. Three of the five marine transects (A, D and F) sampled in 2000 were monitored in subsequent years. Areas with a clustering of sample sites (typically red) indicate intensively studied areas of the station. The background Quickbird satellite image is copyrighted by DigitalGlobe, Inc.

To robustly document the spatial stability of the extent of terrestrial contamination, the total number of samples collected was tripled to a minimum of 51 samples each year. Data analysis also indicated that random sampling nested in 25 m grids more effectively characterized areas of known chemical contamination than 5 and 100 m grids. In seven areas of known contamination, samples at 16 random sites were collected each year within a 25 m grid (16 samples/25 m grid $\times$ 7 sites $=$ 112 samples). A minimum of 163 samples were collected annually from 2003 to 2007 to quantify the spatial extent of terrestrial contamination. Opportunistic sampling beyond the minimum sampling effort was performed as time allowed. Of the original variables, petroleum hydrocarbons and selected metals were the most useful indicators of human impact in the terrestrial setting.

In the marine setting, probabilistic and fixed-point datasets demonstrated that a fixed-point sampling design provided the most robust representation of disturbance [29]. Marine sampling was limited by the water depth accessible by divers and safety considerations. Of the original variables, carbon content, grain size, toxicity, petroleum hydrocarbons, polychlorinated biphenyls, selected metals, and characterization of the benthic infauna communities were the most useful indicators of human impacts in the marine setting. 'Through the ice' sampling techniques need to be developed to allow for sampling beyond the depth limit of divers to establish the spatial limit of human impact in the area.

Statistical analyses indicated off-station control sites and samplings along disturbance gradients were effective in quantifying natural variability. Three of the five marine transects sampled in the pilot study were sampled from 2003 to 2007. Based on the results of the pilot study (1999–2002) the long-term marine monitoring program design was implemented in 2003 (figure 2).

2.1. *Sample collection and methods*

Clean sampling and storage techniques were used to collect samples for chemical analyses [31, 32]. Divers were deployed through access-holes drilled in the ice to collect marine sediments using hand-driven 6.7 cm diameter corers. Three cores were collected for chemical analyses and three for benthic analyses. In addition, three 2 cm diameter hand-driven sediment corers were used to sample sediments for toxicity analyses. Upon return to the surface, sediments were extruded from the top three centimeters of the cores for chemical and toxicity analysis. Sediments for benthic community analyses were extruded from the top 10 cm of the larger cores, preserved in 10% buffered formalin and stained with rose bengal. Sediments for toxicity analyses were placed in clean Petri dishes and refrigerated prior to analysis on location. Chemical contaminant methods for soils, sediments and tissues were those of the National Oceanic and Atmospheric Administration 'Status and Trends Program' and the United States Environmental Protection Agency [31, 32]. Grain size analysis employed a pipette method [33]. The toxicity of sediments was determined with the Microtox® method using a bioluminescent bacterium *Vibrio fischeri* NRRL B-11177 [34–36]. Organisms retained on a 0.5 mm sieve were sorted for benthic biological analyses. After sieving, organisms were counted and, in most cases, identified to the species level. Before weighing, organisms were separated into higher taxa and weighed to calculate wet weight biomass. Megafauna were excluded from biomass measurements.

2.2. Data synthesis

Data synthesis and interpretation was based on analysis of variance (ANOVA), non-metric multi-dimensional scaling (MDS), and principal components analysis (PCA). Sampling location was a surrogate for anticipated differences in contaminant and/or disturbance levels. The PCA of all abiotic variables reduced a large number of physicochemical variables to two composite variables that were uncorrelated and contained most of the variance in the data. These variables were used as dependent variables to predict and explain biological responses [37]. The MDS analyses allowed comparison of community structure by reducing the abundances of all species present in each time-site combination to a single point on a two- or three-dimensional plot [38]. The distance between each date-site combination on the resulting MDS plot can be related to the difference or similarity in community structure between date-site combinations. Ten biotic metrics were used to calculate a benthic index of biotic integrity (BIBI) [29]. The BIBI formula was modified to include percentages of annelids and crustaceans as metrics [39].

The terrestrial human-built environment was characterized using aerial photography including locating buildings, fuel tanks, and roads. Disturbance of the surface was judged based on the absence of patterned ground [16]. Much of the imagery had spatial resolutions meeting the USGS's national map accuracy standards [40]. Beginning in 2001, high-resolution Quickbird satellite images were used to supplement aerial photographs. Geographic Information Systems (GIS) were used to select sampling sites and to analyze the photographic archives to map changes in the station's infrastructure and physical disturbance [16]. Data quality objectives were specified in regards to accuracy, precision, method detection limits, and completeness. For analytical data, quality assurance and quality control was that of the methods utilized [31, 32]. While it is difficult to precisely delineate the station's boundaries, the area outlining the station in the right panel of figure 1, covers approximately 0.65 km^2. The physical infrastructure of buildings and fuel tanks covered 0.05 km^2 in 2010 while the road network covered approximately 0.2 km^2.

3. Results and discussion

The following discussion is based on monitoring data collected from 1999 to 2007. Determination of physical disturbance of the land surface benefitted from photo-documentation dating to the 1950s.

3.1. Physical disturbance

To determine the area impacted, comprehensive mapping of disturbance at McMurdo Station through time was undertaken and is discussed in detail elsewhere [16]. The total ice-free area around the station examined totaled $\sim$3.7 km^2. Mapping incorporated all usable aerial photography of the station and was accomplished by overlaying a hexagonal grid composed of individual 50 m diameter hexes on the geo-rectified photographs. The photographs were examined in sequential order and the date when the first significant disturbance was visible in each hexagon was recorded. The disturbances considered included construction of buildings or roads, cargo storage, landfills or surface scraping in addition to loss of patterned ground. Two and one-half square kilometers of the area surrounding McMurdo Station had experienced some impact by 1993 (figure 3). To place the extent of this physical disturbance in context, a relatively snow-free Quickbird satellite image acquired on 25 December 2008 covering $\sim$16.7 km^2 of the southern portion of the Hut Point Peninsula; including McMurdo Station, Scott Base and Arrival Heights as well as other isolated rock outcroppings; revealed 5.4 km^2 to be snow and ice-free. The snow and ice-free area is variable from year-to-year and dependent on the time of year.

Terrestrial physical disturbance was restricted to a few square kilometers near the station (figure 3). Most disturbance of the surface had occurred by the 1970s as major construction to establish a permanent station had been completed. Construction relied on local sources of building fill. In many cases, surfaces were scraped to prepare building sites and the surroundings were contoured to accommodate the station. Scrapping of the surface in later years was mostly confined to already disturbed areas. The spatial extent of physical disturbance has been stable for more than 30 years. Indications are that disturbed land surfaces will not recover for many tens, if not hundreds, of years or more. Once disturbed, land surfaces are slow to recover because run-off is negligible since temperatures are perennially cold limiting the presence of liquid water and landforms take years to develop because natural processes are slow to redistribute material.

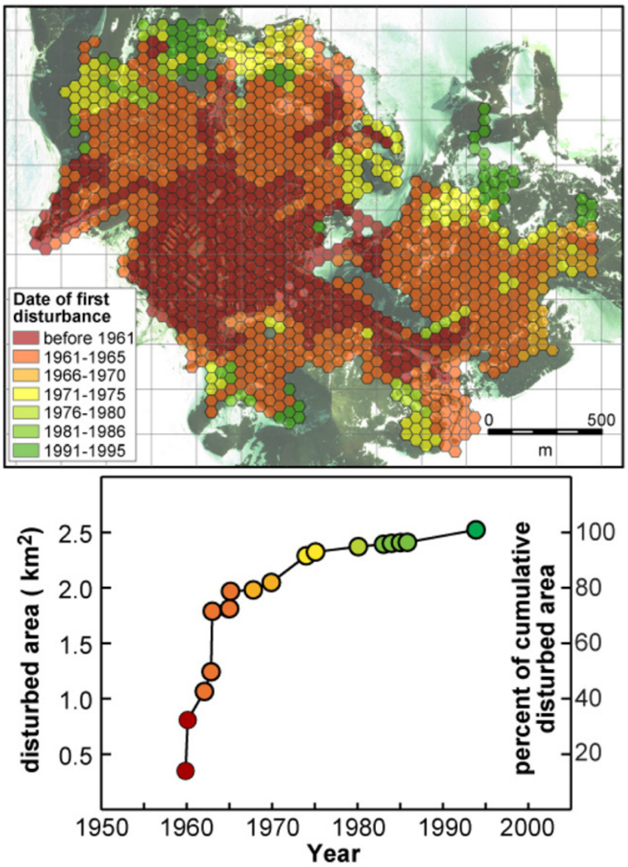

Figure 3. Spatial and temporal changes in physical disturbance at McMurdo Station, Antarctica from 1960 to 1995. The background Quickbird satellite image is copyrighted by DigitalGlobe, Inc.

3.2. Chemical contamination

Petroleum hydrocarbons from fuel are the largest volume of potential contaminants brought to and used at Antarctic scientific stations. Correspondingly the most prevalent contaminant detected in surficial soils at McMurdo Station is fuel-related petroleum hydrocarbons (figure 4). While surficial soils were analyzed, analyses of profiles with depth suggested sampling to greater sub-surface depth would not uniformly result in higher measured concentrations or change spatial patterns. This is due to the shallow impenetrable, ice-cemented surface layer that is a barrier to deeper penetration of contaminants. Each control site was treated the same as the intensive sampling sites with 16 random samples collected in a hexagon with a radius of 12.5 m. Each control hexagon was randomly sited in undisturbed, ice-free areas.

At most locations, total petroleum hydrocarbons (TPH) in surficial soils at McMurdo Station were low in concentration being within two standard deviations of nearby control sites. Contaminated surficial soils occurred in patches of tens to hundreds of square meters. Of all soil samples collected at McMurdo Station between 1999 and 2007, 61.5% contained TPH above 30 ppm while 57.9% of all samples contained TPH levels above 100 ppm. As sampling in this study was intentionally biased towards areas of known or suspected impact, these percentages overstate petroleum hydrocarbon contamination at the station. Of the 770 random samples collected 27.7% have TPH concentrations at or above 30 ppm and 11.3% have concentrations at or above 100 ppm. Hydrocarbon contaminants were highest in areas where fuel was utilized or stored such as refueling stations, the helicopter pad, vehicular traffic routes and parking areas, and the vehicle maintenance facility (indicated by the concentrated sampling efforts in figure 2). Highest TPH concentrations were associated with recently spilled fuel. On-going activities in these areas pose a risk for continuing contamination (figure 4). Records indicate that accidental spills occur at the station and at locations where operations are conducted away from the station such as runways. Activities related to fuel and vehicle usage have remained in the same location for years therefore fuel spills frequently occur in areas previously contaminated partially accounting for the stability of hydrocarbon contaminant spatial patterns. Correlation of soil fuel contamination and spill locations is confounded as spills are often remediated and contaminated soil removed. To reduce and contain fuel releases, fuel storage areas have been consolidated in upland areas that experience minimal run-off, flexible pipelines were replaced with fixed-hardened pipelines, and fuel storage facilities are placed within lined berms. There was little evidence of the redistribution of fuel spills away from the point of release since run-off events are few and remedial activities rapid. Drainage pattern studies and monitoring of run-off events are needed to confirm this conclusion.

Petroleum hydrocarbon residues in soils were biodegraded except in areas where recent spills occurred. Residues were detected as an unresolved complex mixture (UCM) of compounds indicating that reduced toxicity might be expected as a function of time after release (i.e., loss of aromatic hydrocarbons). The natural processes of evaporation and biodegradation by indigenous microbiota can remove labile hydrocarbons from soils. Rates of hydrocarbon microbial degradation and evaporation are generally lower in polar climates compared to temperate climates and residues can persist for decades. Determining TPH concentrations that would be expected to elicit a biological response is difficult. TPH measures a complex and variable mixture of hydrocarbons and few studies of biological responses to contaminants in Antarctica have been reported [41–43]. Studies of the effects of diesel fuel and lubricant oils on marine sediment microbial communities at Casey Station, Antarctica found that a concentration of 1043 ppm of arctic diesel elicited a biological response [42]. A second study at the same site found that concentrations of ∼4000 ppm of lubricating oil in sediments caused changes in marine benthic copepod populations after one year's exposure [43]. Comparison of marine and terrestrial organisms' responses is uncertain but broad trends may be inferred. The majority of TPH concentrations in surficial soils in this study were below 1000 ppm and minimal biological effects are expected (figure 4) [42]. Since the available studies assessed the biological effects of differing mixtures of hydrocarbons and refined petroleum products and the biological responses monitored were limited to marine organisms, definitive conclusions about potential terrestrial biological effects at the

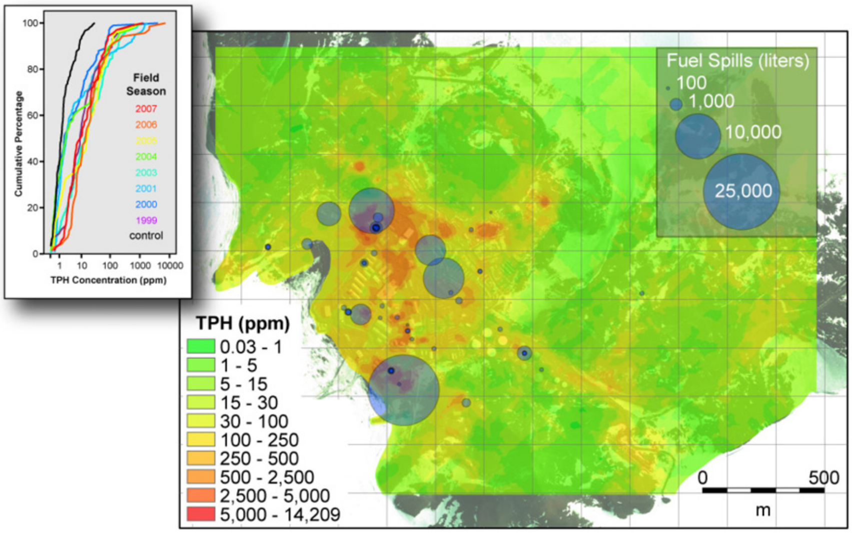

Figure 4. Total petroleum hydrocarbon concentrations (ppm) in surficial soils at McMurdo Station displayed as a continuous surface using ordinary kriging and as a cumulative percentage plot from 1999 to 2007. The location and volume of fuels spills from 1992 to 2004 are superimposed. Areas with a high concentration of sampling locations represent intensively studied sites where contamination is suspected. The background Quickbird satellite image is copyrighted by DigitalGlobe, Inc.

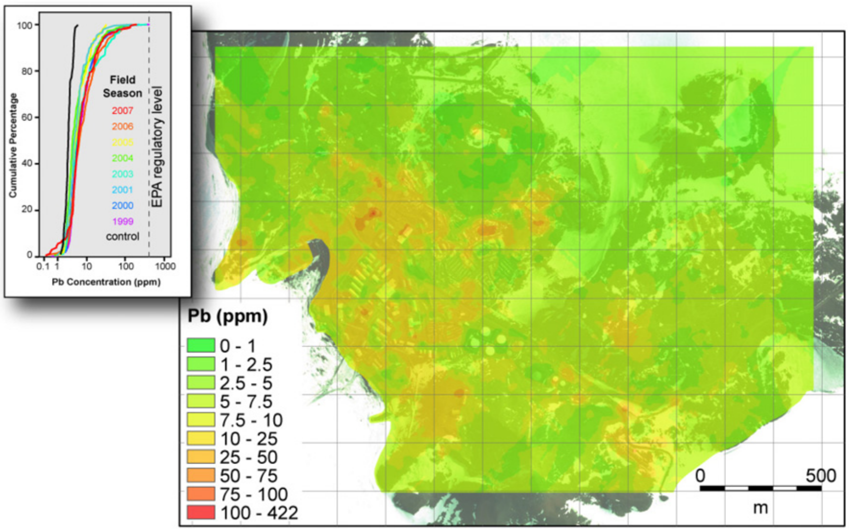

Figure 5. Lead concentrations (ppm) in surficial soils at McMurdo Station displayed as a continuous surface using ordinary kriging and a cumulative percentage from 1999 to 2007 (the 400 ppm EPA regulatory for bare soil level of concern for children's playground areas). The background Quickbird satellite image is copyrighted by DigitalGlobe, Inc.

station are difficult to establish. Measures of contaminant toxicity to indigenous terrestrial organisms at the station are needed to draw robust conclusions.

Metal concentrations on the land surface were usually at or near background concentrations. Arsenic, cadmium, copper, lead, and zinc exceeded background concentrations at a few sites. In general, the spatial patterns of metal contamination were similar to those of petroleum hydrocarbons suggesting an anthropogenic origin. Elevated lead concentrations may be a legacy of leaded fuel use or be derived from other anthropogenic sources such as paint, plumbing materials, and solder [44–48]. Most surficial soils at the station contained metal concentrations below levels known to elicit biological changes in temperate climates. As with TPH contamination, few (if any) studies of indigenous biological community's responses to metal contamination have been conducted (figure 5). Temperate climate comparisons are only provided for context and *in situ* response is difficult to assess. Many metals are natural constituents of soil minerals. Variations in aluminum, iron, magnesium, beryllium, calcium, cobalt, manganese, nickel, and vanadium concentrations have been attributed to differences in soil mineralogy [14, 47]. Mineralogical metals are generally less bioavailable but biological responses to exposure to naturally occurring metals cannot be ruled out [47]. Human activities, such as scraping and construction, can result in a redistribution or

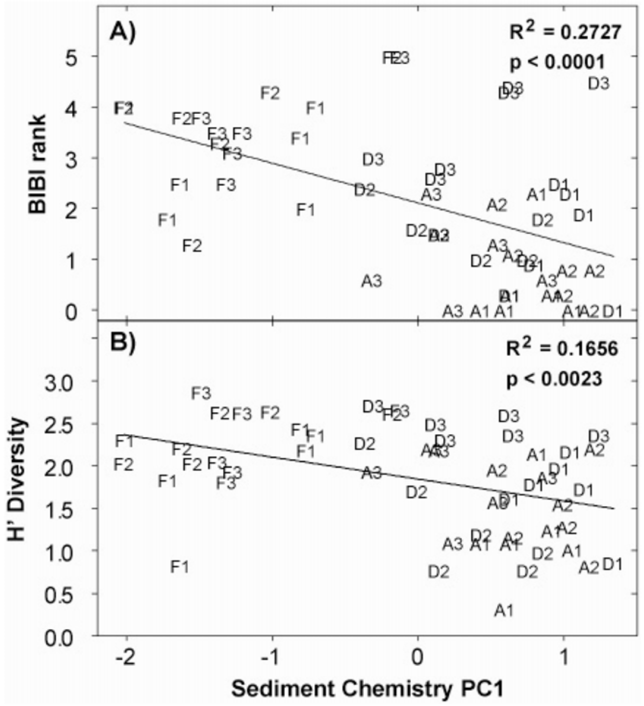

Figure 6. Principal component 1 (PC1) versus (A) BIBI rank, and (B) H' diversity. Data points represent sampling sites. An increasing PC1 score represents increasing sediment contaminant concentrations (marine sampling locations are shown in figure 2).

mobilization of naturally occurring metals affecting their bioavailability.

Past disposal practices have resulted in an area of several hundred square meters of contaminated sediments in Winter Quarters Bay (WQB) [25, 27]. PCB contamination in WQB was first documented in the late 1980s [22]. PCB congener patterns are similar to Aroclor 1260 with few changes in the congener distributions over the last thirty years. PCB concentrations in sediments collected from 2000 through 2007 were highest at the sewage outfall with PCB concentrations of 7022 ppb in a sample collected along transect D and in WQB with PCB concentrations of 2026 ppb in a sample collected along transect A (figure 2). PCBs were not detected in sediments at control sites. While localized in a restricted area of WQB, PCB concentrations were similar to those at some of the most contaminated sites in temperate climates. An unusual contamination by polychlorinated terphenyls, of unknown toxicity, was also present suggesting that several kilograms of a concentrated mixture of chlorinated compounds were disposed of in the bay at some time in the past (pre-1980). Previous assessments concluded that dredging and removal of these sediments is cost prohibitive and might result in a wider dispersal of contaminants in the area since WQB sediments are stabilized behind a sill.

The concentrations and spatial patterns of contaminants at McMurdo Station were similar over nine years. Recent additions of contaminants appeared to be minimal due to the more stringent environmental controls adopted in the 1980s but more definitive studies of run-off patterns and contaminant loads are needed. Contaminant hydrocarbons

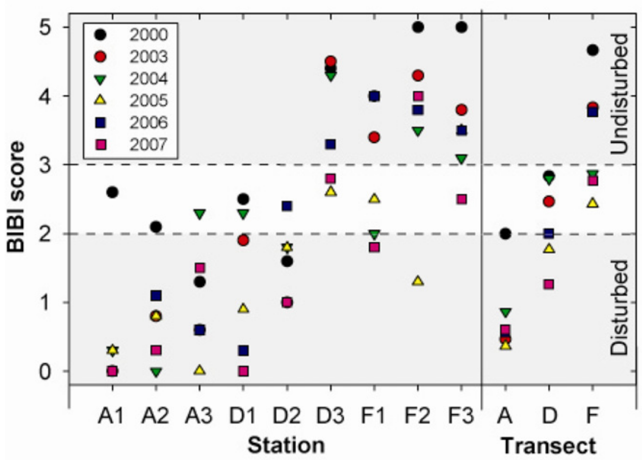

Figure 7. Mean benthic index of biotic integrity (BIBI) score for each station and transect (locations are shown in figure 2).

were biodegraded in both the terrestrial and marine setting indicating an indigenous population of hydrocarbon-degrading bacteria had altered releases over time [49, 50]. However, rates of degradation in cold climates are expected to be slower than in temperate climates [15, 50–53]. The unaltered nature of PCBs indicates *in situ* microbes have limited capacities to degrade synthetic chemicals suggesting that released synthetic chemical contaminants will persist for tens if not hundreds of years if natural processes are the only removal process [54]. The mixture of contaminants detected at McMurdo Station is similar but in lower concentrations than temperate climate localities with comparable human activities [55–58].

3.3. Biological responses and contaminant uptake

As mentioned above, there are few biological organisms on land, other than infauna and microbiota, so *in situ* biological indicators of impacts in soils were not available. There is an abundant benthic community in marine areas adjacent to McMurdo Station suggesting biological indicators of human impact used in other climates might be applicable as indicators at McMurdo Station [59–61]. In the marine setting, macrofauna community structure changed over time, but in the same direction at all stations except for the station nearest the sewage outfall. In contrast, Shannon–Weaver diversity (H') and the benthic index of biotic integrity (BIBI) rank negatively correlated with chemical contamination (figure 6). BIBI ranks were higher at control sites than contaminated sites, except for two year-site combinations, indicating degradation of biological integrity in response to anthropogenic disturbances (figure 7).

Naturally occurring sponge spicules interfered with toxicity analyses causing undisturbed areas to be misclassified as toxic. Contaminant concentrations, toxicity, and community structure did not significantly change in nine years at a given site except at the station (D2) near the former sewage outfall indicating little temporal or spatial change in stressor distributions with time. Acclimation of indigenous populations is also a possibility. Years of sewage disposal enriched organic matter in sediments offshore of the station's sewage outfall [62, 63]. At this site, benthic community responses to organic enrichment confounded responses to toxic chemicals. Subsequent to the introduction of waste treatment and relocation of the outfall, infauna benthic communities sampled closest to the outfall began to deviate in community structure from the surrounding sites. In 2005 and 2006 macrofauna community structure at the sewage outfall resembled surrounding stations once again.

Contaminants were bioavailable as demonstrated by their presence in marine benthic organism tissues. Polycyclic aromatic hydrocarbon (PAH) and polychlorinated biphenyls (PCB) in epifauna tissues decreased with distance from WQB. PAH were dominated by low molecular weight hydrocarbons indicating exposure to fuel-sourced hydrocarbons. Pyrogenic hydrocarbons, indicative of high temperature exposure of petroleum products, were also detected and may be from waste petroleum products such as used-crankcase oil. Tissue PCB concentrations in some fish and bivalves in WQB and at the sewage outfall were above 2 $\mu g\ g^{-1}$ (wet weight), the FDA advisory level for human consumption [64]. PCB concentrations in tissues decreased with distance from WQB. At control sites, PCB concentrations in some tissues were above 100 $ng\ g^{-1}$ (wet weight). Elevated PCB tissue concentrations in organisms at control sites suggests that the spatial range of some fauna extends beyond the area of contaminated sediments or that on occasion contaminants are transported beyond WQB. It was not possible to determine if tissue contaminant concentrations were changing with time because the species available for collection and analysis varied from year-to-year. Additional sampling for several more years will be necessary to discern temporal trends in bioaccumulation. There is a paucity of indigenous epifauna close to the station that can serve as bioindicators, such as bivalves, and sustain long-term sampling.

4. Summary

Long-term monitoring at McMurdo Station has demonstrated that a number of indicators used in temperate climates are effective in quantifying spatial and temporal trends in anthropogenic disturbances in these environments. The indicators utilized vary in a predictable manner based on temperate climate experiences. The mixture of contaminants detected at McMurdo Station was analogous to those at other inhabited sites with a similar suite of stressors. Contaminant concentrations were lower than at comparable temperate climate sites except for sediment contamination in WQB. Due to the slow rates of *in situ* microbial degradation chlorinated chemicals can be expected to persist for years, possibly decades, while petroleum hydrocarbons were degraded *in situ*. Marine benthic communities have responded to contamination in WQB with reduced ecological integrity where contaminant concentrations are highest. Based on results to date, it is recommended that monitoring elsewhere in Antarctica adopt a similar framework to quantify anthropogenic disturbances including measurement of contaminant dose (concentrations), toxicological properties and *in situ* biological responses over small spatial scales (because disturbance is localized) and over long timescales (because rates of natural removal processes are slow). The spatial extent of disturbance at Antarctic scientific stations with similar physical settings and anthropogenic activities can be expected to be restricted to within a few hundreds meters of the station and monitoring should be focused in these areas. The long-term monitoring of human disturbances at McMurdo Station, Antarctica continues today.

5. Brief

Spatial and temporal patterns of human disturbance at McMurdo Station, Antarctica were used to assess program design elements and inform monitoring efforts elsewhere in Antarctica.

Acknowledgments

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