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On site remediation of a fuel spill and soil reuse in Antarctica

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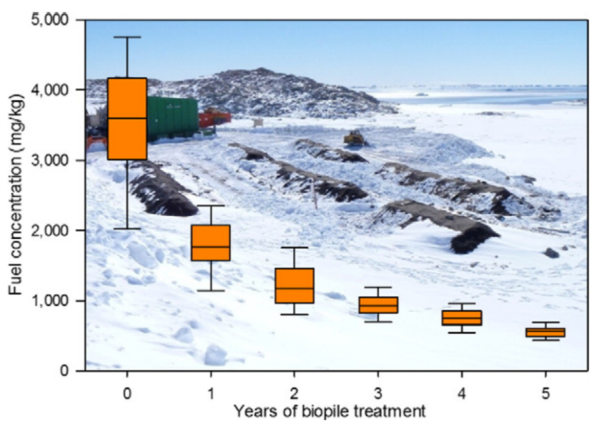
HIGHLIGHTS

- First large-scale remediation of a fuel spill in Antarctica
- Soil was remediated in biopiles using native bacteria with no external heating.
- Antarctic bioremediation is feasible despite cold temperatures and short summers.
- 370 t of the remediated soil was reused onsite.
- Guidance for biopile design and management for other Antarctic contaminated sites

GRAPHICAL ABSTRACT



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ABSTRACT

The first large-scale remediation of fuel contamination in Antarctica treated 10000 L of diesel dispersed in 1700 t of soil, and demonstrated the efficacy of on-site bioremediation. The project progressed through initial site assessment and natural attenuation, passive groundwater management, then active remediation and the managed reuse of soil. Monitoring natural attenuation for the first 12 years showed contaminant levels in surface soil remained elevated, averaging 5000 mg/kg. By contrast, in five years of active remediation (excavation and biopile treatment) contaminant levels decreased by a factor of four. Chemical indicators showed hydrocarbon loss was apportioned to both biodegradation and evaporative processes. Hydrocarbon degradation rates were assessed against biopile soil temperatures, showing a phase of rapid degradation (first 100 days above soil temperature threshold of 0 °C) followed by slower degradation (beyond 100 days above threshold). The biopiles operated successfully within constraints typical of harsh climates and remote sites, including limitations on resources, no external energy inputs and short field seasons. Non-native microorganisms (e.g. inoculations) and other organic materials (e.g. bulking agents) are prohibited in Antarctica making this cold region more challenging for remediation than the Arctic. Biopile operations included an initial fertiliser application, biannual mechanical turning of the soil and minimal leachate recirculation. The biopiles are a practical approach to remediate large quantities of contaminated soil in the Antarctic and already 370 t have been reused in a building foundation. The findings presented demonstrate that bioremediation is a viable strategy for Antarctica and other cold regions. Operators can potentially use the modelled relationship between days above 0 °C (threshold temperature) and the change in degradation rates to estimate how long it would take to remediate other sites using the biopile technology with similar soil and contaminant types.

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1. Introduction

As human activities in the Arctic and the Antarctic have increased, so has use of hydrocarbon fuel, and with it the potential for fuel spills. Fuel spills are common, often from poor handling, storage or disposal, and have left significant localised impacts on the environment (Aislabie et al., 2004; Snape et al., 2006; Filler et al., 2015). Presently, in the polar regions, countries and companies compete for sovereignty, tourism, commercial activities, natural mineral and energy resources and pursue scientific investigations (Ebinger and Zambetakis, 2009; Stonehouse and Snyder, 2010). Despite improved documentation for environmental management practices and spill response strategies, small and large fuel spills still frequently occur. Both legacy and modern spill events can leave long-term, persistent and adverse impacts to the local natural environment unless clean-up initiatives are enacted promptly and completed. Climate change will also increase the adverse impact as terrestrial spills that were relatively contained within permafrost will increase in mobility (Bargagli, 2008; Saul and Stephens, 2015). Successful remediation and close-out of fuel spill sites is rare in polar regions. For example, of the approximate 2400 reported sites in the Canadian Arctic, only 37 have remediation planned or completed (Snape et al., 2008; Filler et al., 2015; Indian and Northern Affairs Canada, 2016). In the Antarctic, of 200 estimated sites, only 1 minor site (World Park Base) has been remediated and completed (Filler et al., 2015).

Antarctica is managed by many nations operating under a Treaty System, with The Protocol on Environmental Protection encouraging the clean-up of past and present fuel spills. The Protocol or domestic legislation that enacts the Protocol does not specify guideline levels and there are no provisions for attributing liability. Clean-up is not required if the removal process creates greater adverse impacts than leaving waste or contaminated soil *in situ* (Antarctic Treaty, 1991b).

In Antarctica, the majority of terrestrial fuel spills are at research stations on the rare ice-free areas that make up only 0.3% of the continent (Aislabie et al., 2004). Soil and gravel are precious resources and rock quarrying in Antarctica is often environmentally undesirable. Fuel spills on land compromise this valued resource. Soil organisms are an interdependent part of the biological communities, and ecosystem recovery after a spill is suppressed by low temperatures, low nutrients and low moisture content (Snape et al., 2008; Nydahl et al., 2015; O'Neill et al., 2015).

Bioremediation of hydrocarbon-contaminated polar soil has been investigated in laboratory trials (Borresen et al., 2003; Ferguson et al., 2003a,b, 2008; Bell et al., 2011; Chang et al., 2010; Kauppi et al., 2011; Martínez Álvarez et al., 2015), biopile trials and landfarming studies in the Canadian Arctic (McCarthy et al., 2004; Filler et al., 2008; Paudyn et al., 2008; Greer, 2009; Sanscartier et al., 2009a,b; Kauppi et al., 2011) and in other Northern hemisphere cold regions (Lebkowska et al., 2011; Gomez and Sartaj, 2013), and via theoretical contaminant degradation modelling (Coulon et al., 2010; Whelan et al., 2015). However, until now, large-scale remediation efforts in Antarctica have not been undertaken, possibly because of unproven technology coupled with high costs, strict continental quarantine regulations that limit the use of some types of traditional amendments (i.e., organics) and complex operational logistics.

This study presents the first large-scale bioremediation project in Antarctica. Already, 590 m^3 of hydrocarbon-contaminated soil has been remediated on site within engineered biopiles. It compares the limited progression of hydrocarbon degradation during 12 years of natural attenuation to that obtained from excavation and biopile treatment over 5 years. Specific compound ratios are examined to assess the relative contribution of biodegradation and evaporation processes. This study also investigates the influence of temperature on bioremediation to generate biodegradation rates using cumulative days above a temperature threshold, which may assist in predicting the time required to remediate other polar fuel spills.

2. Experimental

2.1. Site characteristics

Australia's Casey Station (66°17′S 110°31′E) is located in the Windmill Islands, Eastern Antarctica on ice-free bedrock and weathered gravel soils. In July 1999 (winter), a spill from a fuel storage tank released approximately 10000 L to the environment. The plume initially moved between the snow and surface of the frozen active soil layer. As summer progressed, the plume migrated into the active soil layer and moved with the surface and subsurface water run-off (Snape et al., 2006). The fuel may have altered the soil properties of the active layer and penetrated into the permafrost, thereby facilitating enhanced transport and a broader impact. The commonly used fuel at Casey Station is Special Antarctic Blend diesel; however, this particular spill was of a unique diesel blend (80% distillate from Bergen, Norway with 20% aviation turbine kerosene) that was only brought to the station once in 1998. The mixture has a unique compositional fingerprint, which simplified tracking the extent of contamination specific to this spill.

The first response to the spill was a hasty construction of a permeable reactive barrier (PRB) using *ad hoc* materials designed for fuel spill response; however, this proved to be ineffective. An initial remediation strategy of monitored natural attenuation was then adopted, while more active options were considered and planned.

The site down-gradient of the fuel storage tank consists of a shallow drainage pathway that exits to a melt water lake and potentially to the ocean. An initial site assessment was conducted in 2000, consisting only of surface soil and water sampling. The extent of contamination and movement of fuel through permafrost soil layers and below the surface was not investigated.

In 2005, clean-up efforts began as part of program to design, research and implement remediation technologies for contaminated Antarctic sites. The risks to the localised environment were considered too high to continue with monitored natural attenuation as a remediation strategy. Furthermore, it was judged unlikely that contamination levels would substantially reduce without active intervention. Applying a technique that would keep the soil in Antarctica was important to avoid importation issues, environmental risks, high costs and the wasteful use of a scarce soil resource. Therefore the “dig and haul” option of removing the contaminated soil to Australia for safe disposal in a landfill was not the preferred option.

At the onset, it was unknown if remediation approaches used in temperate regions would be suitable for this coastal Antarctic site, and there are environmental and economic risks associated with using unproven remediation technologies in Antarctica. Other challenges, typical of remote sites, were operational: short field seasons, difficult site access, limited transportation of people and equipment, and a high degree of uncertainty in planning and execution of field seasons.

The second stage of remediation began in 2005 with passive *in situ* treatment of groundwater using a funnel-and-gate PRB installed down-gradient of the source zone to manage off-site migration of contaminants (Mumford et al., 2013, 2014).

The third remediation stage, ultimately implemented in 2011, was excavation of the contaminant zone and active remediation using six large biopiles (Fig. 1). The biopiles were located beside and partially above the spill zone, and were oriented east-west, parallel to the dominant wind direction, meaning snow build up was on the leeward west side, exposing the north and south sides and ensuring they were not buried beneath an insulating snow layer. The long edge faces north allowing direct solar radiation to hit the biopiles and extend the period of time soil remains unfrozen. Endemic microbial activity was stimulated within the soils through aeration (mechanical turning), fertiliser and leachate re-distribution to increase soil moisture. Biopiles 1 through 4 were constructed between January and February 2011, and last sampled in November 2014, prior to being dismantled