Comparing Two Remediation Alternatives for Diesel-Contaminated Soil in the Arctic Using Life Cycle Assessment

By

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Abstract

Contaminated sites in the Arctic pose risks to the environment and human health, and provide a major challenge to scientists attempting to carry out remediation on these sites. This project examines background information on the Arctic, the unique challenges that the Arctic poses for remediation, the types of remediation technologies that can be applied to the Arctic, and how life cycle assessment can be used to determine the effectiveness of remediation in the Arctic. This information is then applied to a theoretical case study involving remediation of a diesel spill within the city limits of Iqaluit, Nunavut. A simplified life cycle assessment is used to examine the benefits and drawbacks of landfarming within Iqaluit city limits versus shipping contaminated soil south to a landfill. This assessment is accomplished through comparison of toxicity to those involved in the remediation, length of time required for remediation, CO_2 output from the remediation itself, and economic benefits to the community. Landfarming was found to be the better technique overall, as it has lower CO_2 production and has greater financial benefits to the community of Iqaluit. However, it is a more time consuming process, and may result in higher toxicity due to volatilization of diesel.

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1.0 General Introduction

The Arctic is a unique and very distinct area of the world, and although it is perceived as being a pristine landscape this is not entirely true. There has been extensive human activity in the Arctic over the past number of decades, and unfortunately this activity has resulted in extensive petroleum hydrocarbon (PHC) contamination of this ecosystem. Approximately 60% of contaminated sites in Canada involve petroleum hydrocarbons, illustrating the importance and scope of this issue (Sanscartier *et al.,* 2009b). Clean-up in the Arctic is a challenge because of its climate and remote location, and therefore our usual clean-up methods for temperate climates cannot easily be applied. Research is ongoing into how best to remove these harmful contaminants, without causing any further damage in the process. This paper will examine various methods for PHC clean-up in the Arctic, and will attempt to explain some of the challenges being faced by project managers, engineers, and scientists alike as they try to repair the extensive damage done to this beautiful landscape. These clean-up methods can be quantified using life cycle assessment (LCA). LCA is a type of cradle-to-grave analysis, a useful tool that enables/allows the user to compare different remediation strategies and determine which strategy would have the most benefits with the least amount of damage caused to the environment. Social, economic and environmental factors can be taken into account to determine a remediation plan that is most appropriate for each situation and which may be unique.

The following project was completed as a requirement for a course-based Master's of Environmental Studies degree from the School of Environmental Studies at Queen's University. The literature review was completed to provide background material, which was then applied to the final section. The literature review focuses on diesel as a contaminant in soil, the challenges of carrying out remediation projects in the Arctic, different remediation techniques that can be applied to Arctic clean-ups, and how life cycle assessment may be applied to remediation. The final section examines a hypothetical case study involving a diesel spill in Arctic soil, and applies a very simplified form of life cycle assessment to examine the benefits and drawbacks of two different remediation strategies. These different strategies are compared in terms of economic benefits to Iqaluit (where the diesel spill took place), CO_2 output (as a surrogate for environmental risk), toxicity to human health as a result of the remediation (represented by the amount of diesel volatilized) and also time requirements for each scenario.

The information collected was approached from a public perspective, and only information that is readily available through the Internet or peer-reviewed journals was used. As contamination in the Arctic is an every-growing concern, and life cycle assessment has not often been applied to remediation efforts taking place in an Arctic, this made for a very interesting case study. It also demonstrates the need for more research and case studies to be carried out in this field.

2.0 Literature Review

2.1 Goals and Objectives of the Literature Review

This literature review will examine the issues of petroleum hydrocarbon contamination in the Arctic focusing on diesel spills in Arctic soil. This problem will be reviewed in the context of spills within remote Arctic communities and the difficulties associated with such isolated locations and harsh conditions. Total petroleum hydrocarbons and their uses in the Arctic will be discussed, along with the issues of both historical and current spills. Regulations detailing clean-up requirements for petroleum hydrocarbons are explained, as well as toxicity of various petroleum hydrocarbons with a focus on diesel.

Several different remediation strategies will be explained in detail, including: natural attenuation, excavation, soil washing, landfilling, capping, bioremediation, biopiles, landfarming and phytoremediation. Finally an explanation of life cycle assessment will be given. This thesis will also detail how life cycle assessment can be applied to remediation of diesel spills in Arctic soil. This will include a brief history of LCA and the challenges of applying LCA in the Canadian Arctic.

2.2 Total Petroleum Hydrocarbons

Some of the most common contaminants in the Arctic are oil and its refined products (total petroleum hydrocarbons or TPHs) (Chang, 2010). Hydrocarbons are the simplest type of organic compound, because TPHs contain only H and C atoms. The majority of hydrocarbons found naturally occur in crude oil, and decomposed organic matter provides the carbon and hydrogen.

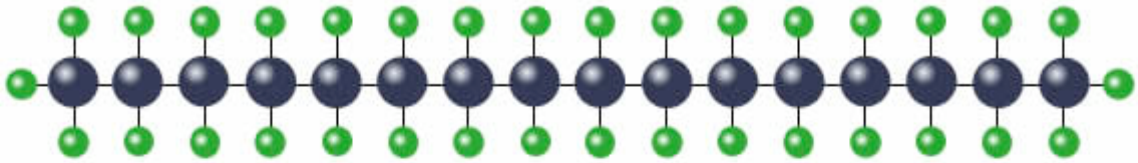

Figure 1. Chemical structure of a typical diesel molecule. Adapted from www.firmgreen.com

Figure 1 illustrates a typical molecule of diesel, made up of carbon and hydrogen atoms that are present in different amounts depending on the hydrocarbon. The number of carbon atoms present will determine the properties of the hydrocarbon compounds, as illustrated in Table 1.

Table 1. The general properties of different hydrocarbon ranges (adapted from CCME, 2008a).

Number of Carbon Atoms	Properties
<10	Highly volatile, soluble, mobile, easily biodegraded
10-16	Volatile, lower solubility, somewhat less mobile, easily biodegraded
16-34	Non-volatile, limited solubility, less biodegradable than C_{10}-C_{16}
>34	Non-volatile, limited solubility, not easily biodegradable

Common fuels such as gasoline and natural gas are made up of mixtures of hydrocarbons, and all different fuel types are derived from crude oil which contains hundreds of different types of hydrocarbons (Silberberg, 2004). Hydrocarbons contained within crude oil must be separated before they can be useful, and this separation is accomplished through the process of oil refining.

Different hydrocarbon chain lengths have different boiling points, so they can be separated using a fractional distillation column. Crude oil is heated and different hydrocarbons are removed according to their vaporization temperatures (Freudenrich, 2001). Petroleum gas, gasoline, kerosene, lubricating oil and diesel are some of the compounds that may be derived during the distillation process. This paper will focus on diesel contamination within Arctic communities.

Diesel fuels are a type of fuel oil, and all fuel oils consist of complex mixtures of aliphatic and aromatic hydrocarbons. Aliphatic alkanes make up 80-90% of fuel oils and aromatics make up 10-20%. Diesel is a mixture of hydrocarbon chains with 8-21 carbon atoms and has a boiling range of 200 to 325 degrees Celsius (Collins, 2007).

2.2.1 Use of Diesel in the Arctic

Diesel fuel is used in mining, oil and gas production facilities and military base operations (Chang, 2010). Diesel is also used extensively, along with gasoline, in every Arctic community, to provide heat, electricity and transportation. Contamination from petroleum products is widespread in the Canadian Arctic and most commonly found at former military and industrial sites, scientific research stations, in communities, at remote airstrips (Filler *et al.,* 2008.), in gravel pads, at fuel storage and dispensing facilities, along transport corridors (pipelines and roads) and at mine sites (Filler *et al.,* 2009). Hydrocarbon fuels including arctic-grade diesel, lubricating engine oils, JP-5 fuel, kerosene and motor oils are used in cold regions for heating, transportation and electricity generation (Chang, 2010).

In 2001, the territory of Nunavut consumed 33 million litres of diesel for the production of electricity, and over 9 million litres of that was used to run the capital of Iqaluit (Whitlock, 2001). The inhabitants of Iqaluit at that time (a population of approximately 5000 people) consumed a further 20 million litres of diesel fuel that year alone for space heating (Whitlock, 2001).

The amount of fuel required in the Arctic is likely to increase in the coming decades. In 2006 the population was 6,184, an increase of 18.1% from the 2001 census (Statistics Canada, 2006). Furthermore, discoveries of oil and diamonds is going to result in more people visiting or moving to the Arctic, and as the population of Canada's Arctic increases, so will fuel requirements and fuel spills.

About a quarter of the world's remaining petroleum resources are found in the Arctic, and there are also deposits of gold, silver, lead, tin, uranium copper and zinc (WWF Canada, 2011a). Several companies are already operating in the Arctic including Peregrine Diamonds Ltd., HTX Minerals Corp. and Nunavut Resources Corp, all of which have plans for mineral project development and exploration in the Arctic (HTX Minerals Corp., 2012; Peregrine Diamonds, 2012). One aspect of the Arctic which garners commercial interest is the melting of sea ice, which makes drilling for oil in the Arctic ocean a more realistic venture than in the past. Increasing oil prices and advances in technology mean that the petroleum industry is able to access this area more readily, and more people are likely to move to the Arctic to take advantage of jobs that would be created as a result. Drilling for oil in the Arctic could result in disasters that would devastate the fragile ecosystems of this part of the world. Offshore drilling could result in both minor and major spills, occurring during transport to land via tanker or damage to a pipeline. It would be time-consuming and expensive to get equipment to the area where the spill occurred, and ecosystems in the Arctic could be damaged beyond repair before anyone could reach the location of the spill. However steps are already being taken to protect the Arctic from the potential for future offshore drilling spills. The National Energy Board (NEB) recently reviewed Arctic offshore drilling policies and decided to maintain the Same Season Relief Well policy that minimizes the risk of a multi-year spill, and within this report the NEB established comprehensive filing requirements for offshore drilling in the Canadian Arctic (WWF Canada, 2011b).

2.2.2 Historical Contamination and Current Spills

Spills are a fact of life in the Arctic, due to the amount of fuel that must be used to run generators and provide transportation. Crude oil spills from ruptured pipelines in the Arctic represent the largest source of petroleum contamination on land, followed by spills from tankers or resupply vessels that end up on shorelines (Filler *et al.,* 2008.). Diesel fuels are the next most common spills and are usually caused by infrastructure failure, human error during transfer of fuel, sabotage or intentional damage and natural hazards (Filler *et al.,* 2008).

Diesel spills are an important issue in many small Northern and Arctic communities such as Attawapiskat, a small native community in remote northern Ontario a population of approximately 1500 (CBERN). In 1979, there was a massive diesel leak in the community. Instead of remediating the spill, J.R. Nakogee School was built to act as a sort of cap. In the year 2000, the school was abandoned due to health and safety issues, and students have been in portables ever since (Finlay *et al.,* 2010). Many spills in the Arctic happen in small, isolated rural communities as all of these communities still rely on diesel for transportation and to run generators that provide heat and electricity (AANDC, 2010; Whitlock, 2001). As these communities grow and there is more development in the Arctic, better preventative measures will be required in additions to more efficient clean-up efforts.

In the Canadian Arctic there are as many as 662 contaminated sites, with over 150 that are contaminated with petroleum hydrocarbons (Dubois, 2009). This includes approximately 30 sites in the Northwest Territories, 149 in Nunavut and 10 in the Yukon (Dubois, 2009). One major example of contamination was identified in the Distant Early Warning (DEW) Line sites that were constructed by the military in the late 1950's during the Cold War (Chang, 2010). These sites were a line of 63 military radar stations that operated across Alaska, northern Canada and Greenland (Poland *et al.,* 2001). By the 1980's, the DEW line facilities were becoming obsolete, and the decision was made to close down sites that would not be used, or to upgrade them to current technological standards. Those that were not decommissioned became part of the North Warning System, which was created in 1985 following an agreement between Prime Minister Brian Mulroney and President Ronald Regan. The DEW line was officially deactivated in 1993 (*Arctic Territory Series*, 2007). The sites are now mostly controlled remotely due to advances in radar surveillance, however most still use diesel generators to produce heat and electricity (NASA, 2007). Prior to surveillance site upgrades, petroleum hydrocarbons (usually diesel fuels) were used to generate electricity and heat as well as for transportation. Environmental assessments of the DEW line sites have detected hydrocarbon spills and leaks into soil, and contaminant depth is usually one to two metres (Zanzinger *et al.,* 2002). The North Warning System Office of the Canadian Department of National Defense is currently undertaking a $320 million program to clean-up these sites, to prevent the movement of contaminants into the sensitive Arctic ecosystem and restore them (Zanzinger *et al.,* 2002).

Another difficulty faced by those attempting to clean-up sites in the Arctic is the fact that many contaminated sites in this area have legacy contamination. This means that the contamination may have been on the sites for many years, and as a result, the hydrocarbons are weathered (Sanscartier *et al.,* 2009a). Weathered petroleum hydrocarbons are typically of medium to high molecular weight, and have been present in the soil for a long time. They have lower bioavailability than low to medium molecular weight hydrocarbons (Brassington *et al.*, 2007), which means they present different challenges compared with recent spills. Much research so far has been focused on low to medium molecular weight compound mixtures such as diesel fuel, but when these compounds are present in the environment for an extended period of time, predominantly medium to high molecular weight hydrocarbons remain (Sanscartier *et al.*, 2009a). These are often overlooked but these weathered hydrocarbons should receive more attention than they have to date, because they can pose potential risks to human health (Brassington *et al.,* 2007). Some studies demonstrate that bioremediation (any biological process that results in the degradation or breakdown of contaminants [Filler *et al.,* 2008]) may be effective for weathered medium to high molecular weight hydrocarbons, however bioremediation is not as effective as when applied to low to medium weight hydrocarbon fractions (Sanscartier *et al.,* 2009a).

2.3 Regulations and Guidelines

Despite the fact the Arctic is an area of international interest, there are currently no universal guidelines for clean-up of soil contaminated by petroleum hydrocarbons. Canada does regulate the Arctic through domestic guidelines and legislation, through organizations such as Environment Canada and the Canadian Council of Ministries of the Environment (CCME). Their guidelines are not specific to the Arctic however, although they do attempt to accommodate this unique region (Filler *et al.,* 2008). Spills cause more damage in cold regions versus temperate climates, and Arctic ecosystems have a much harder time recovering. This is because natural attenuation occurs at a very slow rate in the Arctic, and off-site migration happens quickly. It is also much more expensive to remediate a spill in the Arctic than in more developed southern regions. Operations such as dig-and-haul are sometimes prohibitively expensive and furthermore can degrade permafrost. On-site remediation alternatives, despite their low cost, are still not widely adopted because of remote access and high energy costs (Rayner *et al.,* 2007). These considerations are important when attempting to follow guidelines for clean-up and remediation in the Arctic.

The CCME established a set of guidelines titled Canada-Wide Standards for Petroleum Hydrocarbons (PHC) in Soil in 2001. They are not “standards” in a legal sense as they are not enforceable by law, however they set remedial guidelines for contaminated soil and subsoil in four different land use categories

(CCME, 2001). Remediation is usually triggered by the need to accommodate a new land use or increasing use of the land when human and ecological exposure to petroleum hydrocarbons needs to be avoided (CCME, 2001). It is important to have a set of guidelines that will standardize an approach to petroleum hydrocarbon clean-up, because without them either under-management or over-management of contaminated sites may occur. Over-management may limit land sale transactions or possible development for real estate because of high remediation costs, and under-managed sites may continue to threaten human or environmental health (CCME, 2001). The Canada-Wide Standards however, do not set remedial timelines that must be followed during clean-up. These standards only specify methods and outcomes that must be attained to allow for consistency in clean-up. Timelines often depend on the timeframe for the proposed use of the site (CCME, 2001). These standards are based on assessments of risks posed to humans, plants, animals and environmental processes in four land use categories: agricultural, residential/parkland, commercial and industrial. The standard is laid out in three tiers, each of which incorporate different amounts of site-specific information. Environmental and human health protection goals don't vary between the tiers, and these goals are stated in the Tier 1 levels in Table 2.

Table 2. Summary of Tier 1 TPH Levels (mg/kg) for surface soil (CCME, 2001).

Land Use	Soil Texture	Fraction 1 (C_6-C_{10})	Fraction 2 (>C_{10}-C_{16})	Fraction 3 (>C_{16}-C_{34})	Fraction 4 (>C_{34})
Agricultural	Coarse-grained	30[b]	150	300	2800
	Fine-grained	210 (170[a])	150	1300	5600
Residential Parkland	Coarse-grained	30[b]	150	300	2800
	Fine-grained	210 (170[a])	150	1300	5600
Commercial	Coarse-grained	320 (240[a])	260	1700	3300
	Fine-grained	320 (170[a])	260 (230[a])	2500	6600
Industrial	Coarse-grained	320 (240[a])	260	1700	3300
	Fine-grained	320 (170[a])	260 (230[a])	2500	6600

[a] = where applicable, for protection of potable groundwater
[b] = assumes contamination near residence

Tier 2 levels may be used when site-specific information indicates that the site conditions exist that modify human or ecological exposure to petroleum hydrocarbon contamination and therefore alter the risks significantly relative to generic Tier 1 conditions, Tier 2 levels are derived on a site-by-site basis (CCME, 2001). For Tier 3 levels both site-specific risk assessment and management are used to develop site-specific cleanup levels and related management options. Background information has been established to direct this process and is documented in the *Guidance Manual for Developing Site-specific Soil Quality Remediation Objectives for Contaminated Sites in Canada* (CCME, 1996).

It is necessary to determine the various land uses, exposure pathways and potential receptors when deciding what level of clean-up will be required. There are also other regulations that may be useful when determining clean-up tactics, such as those provided by Aboriginal Affairs and Northern Development Canada (AANDC). AANDC's protocols take into account all legal requirements, standard environmental management practices and also remediation costs when determining the most appropriate clean-up to undertake (INAC, 2005). Both INAC and DND are attempting to restore contaminated sites to environmentally safe conditions, prevent migration of contaminants into the Arctic ecosystem, remove any hazards to human health and also implement cost effective solutions. INAC also has several other considerations, which include respecting historical agreements and obligations, applying CCME environmental protection approaches, recognizing the threat of global warming to the Arctic and ensuring long term effectiveness of remediation efforts (INAC, 2005).

The Dew Line Clean-up Protocol (DLCU) was developed by DND as a strategy for remediation of DEW line sites managed by DND. This protocol was developed before there were any remediation standards specific to the Canadian Arctic, and it was first used for remediation in 1996. A number of changes have been made since then to address various issues and changing regulatory frameworks (INAC, 2005).

Canadian standards can also be compared and contrasted with international standards, such as those from Australia as they are applied to Antarctica. In Australia the approach to management of contamination is carried out at both a national and state level. The National Environment Protection Measure (NEPM) establishes a nationally-consistent approach to the assessment of site contamination and contains two schedules: schedule A identifies the recommended processes for the assessment of site contamination and Schedule B which is made up of 10 general guidelines for the assessment of site contamination (EPHC, 2012). There are also individual State Environment Protection Acts and Regulations that attempt to achieve a balance between social, economic and environmental aspects of clean-up programs. Many of these programs recognize that in some cases clean-up is not practical or necessary, and allow alternative clean-up methods that may take longer, or methods that do not remediate to expected levels (Sustainable Remediation Forum Australia, 2009). Contamination is present if pollutants are present in concentrations listed in Australia's guidelines, which are laid out by the Department of Environment and Conservation. These guidelines include levels for TPH fractions that similar but not identical to Canadian guidelines (Department of Environment and Conservation, 2010). In addition, they are divided up into two categories: ecological and health investigation levels, instead of different land use categories as defined by Canadian guidelines.

Another interesting comparison of environmental standards can be made between Antarctica and the Canadian Arctic. Even though both have similar temperature and climate conditions, Antarctica has much more stringent guidelines. For example, under Canada's Antarctic Environmental Protection Act, there cannot be any open air burning of waste. This would include release of volatile organic compounds (VOCs) into the air; so far VOCs are not regulated at all in the Canadian Arctic (Environment Canada, 2011b).

2.4 Toxicity of Petroleum Hydrocarbons

Petroleum hydrocarbons can cause problems when released into the soil. They can be transported through soil, air or water and can result in fire hazards, human and environmental toxicity, odour and impairment of soil processes such as water retention and nutrient cycling (CCME, 2011)

Oil and fuel spills have potential human health and environmental impacts. The properties of petroleum hydrocarbons in contaminated soils depend on the petroleum source, the composition, the degree of processing (crude, blended or refined) and the extent of weathering due to time spent in the environment (CCME, 2001). Most components of petroleum hydrocarbons are toxic to some degree, and due to the complexity it can be difficult to assess human and environmental health risks associated with contamination in soil (CCME, 2001). Human health impacts result from environmental exposure as well as from occupational exposure, and both potential risks should be considered when assessing clean-up options. Health risks depend on the type of petroleum hydrocarbons, and the exposure pathway. Diesel and jet fuel, for example, contain compounds with potentially carcinogenic effects (Hutchenson *et al.,* 1996). Studies have been carried out since the 1980s trying to establish whether diesel fumes may be linked to cancer, and the International Agency for Research on Cancer (IARC), part of the World Health Organization, now classifies diesel engine exhaust as carcinogenic. Silverman *et al.,* (2012) showed an increase in lung cancer deaths in underground miners. In this study, diesel exhaust exposure was represented by respirable elemental carbon and the study evaluated the exposure-response relationship between diesel exhaust and lung cancer mortality. They showed a strong relationship between diesel exhaust and lung cancer mortality, and heavily exposed workers were three times more likely to die than workers exposed to the lowest amount. Other studies comparing lung cancer and diesel exhaust also found an elevated risk of lung cancer in diesel-truck drivers (Garshick *et al.,* 2008; Steenland *et al.,* 1990).

Alkanes (e.g. – *n*-hexane) may result in mucus membrane irritation or a disruption in central nervous system (CNS) function (Hutchenson *et al.,* 1996). CNS effects and dermal sensitivity are most common from exposure to fuels with lower molecular weights (C_5 through C_9). Since carbon chain length affects lipid solubility, smaller carbon chains react more readily with the lipid membrane of nerve cells than longer carbon chains (Hutchenson *et al.,* 1996). Compounds with larger carbon chains may exhibit mutagenic and carcinogenic properties (Suleiman, 1987). Aromatic compounds (e.g. – benzene) target a variety of systems and organs in humans including the CNS, liver, kidney and hematopoietic system. They are highly lipid soluble, and are readily absorbed through the gastrointestinal tract of mammals (Samata *et al.,* 2002). Many are toxic or mutagenic; benzene is one of the most hazardous due to its carcinogenic properties (Hutchenson *et al.,* 1996).

Diesel vapours or fumes may cause respiratory irritation, resulting in coughing or difficulty in breathing. There may also be irritation to the nose, throat, lungs, respiratory tract and CNS effects including dizziness, headache or loss of coordination. Contact with contaminated soil can cause irritation to the skin if it occurs regularly (MSDS, 2006).

There is also concern for children in communities where contamination is present, due to potential long-term health effects of growing up around contaminated soil and water (ATSDR, 2011). A study was performed by Ausma *et al.,* (2002) to confirm whether emissions from a landfarm could impact local residents up to 500 m away. Human inhalation exposure limits for total petroleum hydrocarbon volatiles have not been established, however some petroleum products are of greater concern than others. Benzene, toluene, ethylbenzene and xylene (BTEX) are of the greatest risk to humans because of their toxic, carcinogenic and mutagenic properties. BTEX is only present in diesel in trace quantities. The Ausma *et al.,* (2002) study found that effects on workers or nearby residents would be minimal and no greater than exposure to other sources of volatile hydrocarbons, however they suggest that it would be beneficial to develop methods to assess health risks from very low-level exposure to volatiles released during soil bioremediation.

In summary, this wide range of negative effects of petroleum hydrocarbons indicates how important it is to limit human access to contaminated sites, and to carry out proper human health risk assessments before any work is performed to clean-up.

Several exposure pathways must be considered when evaluating risks to human and ecological health. These include soil ingestion, contact with soil, consumption of contaminated food or water, inhalation of vapours or offsite migration of contaminated soil/dust (CCME, 2008). Vapour inhalation and offsite migration of contaminated soil are of particular concern in Arctic communities where diesel spills are commonplace.

2.5 Remediation Techniques

Clean-up of petroleum hydrocarbons can be a challenge, and there are many factors that affect decision-making during the remediation process. Financial constraints, regulatory pressures, risks (perceived or real), liability and land ownership all contribute to the choice of remediation strategies (Filler *et al.,* 2009). In addition, the unique features of the Arctic and its distance from any large Canadian cities make clean-up a greater challenge than in more southern locations. Permafrost, cold temperatures, short summers, long dark winters and cold-tolerant microorganisms are just a few of the environmental characteristics of this region, and all have an impact on how clean-ups are carried out (Filler *et al.,* 2008). The Arctic also has low biological productivity due to the extremely short summer, therefore if the ecosystem is damaged by a spill it will recover much more slowly than a warmer climate (AMAP, 1998). A number of remediation techniques are available for clean-up of petroleum hydrocarbons, including natural attenuation, bioremediation, landfilling, landfarming, biopiling, phytoremediation, capping, thermal desorption and soil washing (Sanscartier *et al.,* 2009b; Paudyn *et al*., 2008; Thomassin-Lacroix *et al*., 2002; Feng *et* al., 2001; Filler and Carlson, 2000; Margesin *et al.*, 2001a; Palermo, 1998). All of these strategies can be effectively applied in southern climates with longer summers and warmer temperatures, however not all are applicable to the Arctic climate and environment. The Arctic is highly variable in terms of climate and environmental characteristics, and no treatment option can be applied in all situations.

Considerations that must be taken into account when deciding on a strategy include an understanding of cold temperature effects on physical and biological processes that occur in contaminated soil, site-specific weather conditions, and unique characteristics of the site (Filler *et al.,* 2009).

2.5.1 Natural Attenuation

Natural attenuation is an approach that relies on intrinsic biological processes without human intervention. It is appealing because of its low cost, and may be chosen as an alternative when disturbances from assessment and remediation will cause greater damage to the ecosystem than leaving the contamination in place (Filler *et al.,* 2009. The process of natural attenuation will in most cases be largely ineffective in the Arctic because it is limited by low nutrients, low temperatures and water availability (Rayner *et al.,* 2007). Furthermore, contaminants may migrate away from the original spill by washing away during the summer thaw, causing more widespread damage (Gore *et al.,* 1999). Concentrations of petroleum hydrocarbons in Arctic soil will remain high for many years, and a more invasive treatment approach will likely be required to get rid of the contaminants in a timely fashion. However, natural attenuation could be combined with technologies such as permeable reactive barriers (Snape *et al.,* 2001) to prevent off-site migration in areas where the contamination will not create substantial impacts on the surrounding environment (Filler *et al.,* 2006).

2.5.2 Excavation, Soil Washing, Landfilling, Capping

Excavation, soil washing, transport to a landfill and capping of the contaminated site are less viable options for the Arctic due to high costs and the distances required for transportation. Excavation involves the removal of contaminated soil to a landfill, but it is limited to the short warm season and is only practical where roads and necessary infrastructure are already in place (Filler *et al.,* 2009). There may also be environmental consequences, such as damage to permafrost during excavation that could exceed the amount of damage caused by the original spill (Poland *et al.,* 2003).

Soil washing is an *ex-situ* process for scrubbing soil to remove contaminants. Soil washing may involve the use of surfactants, emulsifiers or other additives which increase hydrocarbon solubility in water (Banat, 1995). There are a variety of solvents available, which may be selected depending on soil type or the type of contamination present. Hydrocarbon contaminants usually bind to smaller soil particles so smaller particles can be separated from larger ones to reduce the volume of contaminated soil, after which contaminants can be floated or skimmed off the surface (Feng *et al.,* 2001, Khan *et al.,* 2004). This technology is becoming more common; however there are limitations to soil washing that must be taken into consideration. Complex mixtures make it difficult to choose the correct washing fluid, it does not destroy the contaminants so they must be dealt with afterward, and water used for washing must also be treated before it can be discharged (Federal Remediation Technologies Roundtable, 2007).

In-situ capping is a remediation technique for contaminated soil that involves isolating it beneath a layer of clean soil or other suitable material to prevent further spread of the contaminant. This technique has been proven effective in many case studies involving sediment and it was used during remediation of the Fox-C Ekalugad Fjord (Palermo, 1998). There are, however, drawbacks. The efficiency of the cap decreases over time so it is not a permanent solution, and furthermore it can only be implemented in shallow contaminated soils (Khan *et al.,* 2004). Capping of contaminated soil also eliminates any possibility of natural attenuation occurring.

2.5.3 Bioremediation

Bioremediation refers to "any biological process, through the action of bacteria, fungi, plants or managed biodegradation, that transforms or breaks down environmental contaminants" (Filler *et al.,* 2008). Bioremediation techniques are relatively low-cost and non-invasive approaches for clean-up in cold regions, and in some cases they can work relatively quickly to clean-up contamination to a reasonable level. However, many of these techniques have to be modified so that they will be effective in the Arctic. There are both *in situ* and *ex situ* techniques, and there are benefits and drawbacks to both approaches. This type of technology is already proven to be successful in more temperate climates, however there are aspects of polar soil that make bioremediation much more challenging. Some examples of the difficulties are cold soils are often low in nutrients such as nitrogen and phosphorus, have little available water, are frozen for most of the year and may exhibit extremes in pH or salinity (Filler *et al.,* 2008, Chang *et al.,* 2010).

Hydrocarbon-degrading bacteria do occur in Arctic soil. For example, *Rhodococcus, Sphingomonas* or *Pseudomonas,* which are alkane-degrading bacteria have been found (Aislabie *et al.,* 2006). These bacteria are well adapted to survival in the inhospitable conditions including very cold temperatures, low nutrient availability and fluctuating freeze-thaw cycles. These bacteria are capable of de-contaminating the soil without further intervention, and in warmer climates the process of natural attenuation may be effective in a time frame that is comparable to other more active remediation strategies. However the Arctic temperatures slow this process down considerably, so the rate of biodegradation may be increased through addition of nutrients, nitrogen fertilization of the soil and soil temperature manipulation (Rike *et al.,* 2003). Nutrients such as nitrogen and phosphorus are the major limiting factors when it comes to bioremediation, and studies have shown a significant enhancement and acceleration in hydrocarbon degradation when fertilizer is added to contaminated soil (Margesin & Schinner, 1997). Naturally occurring microbial populations may also be supplemented or bio-augmented with introduced strains, which increases the rate of biodegradation (Margesin & Schinner, 2001b). Some studies have suggested that introduced microorganisms were acting in competition with indigenous populations, making it even more difficult for the indigenous ones to perform. Thus there was an indication that in some cases it is unnecessary or even undesirable to add cultured bacteria to a contaminated site (Demque *et al.,* 1997).

Passive soil warming of cold soil through the use of plastic covers to absorb and retain heat has had success in increasing rates of degradation. Plastic covers inhibit evaporative loss of hydrocarbons through volatilization, so usage depends on the individual case study (Filler *et al.,* 2008).

2.5.4 Biopiles

Biodegradation of hydrocarbons by naturally occurring microbial activity is one of the primary mechanisms that allows them to be eliminated from the environment. Hydrocarbons can be degraded provided that factors such as nutrient availability and temperature are favorable for these naturally-occurring microbes. Optimal biodegradation temperatures are usually between 15-30°C, however this is very difficult to achieve in the Arctic (Thomassin-Lacroix *et al.,* 2002). A bioremediation technique that may be applied in Arctic conditions to achieve these temperatures is the use of biopiles. A biopile is a remediation technique where soil is piled over an air distribution system and aerated to enhance microbial activity. Biopiles have the added benefit of requiring less surface area to treat a comparable volume of soil, compared with landfarming (Section 2.5.5), however they are more expensive to build and operate (Sanscartier *et al.,* 2009b). The aeration system may also be used to provide heat in cold regions, which increases the length of time for treatment each season and therefore shortens time required for remediation (Sanscartier *et al.,* 2009b, Filler *et al.,* 2001). Unfortunately heat may dry the soil, and this will slow down the rate of biodegradation by microbial activity. This problem can be prevented through humidification of air before it reaches the biopile, and studies have shown that humidified biopiles produce significantly lower final petroleum hydrocarbon levels than other systems which do not humidify the soil (Sanscartier *et al.,* 2009b). Inoculations with cold-adapted bacteria or addition of fertilizer to biopiles have also been shown to have significant positive effects in terms of hydrocarbon removal (Mohn *et al.,* 2001).

Piles may also be covered to prevent runoff, evaporation, volatilization and also to promote heating by the sun.

If volatilization of contaminants occurs, this may pose risks to human health if it occurs near settlements. It is still unknown whether release of trace hydrocarbon gases can impact air quality or result in heath risks to workers or residents nearby (Ausma *et al.,* 2002). The interactions of VOCs with the atmosphere are very complex and not fully understood, however they are able to react with nitrogen oxides (NO_x) to produce ozone (O_3). This reaction depends on the availability of NO_x though, and in less polluted areas of the world such as the Canadian Arctic this is not likely to be a major source of O_3 production (Ausma *et al.,* 2002). It is also not a major issue with respect to diesel, because diesel contains low amounts of volatile components. Lighter petroleum products, such as gasoline, tend to be removed from soil mainly through volatilization. In contrast, mid-weight and heavier compounds such as lubricating oils, which to not readily evaporate, are mostly removed through biodegredation (Khan *et al.,* 2004; USEPA, 1995). It is important to balance energy use and costs involved with maintaining soil temperature/humidity, so as not to outweigh the benefits of remediation with the costs of further pollution and environmental degradation (Sanscartier *et al.,* 2009b).

2.5.5 Landfarming

Landfarming is an effective, relatively cheap and environmentally friendly technique. It has become more popular than other remediation technologies because it complies with government regulations, has low energy consumption, low risk of contaminant migration, and can be adapted to different climates or locations (Besaltatpour *et al.,* 2011). Landfarming is a “simple technique in which contaminated soil is excavated and spread over a prepared bed and periodically tilled until pollutants are degraded” (Vidali, 2001). Tilling, aeration and adding moisture to the water are all carried out to increase microbial activity (Khan *et al.,* 2004). Other modifications such as the addition of bulking agents to increase aeration, lime to adjust pH or the addition of cosubstrates to stimulate microbial metabolism can be made to speed up the process (McCarthy *et al.,* 2004). The method requires minimal equipment and does not result in contaminated soil being left in a landfill indefinitely, therefore there is less chance that the fragile Arctic ecosystem will be further damaged in the process. Landfarming can be *in situ* or *ex situ*, and refers to a combination of volatilization and bioremediation/biodegradation that is used to remove total petroleum hydrocarbons (Paudyn *et al.,* 2008). Lighter petroleum hydrocarbons are often removed from the soil through a combination of microbial breakdown and evaporation, however heavier petroleum hydrocarbons such as lubricating oils and diesel (to a lesser extent) do not evaporate and require longer periods of time to degrade (Khan *et al.,* 2004). Because landfarming is a slower process in the Arctic than in temperate climates, contaminants must not be allowed to migrate offsite to previously uncontaminated soil. Prevention of leaching or run-off is often controlled by building a berm around the edge of the landfarm, and lining it with geotextile fabric (Filler *et al.,* 2008).

During the process of landfarming, hydrocarbon contaminated soils are spread out in a layer of 0.3-1.0 metres thick, nutrients are added and the soils are mixed/aerated periodically (Paudyn *et al.*, 2008). Treatment of the soil may be unique for each site and depends on the climate, location, temperature and soil type (Paudyn *et al.;* 2008, Chatham, 2003). Cold climates have proven more difficult for those attempting to use landfarming as a remediation technology, despite consistent success in warmer southern climates. Landfarming has been successful in several case studies, however there are no criteria that can be used to immediately determine if landfarming will be viable at a given site given levels of contamination or location (Paudyn *et al.*, 2008).

When deciding if landfarming may be appropriate, several management factors must be taken into account. Landfarming is limited to biodegradable contaminants, it requires large amounts of land for the treatment area, and there are fairly specific requirements for temperature, moisture, pH and nutrients (Maila and Cloete, 2004). Excess moisture (>33%) can lead to poor aeration of soils and reduce aerobic hydrocarbon degradation, and may also contribute to the spread of contamination because with increasing soil moisture content there is also an increase in transport of petroleum products in soil (Khan *et al.,* 2004; Fine *et al., 1997*). Insufficient water content in the soil may decrease the rate of microbial processes and this may occur because soils contaminated with high concentrations of petroleum hydrocarbons can be very hydrophobic. Such soils do not hold water well and are difficult to irrigate (Filler *et al.,* 2008). Excess fertilizer may result in a reduction in microbial populations when there is not enough water in the soil to dissolve the fertilizer (Filler *et al.,* 2008). Similar to biopiles, in landfarming, volatilization of contaminants can be an important component of biodegradation. This is the case with diesel, although it does not evaporate as effectively as compounds with low molecular weight.

A study in Prudhoe Bay, Alaska measured hydrocarbon loss for one day and found 11% could be attributed to biodegradation while the remaining 89% could be attributed to volatilization and/or leaching (Chatham, 2003). This is a significant loss in contaminants due to volatilization, and production of ground level ozone or release of odorous/irritating compounds should not be discounted.

Landfarming has had varying success in cold climates. Several case studies (Paudyn *et al.,* 2008; Filler *et al.,* 2006; McCarthy *et al.,* 2004; Chatham, 2003) have examined its effectiveness. One case study carried out by Paudyn *et al.,* (2008) found that little bioremediation occurred in landfarms when aeration alone was used, but addition of fertilizer resulted in an increase in bioremediation and more rapid removal of contaminants. However, bioremediation was as successful as aeration at lower temperature (5°C versus 18°C). These results indicate that landfarming at Resolution Island, Nunavut was a success, and the paper states that a large-scale landfarm is currently in operation at the field site. Another study was carried out by Filler *et al.,* (2006) at a site contaminated with fuel oil, where samples were analyzed for a range of compounds including diesel, gasoline, benzene, toluene, and ethylbenzene. They found an apparent correlation between degradation rates and moisture and nutrient availability, indicating how important it is to reduce limitations to microbial processes wherever possible.

2.5.6 Phytoremediation

One interesting development in the field of bioremediation is the use of phytoremediation to enhance degradation. Phytoremediation is "the destruction, removal, or immobilization of soil contaminants brought about by plants and associated organisms" (Filler *et al.,* 2008). There are many different forms of phytoremediation, but most of the research carried out in cold climates has focused on rhizodegradation or rhizosphere-enhanced phytoremediation: the transformation or destruction of contaminants in soil through the action of plant roots and enhanced microbial activity at the soil-root interface (Kaimi *et al.,* 2007; Reynolds, 2004). There are benefits and limitations to this process, and results are not always quantifiable. Advantages to the process include its low costs, applicability to large areas, minimal requirements for infrastructure, ability of plants to re-grow and repair damage, high public acceptance and a reduction in runoff from the contaminated site (Reynolds, 2004). Limitations include that roots cannot penetrate deep into soil, so only shallow contamination will be addressed, treatment time is lengthy, and may take years instead of weeks or months (Reynolds, 2004). The success of rhizodegradation is also dependent on many factors such as temperature, length of growing season, water content of the soil, availability of nutrients and soil chemistry (Filler *et al.,* 2008). As previously discussed, these factors already present challenges in the Arctic. However, with so many potential advantages to this strategy it seems important to continue research to find the best way possible to implement this type of phytoremediation. One benefit of using cold-tolerant grasses during remediation was increased the degradation rate of petroleum compounds in soil (Filler *et al.,* 2008).

2.5.7 In Summary

Cleaning up of petroleum hydrocarbons in the Arctic is complex and difficult, and each contaminated site provides unique challenges. A number of potential options exist for clean-up, but no option can be applied uniformly to every contaminated site. Biopiles, landfarming and phytoremediation are just a few of the options available to those planning a clean-up effort. Choosing the most appropriate remediation technology requires balancing many variables including probability of success, cost and the environment. It is important to view the process of clean-up in a holistic manner instead of as an isolated process. Scientists, engineers and environmentalists need to choose the best remediation technique for the contaminated site, and carry out a clean-up that will be most satisfactory to all the parties involved.

2.6 Life Cycle Assessment: Theory and Uses

2.6.1 A Brief History of Life Cycle Assessment and Its General Application

Life Cycle Assessment (LCA) has been in use since 1969, when it was first performed for Coca-Cola by the Midwest Research Institute in the United States (Jian *et al.,* 2003). LCA work began in Europe shortly after this, and was soon adopted around the world because of its application for resource and energy conservation (Klöpffer, 1997). Since then LCA has been applied to a variety of projects, ranging from the production of chemicals to farming practices.

LCA is a type of “cradle-to-grave” analysis which can be described as “a holistic environmental assessment tool allowing the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product or service throughout its life cycle” (Sanscartier *et al.,* 2010a). To carry out a life cycle assessment, there are several steps that must be followed according to Gaines & Stodolsky (1997) and the USEPA (2006):

1. *Define goals and scoping* - This includes defining the project and determining what is actually required to carry it out. The context in which the assessment will be made must be established and the environmental effects that will be studied during the LCA must be defined.
2. *Inventory analysis* - Once all the requirements are identified, the next step is to assess all the ways these requirements could be satisfied. All inputs and outputs associated with each option must be recognized. For example, when the decision is made to remediate a site, all the different technologies should be listed along with an explanation of what is involved for each one. Energy use, water requirements, materials usage and environmental releases such as waste disposal and air emissions also need to be recognized.
3. *Impact Assessment* – During this step an assessment is made of the potential human and environmental effects due to energy and materials usage, water requirements and environmental releases. This can be carried out using LCA software such as SimaPro or GaBi, or a simplified

assessment may be carried out using an Excel spreadsheet (see final section).

4. *Interpretation* - Once all the data has been gathered and analyzed by the software, a profile can be created for each remediation technology that lists its costs and benefits relative to all the other options, with a clear understanding of uncertainties and assumptions made while generating the results. The best technology can then be applied after determining the goals of the clean-up and which solution best accomplishes those goals. These goals may include financial, regulatory, environmental, social or political constraints that must be addressed.

2.6.2 Life Cycle Assessment and Remediation

LCA can be useful when the decision is made to begin a remediation project. There are many remediation technologies to choose from, and the choice of technology depends on cost, effectiveness and duration of clean-up along with potential environmental or human health risks. To choose a remediation technology without examining the entire process of remediation from beginning to end (i.e. –the whole life cycle) is to risk creating more negative environmental impacts than those resulting from the original contamination. Any remediation that is undertaken must have environmental benefits that outweigh the damage caused by the contamination, however every remediation technology has drawbacks of its own. These negative impacts may include the release of greenhouse gases, depletion of natural resources, noise, venting of fumes, damage during clean-up and costs which can sometimes be prohibitive (Suèr *et* *al.,* 2004). The benefits of remediation can also extend beyond the removal of contaminants themselves, such as providing employment for people living in remote locations where clean-up is occurring. LCA can measure all of these factors and provide the best overall solution.

When used properly, LCA takes into account three types of environmental consequences associated with site remediation. The first environmental consequence includes primary impacts resulting from the contamination itself and changes in site environmental quality. Secondary impacts result from remedial activities themselves and can be global or local (Toffoletto *et al.,* 2005). Tertiary impacts are associated with changes in land use and the eventual fate of the site (Sanscartier *et al.,* 2010a; Lesage *et al.,* 2007). The LCA method can be applied at different levels of complexity and is most effective for sites where the environment is a priority and there are choices available in terms of finances or technical options (Cadotte *et al.,* 2007). Most studies involving LCA only evaluate the secondary impacts of remediation (Volkwein *et al.,* 1999; Diamond *et al.,* 1999), though other studies have been successful in including primary impacts within their scope as well (Toffoletto *et al.,* 2005, Godin *et al.*, 2004). Primary impacts of the contamination should not be neglected, as contaminated soil or water is responsible for a significant portion of the remediation's total impact on the surrounding environment. Without including the effects of primary impacts, it could be easy to forget the importance of remediating contamination to the lowest criteria possible (Toffoletto *et al.,* 2005).

There two different types of remediation that can be incorporated into an LCA – (i) green remediation or (ii) sustainable remediation. Green remediation generally incorporates environmental factors (energy, air emissions, water impacts, etc.), and has a reduced emphasis on economic or societal factors that is only required by regulations (Clayton, 2008). Sustainable remediation as defined by the Sustainable Remediation Forum (SURF) is "sustainable remediation…as a remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources" (Ellis & Hadley, 2009). The SURF definition encompasses green rand is more suitable to remediation in the Arctic, as clean-up efforts have significant impacts on those living and working in communities near the contamination. Goals of sustainable remediation (Bardos *et al.,* 2011) are applicable to any remediation effort both short and long-term and include:

- risk-based land management;
- acceptable wider effects of risk management action;
- transparency of the decision-making process and engagement of stakeholders; and
- balanced environmental, social and economical outcomes.

Including either green or sustainable remediation in a clean-up can help ensure that the environmental impacts of the remediation itself are reduced.

2.7 Life Cycle Assessment: Southern Canada vs. Northern Canada

Life Cycle Assessment has been carried out successfully for different types of projects in many different sectors (Lardon *et al*., 2009; Samaras *et al*., 2008;

Finnveden, 1999). LCA is a helpful tool that could benefit those attempting clean-up efforts in the Arctic, and further research into its applicability for a wide range of uses in the Arctic would be beneficial. However, carrying out a life cycle assessment in the Arctic poses unique challenges and for a number of reasons it is still rarely applied in northern climates. Northern Canadian communities often lack financial resources and technical knowledge required for remediation projects, so the most environmentally friendly solution may be overlooked (Sanscartier *et al.,* 2010b). The Arctic is also remote, and can be difficult to access for gathering data and samples. Economic and social benefits are closely tied to the environment in the Arctic, so they must be considered as well. Two papers by David Sanscartier *et al*. (2010a; 2009c) discuss LCA in detail, as it is applied to remediation of hydrocarbon-contaminated soil in the Canadian Arctic, however more studies are required.

2.8 Strengths and Weaknesses of LCA

Life Cycle Assessment has many benefits, which make it worthy of inclusion in any remediation effort. It is a comprehensive, recognized tool that has been proven for decades and is well accepted within the scientific community. LCA helps track inputs (e.g., energy) and outputs (e.g., pollution) throughout the life of the project, and can prevent shifting of environmental consequences from one area to another. Because every stage of the remediation process is transparent and managed holistically, LCA can also identify any environmental impacts that may have been unintended or hidden (CSIRO, 2011).

There are also potential weaknesses of LCA that must be accounted for during the process. A lot of data is typically required for LCA; collecting it may be complicated and complex software is often required to process it properly. One must take the time to learn how to use the software properly and that can be time consuming. Data from each LCA is also very case specific, and cannot usually be extrapolated to other projects since every assessment is unique. Sometimes LCAs may provide an oversimplified view of a complex process, and since so many assumptions are required, the results are usually just an approximation of actual environmental effects. Depending on the project, collecting data for the LCA may also be time consuming and costly; sometimes there are no reliable data, in which case best estimates are required. LCA is a very useful tool for decision makers, but its limitations should be taken into account when examining results and formulating a plan (CSIRO, 2011). Using other decision-making tools in addition to LCA may provide a more accurate outcome.

3.0 Applying Life Cycle Assessment to a Case Study of Diesel Contamination in Iqaluit, Nunavut

3.1 Introduction

This case study examines the environmental, social and economic implications of remediation of a small diesel-contaminated site in the city of Iqaluit, Nunavut. The study is based on a hypothetical but rather typical and common occurrence: a small diesel spill in a remote Arctic town. Two different remediation scenarios are discussed, inputs and outputs are described, and outcomes of the two different scenarios are compared. A very simplified LCA approach is used to assess the broader environmental consequences of two very different remediation technologies that are commonly carried out in the Arctic to remediate diesel spills.

3.2 Methods

3.2.1 Case Study Definition

The case study is based on a hypothetical spill, which occurred in coarse soil and contaminated an area of approximately 5 m by 10 m to a depth of approximately 0.3 m (15 m^3). The contaminant concentration of the soil was approximately 5000 mg/kg of total petroleum hydrocarbons (Fractions 2 and 3 in the CCME guidelines) (CCME, 2008). The spill of 5000 mg/kg of diesel was well above CCME regulatory limits for residential land. For coarse-grained soil, Fraction 2 ($>C_{10}$-C_{16}) guidelines are 150 mg/kg and Fraction 3 ($>C_{16}$-C_{34}) guidelines are 300 mg/kg. This meant that clean-up was necessary in order to restore function to the site.

The hypothetical spill occurred in Iqaluit, which has a population of approximately 6,699 (Statistics Canada, 2011) and is only accessible by air or sea. Two hypothetical remediation scenarios, both common solutions routinely used in northern communities, were assessed using a simplified LCA approach.

The first case study involved contaminated soil being transported to a permanent facility just outside the city limits, where landfarming was used to remediate the soil. The second study involved shipping contaminated soil via container ship to a landfill located in Quebec. These are both scenarios that are well established for remediation efforts in the Arctic. Ultimately, selection of a remediation technology will depend on the scope of contamination, time limits, and economic constraints.

3.3 Boundaries and Descriptions of Remediation Processes

3.3.1 Landfarming at Local Treatment Facility

Landfarming is a simple, cost-effective, and relatively benign way to remediate petroleum hydrocarbon contamination (Paudyn *et al.,* 2008). This treatment scenario involved transporting approximately two truckloads of soil (15 m^3) to a local treatment facility two kilometers away, where soil was spread into a plot measuring 5 m by 10 m and approximately a half-meter deep. To determine the amount and types of fertilizer required, C:N:P ratios of 100:7.5:0.5 were used (Paudyn *et al.,* 2008). Ammonium nitrate was added as the primary source of nitrogen (it contains 34% nitrogen), and diammonium phosphate was used for the primary source of phosphorus (it contains 46.0% phosphorus and 18.0% nitrogen by weight) (Alabama Cooperative Extension System, 2008). The soil was approximately 5000 mg/kg of diesel, with a mass of soil per m^3 of 1700 kg; this required approximately 3.25 kg of ammonium nitrate and 0.29 kg of diammonium phosphate for the 15 m^3 of soil. After fertilizers were added, soil was periodically tilled to provide aeration. The soil was transported in one trip using two dump trucks, and the facility was located approximately 2 km away from the contaminated site. The site was prepared for landfarming by clearing it of any vegetation, and grading it to be flat. A berm lined with impermeable geotextile fabric liners was built around the site, and a fence was placed around the site to reduce the possibility of local residents coming in contact with contaminated soil.

The soil was tilled once a week to increase volatilization rates of diesel. Sampling of the soil occurred once a month for the first season, and then twice annually for the next two years. Soil samples were transported to a CALA-accredited laboratory in Ottawa for monitoring purposes. This process is illustrated below in Figure 2.

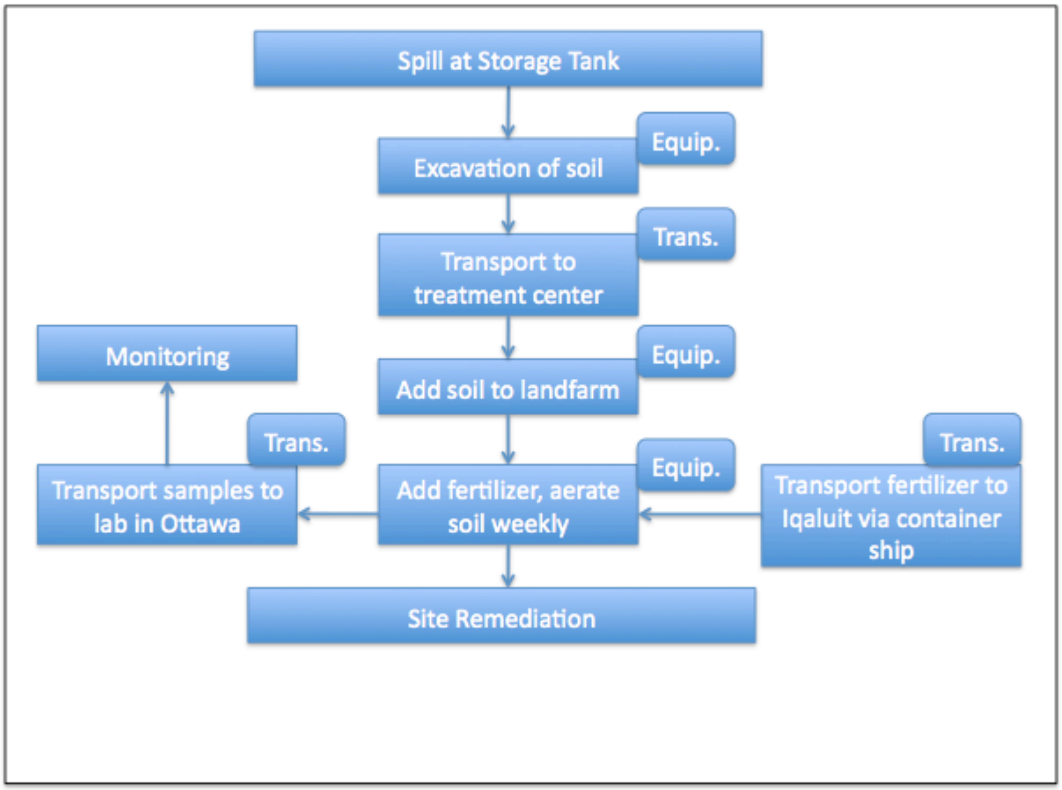

Figure 2. System boundary and flow diagram for landfarming carried out at local treatment centre. "Equip" refers to the requirement for equipment during that step, and "Trans" refers to the requirement of transportation.

3.3.2 Remediation Using Landfilling at a Southern Facility

The second remediation scenario involved transporting the contaminated soil to a southern landfill. Contaminated soil was excavated using a bulldozer, transported by dump truck (two truckloads in one trip), and placed in specialized containers for transporting this type of material. These containers are not available in Iqaluit, so they were shipped to Iqaluit ahead of time. They were shipped via shipping container and then transferred to a barge, which was able to enter the harbor of Iqaluit (too shallow for the container ship to access). There are specialized containers available for shipping contaminated soil from a number of companies operating in Canada. They cost approximately $2,300-$3,300 and each container holds approximately 20 m^3 of soil. Because there was approximately 15 m^3 of soil, only one container was required. Once the soil had been containerized it was transported by barge back to the container ship and then south to Montreal, Quebec. This trip between Montreal and Iqaluit is approximately 1110 nautical miles, and typically takes seven days. Once the ship reached Montreal, the container was loaded onto a semi-trailer truck and driven to the closest landfill approximately 485 km away. This process is illustrated below in Figure 3.

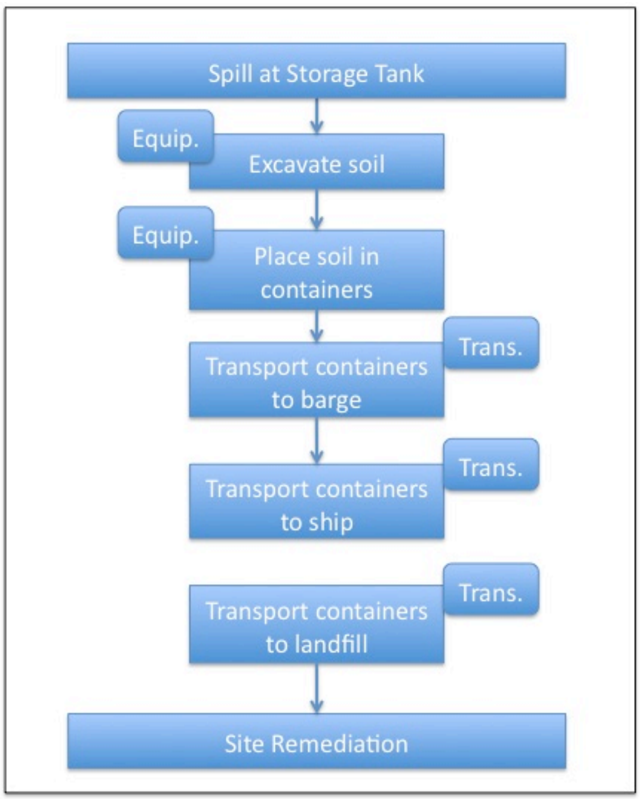

Figure 3. System boundary and flow diagram for transport of soil to landfill at southern facility. "Equip" refers to the requirement for equipment during that step, and "Trans" refers to the requirement of transportation.

3.4 Assumptions for the Life Cycle Assessment

Several assumptions were made in order to simplify the LCA process:

- All transportation of equipment, soil, and samples for analysis to and from the site was included. Emissions were calculated for the appropriate vehicles and fuel used. Emissions were calculated in the form of CO_2 output, and emissions of other greenhouse gases (CH_4 and N_20) were converted into CO_2 as well. In this study, CO_2 will be used as a surrogate for environmental risk.
- Assumptions were made for the fuel consumption of various vehicles. Dump trucks are assumed to get 3.39 km/L, bulldozers use approximately 38 L of fuel per hour, and semi-trailer trucks get approximately 2.97 km/L (Centre for Transportation Analysis, 2011). A container ship burns 13,600 L of fuel per hour (Rodrigue *et al*., 2012), and the flight from Iqaluit to Ottawa requires approximately 8,772 L of aviation fuel for the flight (www.airliners.net).
- Because the weight of the soil and fertilizer is only a small fraction of the weight of the entire container ship, the transport of materials to Iqaluit is not responsible for the CO_2 output of the entire ship. The weight of the soil is approximately 25,500 kg, or 25 gross tons. The average container ship weighs approximately 100,000 gross tons (http://www.containership-info.com), so the soil would account for 0.00025% of the overall CO_2 output. The gross CO_2 output of a container ship travelling for seven days

would be approximately 6,842 metric tonnes (http://www.containership-info.com/).

- For landfarming, only 3.54 kg of fertilizer would require transportation by container ship, which is a fraction of the size of a container ship and would be responsible for very little of the overall CO_2 output.
- An empty shipping container for transporting contaminated soil weighs approximately 2,200 kg or two gross tons (Clean Harbors, 2011), so it would account for approximately 0.00002% of the overall CO_2 output.
- The weight of a full plane is approximately 39,500 kg (www.airliners.net), and the weight of soil samples being transported to a lab in Ottawa would be approximately 10 kg. This is approximately 0.0002% of the overall weight, so the transport of soil samples would only account for a very small portion of the overall CO_2 output for the flight from Iqaluit to Ottawa (total CO_2 output for one flight would be 712.6 metric tonnes).
- Ammonium nitrate is assumed to produce 2460.8 g/kg of CO_2, and diammonium phosphate is assumed to produce 866.2 g/kg of CO_2 (Davis and Haglund, 1999).
- Greenhouse Gas emissions were calculated according to Environment Canada GHG Emission Factors (2011a).
- These calculations were carried out using an Excel-based spreadsheet, although more detailed analyses could be performed using LCA software such as SimaPro.

- The environmental impact of human labor can be calculated, but since people working on the site would otherwise be working in another capacity, their efforts were not translated into CO_2 output.
- Monitoring activities for soils occurring in the lab were not taken into account because their CO_2 output is negligible (Toffoletto *et al.,* 2005), however transportation of samples to the lab was included.
- The duration of remediation involving landfarming was set at approximately three years (A. Rutter, personal communication, July 22, 2012).
- Transportation of soil to the landfill was calculated in the LCA, but treatment of soil in the landfill was excluded from the scope. The reason for this is that the landfill would have been open and accepting waste regardless of whether this clean-up was carried out, and no significant emissions to the environment would occur during the landfilling process (Toffoletto *et al.,* 2005).
- After remediation was completed, clean fill was brought to the site by dumptruck to replace soil that was removed during landfarming or landfilling.

3.5 Results and Discussion

3.5.1 Comparison of Soil Treatment Technologies

3.5.1.1 CO_2 Production

CO_2 production was calculated using Environment Canada Greenhouse Gas Emission Factors (2011a). On this website, tables are provided listing the amount of CO_2 produced for different vehicles and fuels types measured in g/L. The amount of CH_4 and N_20 produced for each variable is also given, though for this study it was converted into CO_2 for simplicity as CO_2 been chose as a surrogate for environmental risk in this study. Fertilizer must be used for landfarming, and even though it is used in small amounts for this scenario, production of fertilizer accounts for considerable greenhouse gas emissions. Jenssen and Kongshaug (1998) estimate that fertilizer production is responsible for approximately 1.2% of the world's total greenhouse gas emissions. Calculating greenhouse gas emissions from fertilizer production is difficult, because there are many types of fertilizer and the processes for their production are complex. A paper by Wood and Cowie (2004) used emission factors to calculate greenhouse gases associated with the production of ammonium nitrate: a fertilizer used extensively around the world. The majority of the emissions associated with fertilizer production are CO_2 emissions from ammonia synthesis and N_2O emissions from nitric acid production. The total grams of CO_2 produced per kg of ammonium nitrate and diammonium phosphate were 2460.8 g/kg and 866.2 g/kg respectively based on Davis and Haglund, (1999). All calculations of CO_2 produced are shown in Table 3 below:

Table 3. Comparison of CO_2 output in landfarming at a local treatment facility versus landfilling at a southern location.

Landfarming at local treatment facility	**CO2 Output (Tonnes)**	**Landfilling at Southern Location**	**CO2 Output (Tonnes)**
Transport soil to treatment facility in two dumptrucks (4 kilometres)	0.003	Ship containers north (7 days)	0.137
Bulldozer use (3 hours)	0.308	Transport soil to containers (4 kilometres)	0.003
Tilling of soil using heavy machinery (15 min/week per season)	1.204	Place soil in container (3 hours)	0.308
Fertilizer production	0.008	Transport soil to container ship with barge (1 hour)	0.361
Transport fertilizer by container ship (7 days)	0.0003	Travel by container ship to Montreal (7 days)	1.71
Transport samples to lab in Ottawa (x8)	1.140	Transport soil to landfill using one semi-trailer (485 km)	0.443
Transport clean fill to site in two dumptrucks (4 kilometres)	0.003	Transport clean fill to site in two dumptrucks (4 kilometres)	0.003
Total CO2 (Tonnes)	**2.67**	**Total CO2 (Tonnes)**	**2.97**

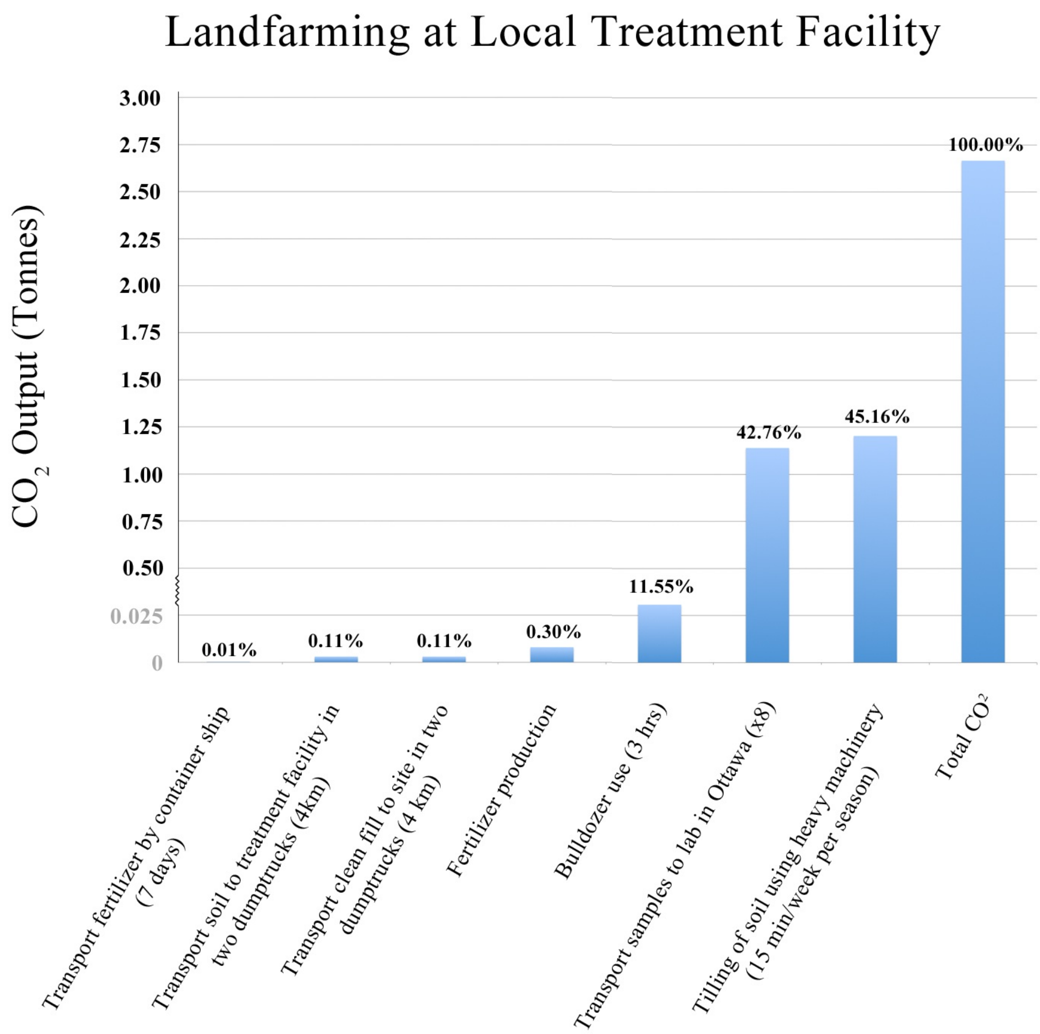

Figure 4. Relative CO_2 output for each different step of landfarming at a local facility.

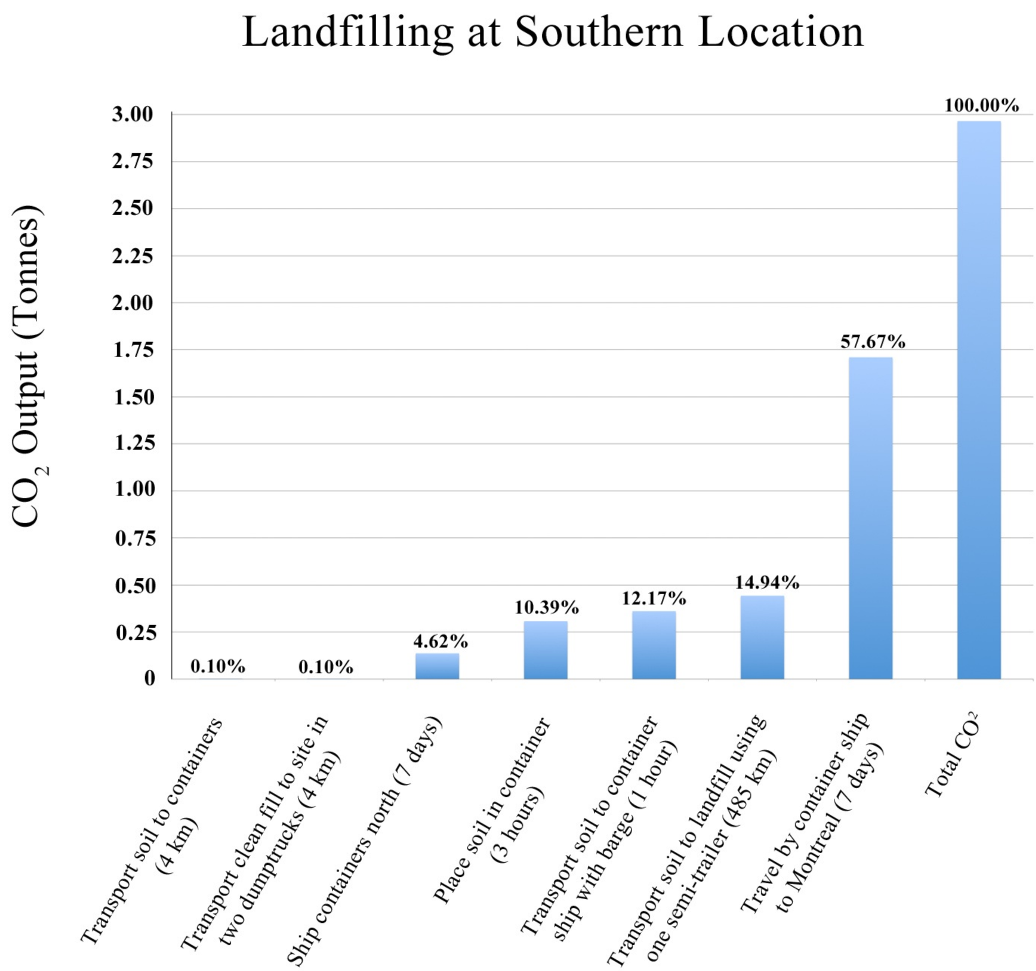

Figure 5. Relative CO_2 output for each different step of landfilling at a southern location.

Shipping contaminated soil south resulted in the highest CO_2 with approximately 2.97 tonnes of CO_2 produced. Landfarming at a local treatment facility and analyzing samples at a lab in Ottawa results in a slightly lower amount of CO_2 produced (approximately 2.67 tonnes). Figures 4 and 5 demonstrate the relative CO_2 output for each scenario. As expected, tilling the soil and flying samples south to the lab produced the largest amount of CO_2 for this scenario. Comparing the greenhouse gas impacts for each remediation technology makes it clear that landfarming at a local treatment facility is the more “environmentally friendly” option when CO_2 emissions are compared. Landfilling also involves the most transport of contaminated soil out of the two scenarios, and it has been demonstrated that impacts related to soil transport are very significant (Diamond *et al.,* 1999). Transportation affects air quality and contributes to global warming, and uses significant amounts of fuel (especially when transportation is by air or sea).

3.5.1.2 Health Effects

Another factor that could be used to compare remediation technologies is the potential risk to human health associated with the presence of contamination on site. Remediation is often carried out for the primary purpose of reducing risks to human or environmental heath (Beinat *et al.*, 1997), so the site poses serious health issues, then the remediation scenario that can be carried out quickly and with the least human exposure to the contaminant will be the best choice.

One possible risk to human health in these scenarios is from diesel exhaust and volatile organic compounds (VOCs). Diesel exhaust is considered either a definite or probably human carcinogen, and has been linked to an increase in lung cancer mortality (Davis *et al.,* 2007). Workers who regularly operate heavy machinery would be exposed to VOCs regardless of where they were working. VOCs are defined by Health Canada (2007) as all organic compounds with boiling temperatures in the range of 50-250°C. Meaning that they are likely to be present as a vapor or gas at normal ambient temperatures.

VOCs may contribute to air quality problems through the production of ground-level ozone or through release of odorous compounds (Ausma *et al.,* 2002).

Although both scenarios will produce diesel fumes, the impact of the volatilization of the VOCs during landfarming needs to be addressed when comparing the two scenarios. Diesel fumes may pose risks to human health, however the risks to those working with contaminated soil during landfarming would most likely be minimal. Some petroleum products are of greater concern than others. Benzene, toluene, ethylbenzene and xylene (BTEX) are of the greatest risk to humans because of their toxic, carcinogenic and mutagenic properties. BTEX is only present in diesel in trace amounts; at approximate weight percentages of 0.1% benzene, 0.7% toluene, 0.2% ethylbenzene, and 0.5% total xylenes (Dunlap and Beckmann, 1988). A study by Ausma *et al.,* (2002) suggests that exposure limits for compounds such as benzene (3.5 mg/m^3) would not be reached during remediation of diesel-contaminated soil at landfarming facilities. This exposure limit is based on Time Weighted Averages assigned by the American Conference of Governmental Industrial Hygienists (ACGIH, 2012), the same agency which Canadian provinces use to develop their regulations for exposure limits to various toxic substances.

Volatilization rates of diesel in soil vary according to research, but may be as high as 58% over a period of 360 days (Kroening *et al.,* 2001). Paudyn *et al.,* (2008) found that at 9°C, the relative rate constants of volatilization only to volatilization and bioremediation was 0.015 to 0.026, in a landfarming trial at Resolution Island, Nunavut indicating that roughly 60% of the diesel will be volatilized during the three year remediation. Volatilization is also affected by soil type and water content. Soil that is too dry will cause adsorption of oil to the soil, reducing volatilization, and soil that is too wet it prevents oil from moving to the surface of the soil and also reduces volatilization (Li *et al.,* 2004). Fine soils with smaller pores will have poorer volatilization rates than soil with larger pores such as sandy soil (Li *et al.,* 2004). Clearly landfarming will expose workers to a higher amount of VOCs than landfilling would (see Figure 8). If soil is simply excavated and transported south, minimal exposure to VOCs will occur. Capture of VOCs would reduce the potential for human and environmental health effects, and would likely increase public support for remediation efforts within a community.

3.5.1.3 Economic Effects

When selecting the best remediation scenario, there are social and economic issues to consider as well as technical ones. Even though CO_2 output from human labor was not included in the LCA, the creation of jobs due to the remediation project is extremely important in a remote community. Landfarming will require workers for soil removal, for tilling while the soil is being treated and for taking soil samples. The economic benefits can be approximated using tables formulated by the Government of Canada for Federal construction contracts. As of May 2006, truck drivers make approximately $19.00/hour and operators of heavy equipment make approximately $20.00/hour (Government of Canada, 2012). In 2011, Nunavut construction workers made an average of $1,343/week (Northern News Service, 2012). For this case study workers would not be required for a full work-week, however if there were more remediation projects taking place in local treatment facilities then it would be possible to employ more people for longer hours. The approximate amount of employment hours for locals in Iqaluit can be calculated as approximately 70 hours for landfarming versus less than 10 hours for landfilling. If soils are shipped south, the only work that will be completed in Iqaluit is operating of heavy machinery to load soil into containers and get it onto the container ship. Therefore, local people will probably support the remediation option that has the most benefits for the community. Landfarming at a permanent local facility will provide the opportunity for employment at a number of stages throughout the remediation including operating of heavy machinery, and jobs at the treatment facility.

Both remediation scenarios will have benefits for the city of Iqaluit, because land that was previously unusable due to contaminated soil will now be safe and accessible for those living in the city. Value of housing could go up around this contaminated site, and successful clean-up of one site opens the doors for other successful remediation efforts in the future. If local residents see that there are tangible benefits from remediation projects, they will likely be supportive of other projects being carried out in the future.

3.5.2 Selection of the Best Scenario

In order to select the best remediation scenario, CO_2 production, health effects, economic effects, and time required for remediation must be balanced and discussed collectively. The scenario that produces the smallest amount of CO_2, has the least harmful human health effects and also has the greatest number of economic benefits for the community will be the most favorable remediation scenario to carry out. Length of time required for remediation may also affect the decision making process. If a company wishes to carry out a remediation in an "environmentally friendly" way, then landfarming is the obvious choice. However, if those responsible for the contaminated site wish to remove liability and responsibility for the contamination as soon as possible, then landfilling may be appealing as it takes a matter of days or weeks versus approximately three years for landfarming as shown in Figure 6.

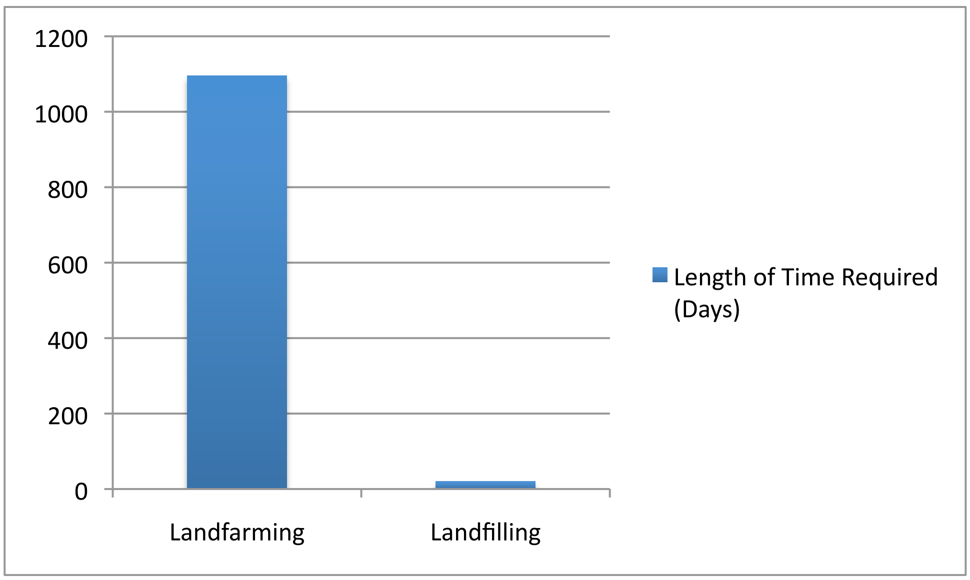

Figure 6. Differences in time requirements for landfarming and landfilling.

Landfarming exposed workers and those living close to the remediation to more VOC emissions as compared to landfilling the soil. Over the course of three years, approximately 50% of the diesel was volatilized (Paudyn *et al.,* 2008), as compared to only about 5% during the three weeks took landfill the soil (Figure 7).

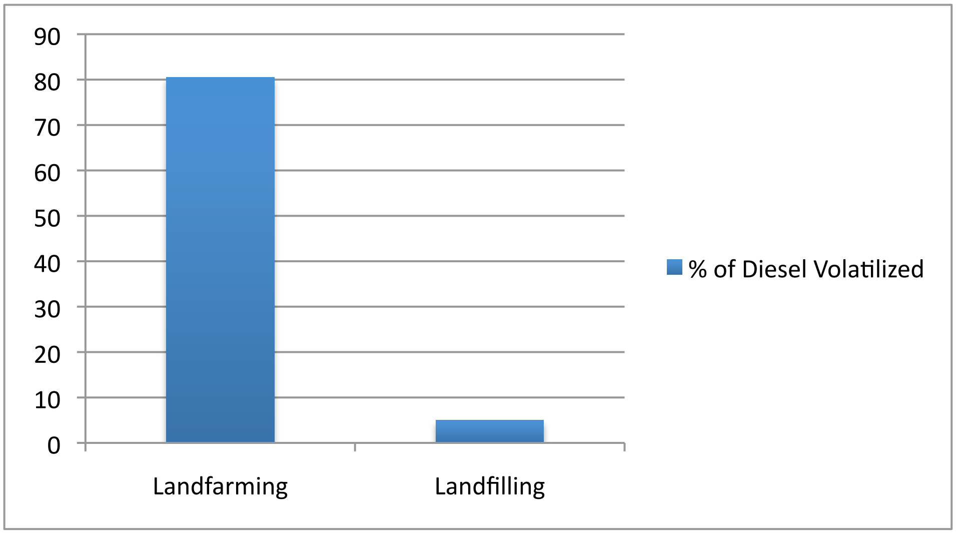

Figure 7. Differences in the amount of diesel volatilized during landfarming versus landfilling.

However, landfarming is better than landfilling in terms of CO_2 production and economic benefits for the region. The amount of CO_2 produced during landfarming was approximately 11% less than landfilling as demonstrated in Figure 8.

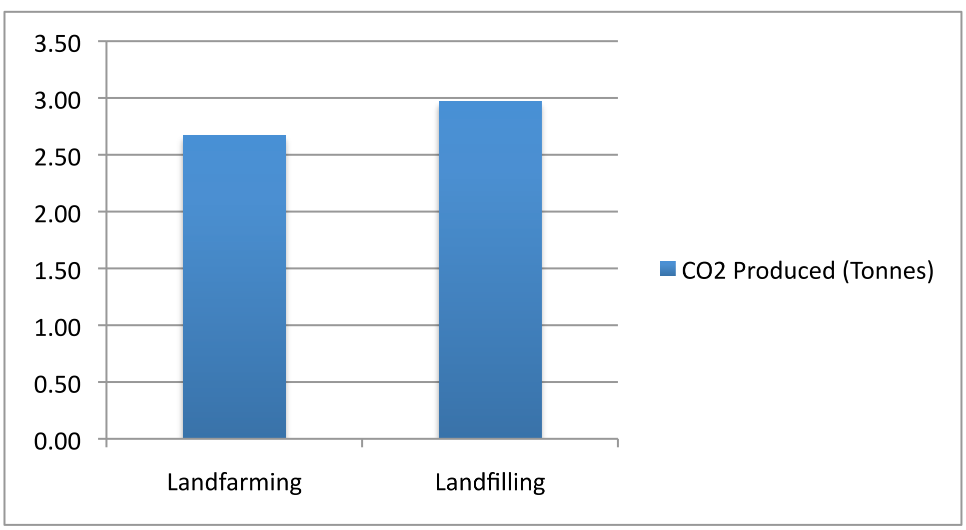

Figure 8. CO_2 produced during landfarming versus landfilling.

Landfarming also provided significantly more employment for locals in Iqaluit, as demonstrated in Figure 9. This employment is important for a city that has a high percentage of young people of working age and an unemployment rate in Nunavut of approximately 15% (Nunavut Bureau of Statistics, 2012).

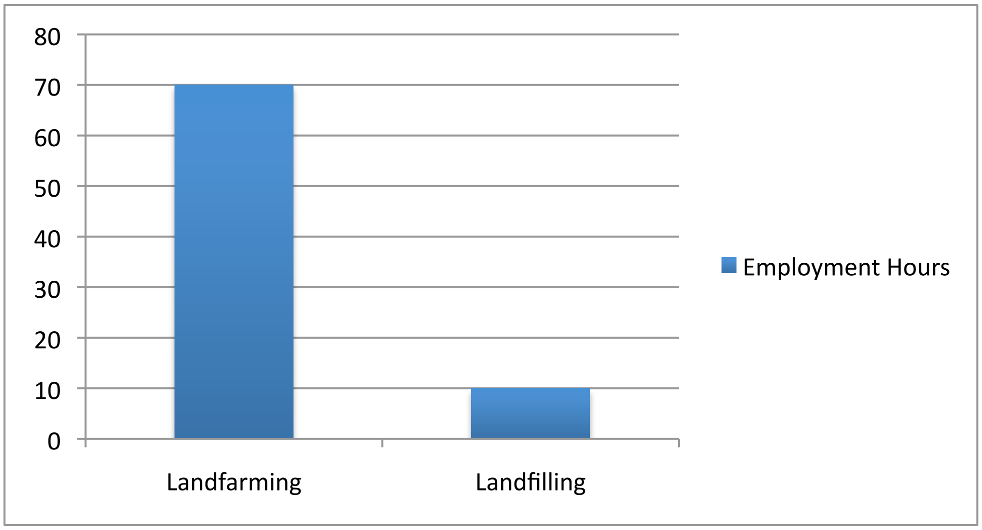

Figure 9. Differences between hours of employment resulting for locals in Iqaluit for landfarming versus landfilling.

3.5.3 Strengths and Limitations of Life Cycle Assessment

Life Cycle Assessment has many benefits to a remediation project. LCA helps track inputs (e.g.- energy) and outputs (e.g.- pollution) throughout the life of the project, and can prevent shifting of environmental consequences from one area to another. LCA can also identify any environmental impacts that may have been unintended or hidden because every stage of the remediation process is transparent and managed holistically (CSIRO, 2011).

LCA also has several shortcomings in the context of this case study that must be addressed in order to improve the process:

- This LCA provides a simplified view of a complex process, and since so many assumptions are required the results are only an estimation of actual environmental effects.

- Collecting data for the LCA can be time consuming and costly depending on the project, and sometimes this data may not be available at all so best estimates are required.
- Data for an LCA is often gathered from a variety of sources, which for this study included newspaper articles, government websites and scientific literature among others. This lack of consistency generates variation, and could make research difficult to replicate or perform in a short period of time. Also, data taken out of context or from other types of industry may result in some margin of error.

For this study, it would be useful if LCA could address both environmental and human health issues, though it can potentially assist with both risk assessment and risk management for human health (Owens, 1997). Major limitations include loss of spatial, temporal, dose-response, and threshold information, so LCA can only identify worst-case scenario human health issues (Owens, 1997). LCA cannot effectively take into account temporal or spatial considerations, so irrelevant or less relevant data may be included in an analysis, resulting in misguided decision making. However, this process may also allow decision makers to see what is causing the highest percentage of human health effects, and take actions to reduce occurrences.

3.6 Conclusions and Recommendations

A simple comparison of two different remediation scenarios has been completed, and findings from the study may be used as a guide for selection of a suitable remediation technology to reduce environmental effects of both the contamination and the clean-up itself. This study does not provide any definitive answers for clean-up of hydrocarbon-contaminated soil in remote locations, however it presents a cradle-to-grave approach to assessment of various impacts and benefits that two different technologies may have.

This was a relatively small-scale and hypothetical project, and it was used to determine the cost and time requirements for the two remediation technologies instead of having any pre-determined financial or time-scale constraints. Because of these parameters, landfarming at a local treatment facility is suitable. This is the least expensive and most environmentally friendly solution, which is desirable for the Arctic. For a larger-scale project, the length of time given to complete remediation would need to be balanced with energy requirements since the soil would most likely be remediated more actively. This lack of restrictions may also be unusual for northern communities, as there are often financial constraints and a shortage of technical knowledge that make it difficult to initiate remediation (Sanscartier *et al.,* 2010b). “Environmentally friendly” solutions such as landfarming are often overlooked in favor of shipping soil south, as there are rarely treatment facilities available close to where remediation is taking place, and those carrying out the remediation often want to remove the contamination as quickly as possible. This thought process could be influenced by raising awareness in northern communities of the environmental impacts of remediation itself, and by building more treatment facilities to clean up remaining contamination in the Arctic.

The CO_2 output from these two scenarios does demonstrate that landfarming is slightly better than landfilling when studying the environmental effects of remediation, however the difference in metric tonnes of CO_2 produced was minimal. This establishes the need to improve upon the steps of landfarming that create the most CO_2. For instance, taking samples to a local lab instead of flying them south. This would greatly reduce the amount of CO_2 output, and would have the added benefit of increasing local employment and a local interest in the remediation effort. A landfill located in the north, dedicated to treatment of contaminated soil, could also accomplish similar goals of increasing local employment and reducing CO_2 produced by transporting the soil south. This option doesn't deal directly with the issue of the contaminated soil and what will happen once it's in the landfill, however landfilling soil is a treatment option which is still very popular, and if time constraints are an issue then this may be the best choice.

As more remediation efforts are carried out in the Arctic, the release of VOCs should be taken into account due to potential effects on human and environmental health. VOCs can contribute to the production of ozone, through the reaction between sunlight, VOCs and nitrogen oxides (Ausma *et al.,* 2002). However, very large amounts of VOCs and nitrogen oxides would need to be present in order for this to occur. VOCs may also have human health effects, especially during times of intense activity such as when new landfarming operations are being constructed.

There are also improvements that could be made in order to facilitate and increase accuracy of Life Cycle Assessments in the Arctic. Standardized data sets could be compiled, so that someone carrying out an LCA would know approximately what sort of impacts there are going to be. Standards such as human labor requirements, CO_2 output for various activities and the approximate time scale for projects could all streamline the LCA and make it much easier to calculate. This would also reduce the need for complicated software in order to get the most accurate results, as scientists carrying out different remediation projects would all be using the same basic data sets. Remediation case studies would also be easier to reproduce, and various costs could be easily estimated before the project was even started.

In conclusion, landfarming at a local treatment facility is the best remediation option for this hypothetical case study because:

- it results in the least amount of greenhouse gases being produced,
- it provides local employment that benefits the city of Iqaluit, and
- it is relatively inexpensive and simple to carry out.

These results cannot necessary be applied to future remediation projects in the Arctic or anywhere else, but perhaps this study can guide those performing remediation efforts in the future to make decisions that will benefit both the community and the environment. LCA is a useful way to include activities in an assessment that may otherwise be overlooked or ignored, and can help remind us that out of sight does not mean out of mind. There should be a net benefit to every remediation carried out, and only by examining every step of the process from start to finish can we get an idea of what the real results of a clean-up will be.

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