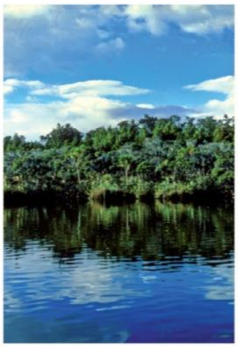

Land application of waste from oil and gas wells: *Implications for food safety and animal welfare*

Landcare Research
Manaaki Whenua

Land application of waste from oil and gas wells

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What impressed you most about this project?

What improvements do you suggest for future projects?

Additional comments?

Contents

Summary

Project and Client

- This report was undertaken by Landcare Research for the Ministry for Primary Industries to provide scientific guidance for the development of technical advice for land application of waste from oil and gas wells (O&G waste) for the protection of food safety and animal welfare.

Objectives

- To provide an assessment of the state of scientific knowledge on the practice of applying waste from oil and gas wells onto or into land; the types and scale of different risks involved; and the practicalities and limitations of testing to assess risk, as well as guidance on assessment and monitoring of waste and the sites to which it is applied.

Summary

- Land application of O&G wastes is considered to pose no attributable risk to food safety or animal welfare, particularly when wastes are incorporated into the shallow subsoil with topsoil overlying the soil/waste layer. In this case, the primary pathway of exposure is via plant uptake, for which there is limited uptake of the main contaminants of concern in the waste, hydrocarbons. Surface application of O&G wastes is considered to pose no attributable risk to food safety and animal welfare when stock are excluded and crops are not harvested until agreed endpoints for soil quality are reached.

State of knowledge

- O&G waste may include waste from both offshore and onshore oil and gas wells and is predominantly comprised of drilling waste, which consists of rock cuttings with some drilling ‘mud’ residue. Drilling muds may be water-based (WBM) or synthetic-based (SBM) and compounds are added to modify the physical characteristics of the mud.
- Land-application of drilling wastes is an accepted practice in a number of countries and regulation and regulatory guidance has been developed to outline acceptable practices to ensure compliance and manage risks to the environment, including where it is applied to land used for pastures.
- The focus of environmental regulatory compliance for land application of drilling wastes is typically around managing waste to meet salinity, metal and hydrocarbon soil endpoints, and controlling movement of contaminants to ground or surface-water environments.
- In New Zealand to date, information on environmental impacts of land application of O&G waste comes largely from compliance monitoring reports from Taranaki and from a limited number of studies that have investigated specific aspects of land application. These studies provide an understanding of some of the environmental risks posed by land application of O&G waste, although further research on some aspects is still required to provide a more detailed assessment.

- Knowledge gaps pertain more to environmental considerations of waste application, than to uncertainties of the risk to food safety or animal welfare. Some knowledge gaps (e.g. leaching from drilling mud wastes) could potentially be addressed by increased/additional monitoring or low-cost specific projects to establish a body of evidence. Other knowledge gaps (e.g. environmental concentrations of drilling additives) may require significant resources to address robustly.

What are the risks?

- The risks associated with the land application of O&G waste depend on both the constituents present in the waste (type and concentration), and the pathways of exposure. If there is no exposure pathway, there is no risk to that receptor.
- The major constituents of the O&G waste are: bentonite clays, barium sulphate, salts and hydrocarbons, with salts and hydrocarbons being the most likely to contribute to any observed toxicity. While a range of other components are used, these are generally considered to be non-toxic or present at concentrations that do not contribute to the toxicity of the waste. Some further work is required to verify this from an environmental perspective.

Food safety and animal welfare

- The potential exposure of livestock to O&G waste will depend on how it has been applied. Livestock could be exposed through ingestion of soil or plants that have taken up components of O&G waste from surface application, while plant uptake is the primary mechanism of exposure of livestock to O&G solid waste applied to the shallow subsoil. However, plant uptake of hydrocarbons is limited.

Environment

- Soil microbes, biota and plants are in direct contact with the soil, hence any potentially toxic components present in the mixed soil/O&G waste may cause detrimental impacts to these organisms if present in high enough concentrations.
- Groundwater may be affected by salts present in the drilling waste leaching through the soil profile, and some movement of low molecular weight hydrocarbons, such as benzene, could also occur. Surface water could be impacted where O&G waste has been surfaced applied and stormwater run-off over the site is not appropriately contained. This is anticipated to be an infrequent occurrence.

Waste, site and soil monitoring

- An important aspect of providing assurance that land-application of O&G waste poses no attributable risk to food safety, animal welfare, trade, or the environment is having appropriate management practices in place, and adequate assessment and monitoring of the waste and sites to which the waste is being applied. Environmental considerations will be the dominant factor influencing these processes.
- Assurance of the protection of food safety, animal welfare and trade largely relies on the traceability of waste application, including compositional analysis and location and method of application, and exclusion of stock crop harvest until soil has met agreed endpoints for key contaminants.

1 Introduction

Land application of waste from oil and gas wells (O&G waste) is a common practice in the Taranaki region. However, with onshore drilling potentially becoming more common in areas outside of Taranaki, there is a need to consider the management of waste from O&G wells across the country to ensure protection of livestock, products, trade, and the environment.

This report provides an assessment of the state of scientific knowledge on the practice of applying O&G waste onto or into land, the types and scale of different risks involved, and the practicalities and limitations of testing to assess risk, as well as guidance on assessment and monitoring of waste and the sites to which it is applied. This report provides scientific guidance to assist Central Government in the management of O&G waste for the protection of food safety and animal welfare. As such, the primary emphasis of this document is on protection of food safety and animal welfare, although a detailed overview of environmental aspects is included to provide a more complete picture of the issues surrounding application of O&G waste to land, and to provide context for the risk to food safety and animal welfare. Further, while many of the aspects discussed in this report have general relevance to wastes from hydraulic fracturing operations (‘fracking’) this report does not apply to fracking return fluids, other than in section 4.3, as this was also beyond scope.

O&G waste that is applied to land may include waste from both offshore and onshore oil and gas wells and is predominantly comprised of drilling waste, which consists of rock cuttings with some drilling ‘mud’ residue. Drilling mud is used to lubricate the drill and allow the rock cuttings to flow back up to the surface. Drilling muds may be water-based (WBM) or synthetic-based (SBM) and contain further compounds added to modify the physical characteristics of the mud. These compounds include weighting agents, viscosifiers, thinners, loss circulation materials (LCM), pH control additives, dispersants, corrosion inhibitors, biocides, filtrate reducers, flocculants and lubricants. Bentonite clay is a common constituent, as are barite (barium sulphate) and salts (sodium, potassium, calcium, chloride). Other wastes include those generated from hydrocarbon exploration and production activities, such as sludge and wax removed from tanks and separators, slops oil from wellhead cellars, oily formation sand, and contaminated soil from leaks and spills. In general, the waste applied to land is probably most adequately described as non-liquid wastes, which are wastes that have a solids content greater than 20% (MfE 2004).

To date, land application of these wastes in the Taranaki region, has been via one-off application to shallow subsoil or surface soils (commonly referred to as ‘landfarming’), mix-bury-cover, or in sumps (although sumps are no longer used and there is only limited disposal via mix-bury-cover). Disposal via mix-bury-cover includes the mixing of soil with the O&G waste prior to disposal and burying the waste below the reach of plant roots and above the water table. In contrast, landfarming operations comprise incorporation, typically through tilling, of O&G waste in surface soil or, most commonly, shallow subsoil, to enable degradation of hydrocarbons by microbial action, and attenuation of metal components. Sometimes organic matter, such as sawdust, may be mixed with the O&G wastes. Topsoil is typically placed over the waste/subsoil mix where O&G wastes have been applied to shallow subsoils. After relaying of topsoil, and/or incorporation into surface soils, sites are typically fertilised, resown with ryegrass/clover and irrigated. Landfarming occurs on land consented for that purpose with stock generally excluded until pasture has been established, although there have been some examples where this has not occurred (PCE 2014). Oil and gas wastes may also be vermicomposted (TRC 2014a) and indirectly applied to land through the manufactured compost.

Landfarming is the common terminology used in New Zealand for the one-off application of O&G wastes to shallow subsoil or surface soils. However, internationally landfarming more commonly refers to the repeated application of hydrocarbon-containing wastes to the soil surface, whereas ‘land spreading’ and ‘land treatment’ are often used interchangeably to describe the one-off application of wastes, typically to the soil surface. In all cases, it is intended that natural soil processes are used to biodegrade the organic constituents in the waste. The objective of a one-off application is to dispose of the waste in a manner that preserves or enhances the subsoil's chemical, biological and physical properties by limiting the accumulation of contaminants and protecting the quality of surface and groundwater.

The benefits of land application of O&G wastes (either on a one-off basis or repeated application) to shallow subsoil or surface soils are in increasing the water- and nutrient-retaining capacity of certain sandy soils, and reducing the amount of waste going to landfill. The potential negative effects of land application are more obvious under repeated application, particularly for environmental effects. With repeated applications, an accumulation of contaminants, such as salts and high molecular weight organic compounds, which are less readily biodegraded, becomes of greater concern and requires management to avoid negative environmental effects.

2 State of knowledge

2.1 International status of land application of drilling wastes

Land application of drilling wastes is an accepted practice in a number of countries. While historical applications of drilling wastes have resulted in negative impacts on the environment (McFarland et al 2009), regulation and regulatory guidance has been developed to outline acceptable practices to ensure compliance and manage risks to the environment, including land used for pastures. For example, in the United States, oil and gas drilling muds and oil-production brines are classified as special wastes, and regulation occurs at a state level. To assist management the US Department of Energy provides the Drilling Waste Management Information System (http://web.ead.anl.gov/dwm/), which is an online resource for technical and regulatory information on practices for managing drilling muds and cuttings, including current practices, state and federal regulations, guidelines for optimal management practices, and case studies for successful applications. US states in which onshore drilling for oil and gas occurs (e.g. Texas, Colorado, Arkansas, Oklahoma) also have specific guidance for landowners considering allowing land application (e.g. McFarland et al 2009; Penn and Zhang undated). In Alberta, Canada, detailed regulatory guidance developed by the Energy Resource Conservation Board has previously informed land-application practices in New Zealand, and has recently been updated (ERCB 2012). Land application to shallow subsoils or surface soils, as practised in Taranaki, is comparable to biodegradation via land treatment, as described in ERCB (2012).

Further, landfarming is a common approach for remediating petroleum hydrocarbon contaminated soil (e.g. Government of Canada 2013; NSW EPA 2014). However, this landfarming differs from that for O&G wastes in that the specific purpose is to facilitate biodegradation in soil with high hydrocarbon concentrations, typically as a repeated activity. As such, closer attention is paid to soil conditions (e.g. soil moisture, pH, existing soil microbial population), and more active management of the soil (e.g. tilling, fertilizer application) is employed to facilitate hydrocarbon degradation. Some O&G waste may not have high hydrocarbon concentrations.

The focus of environmental regulatory compliance for land application of O&G wastes nationally and internationally is typically around managing waste to meet salinity, metal and hydrocarbon soil endpoints, and controlling movement of contaminants to ground or surface-water environments. There is less focus on other components, although it is recognised that additives such as biocides, corrosion inhibitors, de-foamers, emulsifiers and de-emulsifiers, foaming agents, lubricants, polymer stabilizers and breakers, surfactants, and shale control inhibitors may require management. In Alberta, records of the additives used in the drilling process must be provided to enable evaluation of potential toxicity and trace metal exceedances, and licensees are expected to have information on the toxicity of all additives used in the drilling fluid system in the well file (Alberta Government 2012). A recent application for consent to undertake drilling in the Gisborne Region in New Zealand also includes a risk assessment of all the components likely to be used in drilling operations (Transfield Worley 2012).

2.2 What are the risks?

The risks associated with the land application of O&G waste depend on both the components present in the waste (type and concentration) and the pathways of exposure. If there is no exposure pathway, there is no risk to that receptor.

As noted earlier, O&G waste is predominantly comprised of drilling waste, which consists of rock cuttings with drilling 'mud' residue. The major constituents of the waste are:

- bentonite clays – used as gelling agents or viscosifers in drilling muds
- barite ($BaSO_4$ – a density increasing material);
- salts, typically sodium or potassium chloride – used as emulsifiers
- hydrocarbons

The addition of bentonite may improve water and nutrient retention in certain sandy soils. However, too much clay in soils may negatively alter soil drainage characteristics.

Barite concentrations measured in O&G wastes are high (TRC 2014 a, b). The toxicity of barite is attributed to the barium ion (Ba^{2+}) and therefore, the toxicity of a particular barium compound is related to that compound's solubility (CCME 2013). Barite is practically insoluble, unlike other barium salts (e.g. barium chloride and nitrate) and therefore has markedly reduced toxicity (Alberta Environmental 2009; CCME 2013).

Salts are used in drilling muds as emulsifiers and shale control materials (e.g. by controlling the swelling of clays). Salts may cause toxicity to soil invertebrates, soil microbes and plants if present in high enough concentrations. Further, salts may also negatively impact on soil structure and quality. In contrast, elevated salt concentrations in soil may be beneficial for livestock with salt (typically in the form of salt blocks or "lick") is used to address some mineral deficiencies and improve milk production and herd health (Keyes 2012).

The hydrocarbons present in O&G wastes are typically classed as total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAH) and the low molecular weight benzenes, toluenes, ethylenes and xylenes (BTEX). Typically the PAH concentrations of O&G wastes are low (e.g. TRC 2014 a,b).Water-based muds are used for the bulk of drilling operations, while synthetic-based muds, which are more expensive, are used closer to the hydrocarbon reservoir. Thus synthetic-based muds are likely to contain higher hydrocarbon concentrations than water-based muds. Further, synthetic-based muds may be hydrocarbon-, ether-, ester-, or acetal-based (Neff et al 2000) with synthetic hydrocarbons, including normal (linear) paraffins (LPs), linear-olefins (LAOs), poly-olefins (PAOs), and internal olefins (IOs) (Neff et al 2000). Thus the mud itself may contribute to the hydrocarbon content of the waste. If present in high enough concentrations, hydrocarbons may cause toxicity to soil invertebrates and plants, although microbial activity may be stimulated due to the use of hydrocarbons as a carbon source by the microbes.

A wide range of other additives may be used in drilling muds, including thinners, loss circulation materials (LCM), pH control additives, dispersants, corrosion inhibitors, bactericides, filtrate reducers, flocculants and lubricants. These components are generally non-toxic or present in concentrations that do not contribute to the toxicity of the waste (see also section 2.3). The quantity and chemical composition of a particular drilling fluid, and hence of the waste being disposed, will vary with conditions in the hole, such as depth and type of formation. An overview of the compound types used in drilling muds and examples of the specific components used in New Zealand is provided in Appendix 1.

Other O&G wastes include those generated from hydrocarbon exploration and production activities, such as sludge and wax removed from tanks and separators, slops oil from wellhead cellars, oily formation sand, and contaminated soil from leaks and spills. These may contain higher concentrations of contaminants, primarily metals and hydrocarbons, although they typically account for small volumes of waste.

Naturally occurring radioactive materials (NORM), particularly radium isotopes, may be present in O&G waste and international management practices, including disposal to land under certain conditions, have been developed for the oil and gas industry (e.g. OGP 2008). NORM may be present in production water, sands and oily sludges in particular, radium precipitates out on equipment surfaces resulting in sludges and hard scales. Radionuclides in the soil may be taken up by plants and distributed along the food-chain, although the concentrations will vary depending on a number of factors including soil type, the radionuclide being considered, and plant species Desideri et al (2014). Surveys undertaken to date by Taranaki Regional Council staff found that radiation levels were within the ranges of normal background concentrations (TRC 2013). This included surveys at three different land-farming sites, and including waste stockpiles and land to which waste from different well-sites had been applied. However, beyond this study, no further studies have been undertaken that enable assurance that the likelihood of the occurrence of NORM is low.

2.2.1 Livestock and food safety

In general, the primary means by which livestock may be exposed to contaminants is through the ingestion of contaminated soil, the ingestion of plants that have taken up soil contaminants, or ingestion of contaminated stockwater. The potential exposure of livestock to O&G waste will depend on how it has been applied. If wastes have been applied to the surface soil, livestock could be exposed through ingestion of soil or plants that have taken up contaminants, while for O&G solid waste applied to the shallow subsoil, plant uptake is the primary mechanism of exposure. Where O&G waste has been applied below the rootzone (e.g. mix-bury-cover), the only potential exposure is through use of contaminated groundwater as stockwater, or use on farms e.g. washing down dairy sheds. However, if drilling wastes have been appropriately managed, groundwater should not be impacted.

If crops for stock or human consumption are grown on land to which O&G wastes have been applied, there is the potential for plant uptake to occur, providing a pathway of exposure. An illustration of the potential exposure pathways affecting food safety and animal welfare is shown in Figure 1.

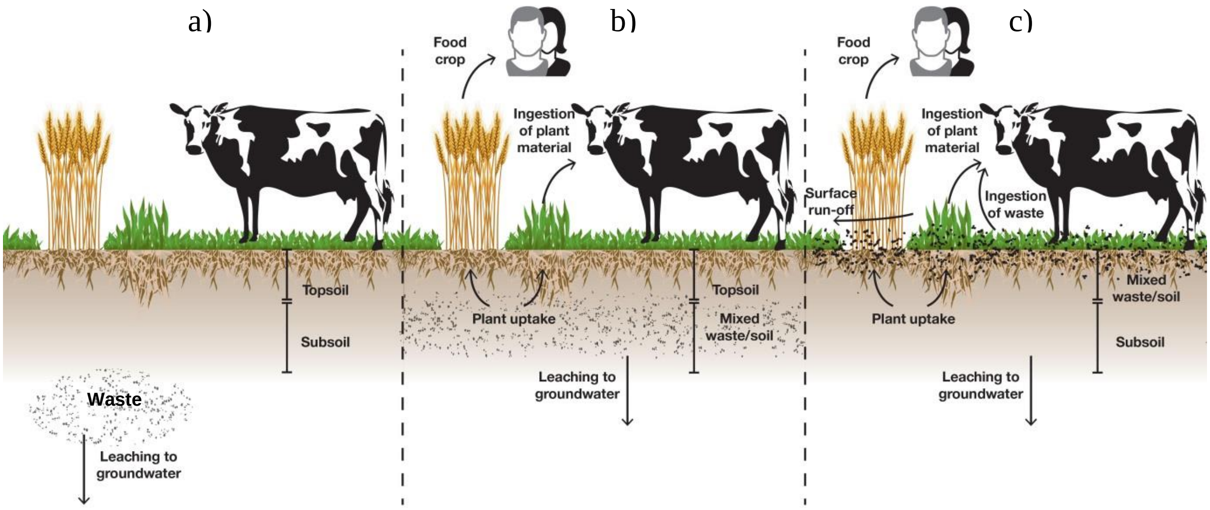

Figure 1 Potential exposure pathways to contaminants associated with O&G waste: a) mix-bury-cover b) shallow subsoil application and mixing and c) surface application and mixing.

While plant uptake is the most common route of exposure, plant uptake of the primary organic components, hydrocarbons, in O&G waste will be negligible. Plant uptake of organic components and metals occurs predominantly from the soil water, which contains only a fraction of these components present in the soil. The ratio of the concentration in soil water to the total concentration in soil depends on a number of factors including soil pH, redox potential, soil organic matter, and soil texture (Kabata-Pendias & Pendias 2000). In soils and sediments where the clay content is relatively low, the availability of organic contaminants is strongly related to the fraction of organic carbon present. Root uptake of organic compounds is related to organic partitioning of the compound, with more lipophilic compounds having a greater uptake (Collins & Wiley 2009). However, translocation to leaf and stems is suggested to be more related to the aqueous solubility of the compound, resulting in limited translocation from root to leaf. Estimates of plant uptake of organic compounds are often made using models (e.g. MfE 2011a; Takaki et al 2014), which tend to over-predict uptake compared to real data (Otte et al, 2001). While there is limited experimental data on plant uptake of total petroleum hydrocarbons (TPH), although there is considerably more for plant uptake of polycyclic aromatic hydrocarbons (PAH) that indicate plant uptake is limited (e.g. Collins & Wiley 2009; Wang et al 2011). It should also be noted that plant waxes comprising long-chain-alkanes (e.g. Wang et al 2013) account for the natural occurrence of some TPH components in plant material.

Metal concentrations in O&G wastes are low (e.g. TRC 2014b, c), with copper and zinc the most often slightly elevated. Plant uptake of metals is dependent on plant species, soil properties and the individual metal, but due to the low concentrations in the O&G wastes metal concentrations in plants will not be significantly elevated. While copper and zinc can be toxic at high concentrations, they are also essential micronutrients and may be deficient in some New Zealand soils (Grace et al 2010). The slightly elevated concentrations in O&G wastes may therefore provide a beneficial effect to soil health and productivity.

Given the range of minor drilling additives used in drilling operations it is plausible that plant uptake could occur depending on the specific component in use. However, assessment of a large range of drilling additives used (Appendix 1 and 2) suggests that plant uptake is unlikely to occur. See also section 2.3.1 for further discussion.

2.2.2 Soil biota and plants

Soil microbes, biota and plants are in direct contact with the soil, hence any potentially toxic contaminants present in the mixed soil/O&G waste may cause detrimental impacts to these organisms if present in high enough concentrations. The key contaminants of concern are TPH, PAH, BTEX, and salts. As noted above, metal concentrations in O&G wastes are low and the metals most likely to be slightly elevated are essential micronutrients, meaning that their presence may provide a beneficial effect. Some minor drilling components are microbiocides and as such are potentially toxic to soil organisms. While these are expected to be present in concentrations that do not contribute to toxicity of the O&G waste some further evaluation from an environmental perspective may be warranted (see also Section 2.4.5).

2.2.3 Ground and surface water

Groundwater may be affected by salts in the drilling waste leaching through the soil profile. Some movement to groundwater of low molecular weight hydrocarbons that have greater water solubility, such as benzene, may also occur. Leaching of other hydrocarbons and metals could occur, although this will be dependent on soil properties, such as organic carbon content, clay content, and pH, and it is not expected to occur to any great extent. It is also not expected that land-applied O&G wastes will be contaminated with hydrocarbons to the extent that liquid hydrocarbons could move to groundwater (i.e. there is no free product); such wastes should be disposed of to an appropriate facility, for example, a landfill designated to receive such wastes. Surface water could be impacted where O&G waste has been surface-applied and stormwater run-off over the site is not appropriately contained. It is unlikely that surface water impacts would arise from shallow-subsoil application of O&G wastes, and surface water impacts would not occur where mix-bury-cover has been used. As such, movement to ground or surface water will not pose any attributable risk to food safety or animal welfare.

2.3 New Zealand state of knowledge

Information to date on environmental impacts of land application of O&G waste comes largely from compliance monitoring reports from Taranaki and from a limited number of New Zealand studies that have investigated specific aspects of land application. These studies provide an understanding of some the risks posed by land application of O&G waste, although further research on some environmental aspects is still required to provide a more detailed assessment (see section 2.3).

2.3.1 Food safety and trade

Milk quality can provide a sensitive indicator of potential contamination by organic contaminants, including those present in O&G waste, in the livestock food-chain. Due to concerns raised about the impact of landfarming on milk quality in 2014 through the media and in a recent Parliamentary Commissioner for the Environment (PCE) report (PCE 2014), MPI undertook an investigation of milk quality in cattle grazed on 17 farms that received petrochemical waste solids for bioremediation, either as a shallow subsoil-applied drilling wastes (referred to as surface application in MPI 2014) application or a mix-bury-cover, and three control sites (MPI 2014). Barium, toluene and long-chain (C25-C35) mineral oil saturated hydrocarbons (MOSH) were detected in milk from cattle from the farms receiving the O&G waste, but also from the control farms, and it was concluded that there was no evidence of milk contamination in cattle grazing on land to which O&G waste had been applied (MPI 2014). This is consistent with the low likelihood of contaminant transfer through plant material or soil to livestock from shallow subsoil-applied drilling wastes. The results of the MPI study are supported by additional testing undertaken by Fonterra on landfarms and farms adjacent to landfarms (pers. comm. Sue Walsh, Fonterra). As milk is a particularly sensitive indicator for organic contaminants, the lack of contamination in milk is evidence that other livestock products (e.g. meat) are also not contaminated by organic components of O&G waste.

Milk quality is not a suitable indicator for potential contamination of livestock products by metal contaminants, however the low concentrations of metals (except barium) in O&G wastes means metal contamination of livestock products is unlikely to occur – and may even be beneficial (e.g. copper and zinc). Barium, in the form of barite, is present in high concentrations in O&G waste. However, barium is also used in mineral supplements for livestock, for example barium selenate, thus its presence in livestock is not indicative of exposure to O&G waste.

Testing undertaken to date does not cover the full range of contaminants potentially present in O&G waste and public and agricultural sector concern can persist over the potential uptake of other contaminants, such as drilling additives (e.g. biocides) into milk or meat. To ascertain whether, these components could impact on food quality (milk, meat, food crops), information on the products used, and their mechanism of action, in New Zealand drilling operations was obtained by the author. This information indicated that some products are consumed in e.g. by forming Material Safety Data Sheets for the products viewed by the author typically identified the specific components of the different products (and formed the basis for much of the information provided in Appendix 1) and enabled the author to seek additional information to evaluate the potential uptake into livestock or food crops of the specific components. Additionally, a desk-based exercise was used to estimate the likely concentrations of a selected component of potential concern present in muds and soils, based on real-use data and worst-case scenarios (Appendix 2). These calculations, and further information support that minor drilling additives do not represent an attributable risk to food safety or animal welfare.

2.3.2 Environmental impacts

The effects of landfarming on nematodes, microbes, soil chemistry and pasture yield, was examined in a field study undertaken by Taranaki Regional Council (TRC 2011). The effects of water-based and synthetic-based drilling muds were compared with control areas where tillage but no spreading of O&G wastes had occurred. The effect over time was also examined, comparing areas where drilling muds had recently been applied with the same areas 1 and 2 years later, and with areas where land application had been used 3 and 4 years previously. The study found the effects on soil biodiversity due to landfarming practices were likely to be subtle, with some statistically significant differences in soil characteristics and soil biota observed between untreated control areas and areas with synthetic-based muds applied. For example, carbon, nitrogen and phosphate levels, and microbial respiration and biomass in particular, were different, although no effects on pasture yield or nematode abundances were observed.

A recent study found that drilling muds were highly toxic to earthworms and caused some stress to indigenous soil microbial populations at drilling waste: soil ratios that might be expected in the waste/soil layer during shallow sub-surface or surface applications (Cavanagh et al 2014). Salts, as indicated by chloride concentration, and hydrocarbons, measured as TPH, appear to be the primary components causing toxicity to earthworms. On the other hand, TPH appeared to stimulate microbial activity, as reflected by an increase in microbial biomass and basal respiration over time with increasing TPH concentration. The most pronounced effects occurred in coastal soil. Marked decreases in TPH concentrations occurred over time in both coastal and inland soil treatments. The combined increase in microbial biomass and marked decrease in TPH concentrations provides evidence for biodegradation by the indigenous microbial community. Nonetheless, the addition of drilling muds also appeared to initially stress the soil microbial community relative to the control, although this effect tended to reduce over time, suggesting adaptation of the soil microbial community. The addition of low-TPH mud (WBM) appeared to inhibit only nitrification in both soils, with the most pronounced effects observed in inland soil. A literature review indicated this effect could be due to the chloride concentration, but an additional inhibitory effect from another unknown contaminant (potentially a drilling additive) cannot be excluded. The same effect was not observed in soils to which the high-TPH mud (SBM) was added, suggesting that TPH may ameliorate this effect, likely through enhanced microbial growth associated with TPH degradation.

Another study investigated a different aspect of environmental impact - the suitability of some Taranaki landfarms for pastoral farming, in particular dairy farming (Edmeades 2013). The study found the landfarms were fit for this purpose, based on consideration of the concentrations of nutrients (both macro and micro), heavy metals, barium and petrochemical hydrocarbons in soils and pastures at three sites. This study also notes the improved pasture yields, which is a commonly reported benefit of landfarming operations. However, it remains unclear as to how much of the improvement related to the application of drilling wastes over and above the changed land management practices on these farms, although improvements in water and nutrient retention in certain sandy soils is a benefit reported internationally (e.g. McFarland et al 2009).

One aspect of environmental impact that has not been quantitatively assessed is the impact of insufficient mixing of drilling mud wastes with subsoils. Insufficient mixing may result in the formation of an impermeable layer that leads to waterlogging of the surface soils. This in turn may lead to negative effects on pasture or plant growth, most likely in a patchy fashion. This has been observed at some landfarming sites and has been attributed to water-logging effects (pers. comm., C Ross, Soil Scientist, Landcare Research). Further, ineffective mixing will limit access for soil microorganisms to degrade hydrocarbons and will create a chemical and physical barrier for earthworms, also limiting hydrocarbon degradation and thus extending the time taken for soil to reach the appropriate soil criteria. Insufficient mixing can be easily remedied, primarily through additional cultivation, if appropriate monitoring is in place to determine when this is required.

2.3.3 Groundwater and surface water

Historically, low levels of groundwater contamination has been found in the proximity of previously unlined waste storage pits in Taranaki (TRC 2014a), although a more comprehensive investigation of the risks to groundwater from land application of O&G waste has not been undertaken. Recent consents in the Taranaki region require storage pits to be lined with impermeable materials and the installation of bores around areas where stockpiling and land application activities are taking place. These actions should limit groundwater contamination and enable detection of any potential contamination.

2.4 Knowledge gaps and uncertainties

Some knowledge gaps and uncertainties about the risks associated with land application of O&G waste in New Zealand remain. These knowledge gaps pertain more to environmental considerations of waste application, than to uncertainties of the risk to animal welfare and food safety. Some knowledge gaps (e.g. leaching from drilling mud wastes) could be addressed by increased/additional monitoring or low-cost specific projects to establish a body of evidence. Other knowledge gaps (e.g. environmental concentrations of drilling additives) may require significant resources to address robustly. The key knowledge gaps are discussed further below.

2.4.1 Leaching

Additional monitoring could assist in providing a better assessment of leaching from drilling mud wastes. In particular, sampling and analysis of soil below the depth of incorporation would indicate whether any significant leaching is occurring, prior to any impacts on groundwater being evident. Desk-top modelling studies could also be used to provide a better perspective on potential groundwater impacts from land application of O&G wastes, particularly in relation to the leaching of salts.

2.4.2 Heterogeneity in waste composition

Heterogeneity in the composition of waste applied to land poses challenges in obtaining samples that are representative of the site and/or ensuring that maximum limits of application are not exceeded. Alternative sampling and testing regimes may provide an indication of the heterogeneity of the applied waste, and therefore the representativeness of a single transect measurement, as is currently used for monitoring. For example, sampling of multiple transects across a field could be undertaken to establish the variability in results due to the heterogeneity of the waste. This in turn would help the interpretation of results from samples taken at different time points, and inevitably slightly different locations, despite efforts to resample at the same locations. Such sampling could initially be undertaken at a limited number of sites, together with an assessment of the expected heterogeneity of the waste based on pre-disposal analytical results. The results of this study would help to inform monitoring practices. Discrete sampling at different locations across a field may be relevant where hydrocarbon concentrations are anticipated to be patchy (e.g. analytical results of the waste indicate heterogeneity) and highly elevated in some locations. It is important to verify that maximum application limits of hydrocarbons are not being exceeded. A potential solution is field screening of the applied waste to identify high hydrocarbon concentration areas, although currently there appears to be limited capability (in terms of equipment) and capacity (skills to operate equipment) to undertake such monitoring in New Zealand.

2.4.3 Biodegradation of hydrocarbons

While some studies indicate that biodegradation of hydrocarbons in the drilling muds does occur in New Zealand soils under laboratory conditions (Cavanagh et al 2014), the extent to which decreases in hydrocarbon concentrations in the field are attributable to biodegradation processes as compared to physical loss – including leaching – is unclear. Microbial activity is typically greatest in the surface soils and reduces with depth. Assessment of microbial activity in the soil at different depths may indicate that drilling muds are best applied at a particular depth, or mixed to a shallower depth, to optimise the potential for biodegradation. A combination of field monitoring and laboratory studies would be required to assess this.

2.4.4 Beneficial effects of land application of O&G waste

Similarly, the extent to which O&G waste provides beneficial outcomes warrants further investigation. While some studies note improved pasture yields, which is a commonly reported benefit of landfarming operations (e.g. Edmeades 2013), there have been no studies distinguishing between response associated with changes in land management (cultivation, application of fertilisers and irrigation) and that associated with O&G waste application. Improvements in water and nutrient retention in certain sandy soils is a benefit reported internationally (e.g. McFarland et al 2009), although not all of the increased water retained may be available to plants (Figure 2). Vermicomposting of O&G wastes is another means of disposal and provides a beneficial product; the vermicomposting process also reduces hydrocarbon concentrations through stimulation of microbial activity. Greater understanding of the beneficial attributes of waste application/processing, alongside any negative impacts, helps to provide a balanced approach to assessing the use of different options for disposal or use of O&G waste. Further, demonstration of beneficial use enables O&G waste to be considered as a useful by-product of drilling operations.

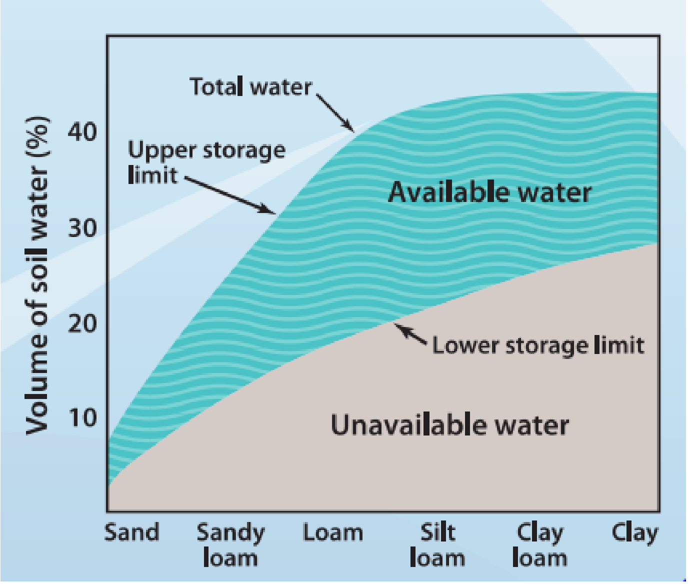

Figure 2 The change in total soil water and plant-available water content in relation to clay content (Sheppard and Hoyle undated).

2.4.5 Minor drilling additives

As noted earlier, minor drilling additives are either non-toxic or expected to be present at concentrations that do not contribute to toxicity (due to low concentrations used and/or degradation or reaction processes). A desk-based exercise estimated the likely concentrations of a microbiocide present in muds and soils, based on real-use data and worst-case scenarios (ie no degradation) (Appendix 2). While these support that minor drilling additives do not represent an attributable risk to food safety or animal welfare, further evaluation is required from an environmental perspective. This could include toxicity assessments such as described in section 2.4.6, or measures of toxicity on terrestrial organisms.

2.4.6 Toxicity of O&G wastes

The toxicity of O&G waste is typically inferred from the chemical composition of the waste, in particular the salt or hydrocarbon concentrations. An alternative approach to assessing potential toxicity to the environment is to undertake toxicity testing of the waste to be applied. For example, in Alberta, Microtox® testing is used as part of routine testing of drilling wastes that are potentially toxic (ECRB 2012). Microtox® testing uses the bioluminescent marine bacterium (*Vibrio fischeri*) as the test organism, and a reduction in light intensity emitted by the bacteria upon exposure to samples is used to indicate toxicity. While the direct relevance of toxicity measured by Microtox® to terrestrial systems is unclear and further testing is required to determine the relationship between toxicity as measured by Microtox® and terrestrial toxicity testing, Microtox® testing may provide a useful quick and standardised relative toxicity measure. However, care is required taken for sample preparation (see ECRB 2012). Some New Zealand research organisations such as National Institute of Water and Atmospheric Research (NIWA) have the ability to undertake such testing.

3 Waste and site assessment and monitoring

An important aspect of providing assurance that land application of O&G waste presents no attributable risk to animal welfare, food safety, or trade is having appropriate management practices in place, and adequate assessment and monitoring of the waste and sites to which the waste is being applied. Environmental considerations associated with land application of O&G waste will be the dominant factor influencing these processes and will provide assurance for protection of food safety, animal welfare and trade. Overall, a number of factors need to be considered, including site topography, site hydrology, and the physical (texture and bulk density) and chemical composition of the waste and the resulting waste-soil mixture. The following section provides an overview of suggested processes, drawing on current practices used in the Taranaki region where relevant. This section is not intended to comprehensively address management practices related to environmental effects, but rather to outline the key aspects that should be considered. This is to provide some context for managing any risks to animal welfare, food safety, and trade but also because many of these practices provide assurance for protection of animal welfare, food safety, and therefore, trade. However, many of the practices used to manage any environmental effects are more than is required to protect food safety or animal welfare.

3.1 Site assessment

The suitability of a site to receive drilling waste should be assessed prior to the application of waste. Aspects to consider include:

- Slope
- Susceptibility to flooding
- Soil type and profile
- Depth to groundwater and direction of groundwater flow
- Distance to surface water
- Baseline concentrations of potential contaminants

Site suitability is essentially based on minimising the likelihood of offsite movement of the waste, and thus minimising the potential for detrimental environmental impacts. Thus sites should be reasonably level and not located in areas prone to flooding. A slope criterion of $<5^o$ has been used in other jurisdictions for landfarming operations (Government of Canada 2013) and seems applicable here. Ensuring sites are not located in a 50- or 100-yr flood zone would be an easy means of ensuring that sites are not in flood-prone areas. In areas where such mapping is not available, visual assessment of the propensity for flooding and an evaluation of the local hydrology may be required. Assessment of the soil type and profile is necessary to ensure that soil drainage characteristics in particular are not negatively affected, specifically by the addition of the clay-containing wastes to soils that already have a high clay content or are prone to water-logging.

To minimise the potential for leaching to groundwater, a minimum depth to groundwater could be specified. For example, a minimum depth to groundwater of 3m is used for Canadian landfarming operations (Government of Canada 2013). The appropriate depth to groundwater may depend on the location (e.g. groundwater in coastal locations is likely to be shallower than some inland locations) and site-specific considerations (e.g. the greater the clay content of the subsoil below the waste application depth, the less leaching of waste constituents occurs). Groundwater flow direction is also important to determine the receiving environment of any potential leaching. For example, where groundwater flows to the sea, there may be less concern about any salinity impacts on groundwater.

Varying distances to surface water are used in international regulatory guidance. For example, a distance of 30 m is used in Texas for drilling mud application, while 500 m is used in Canadian landfarming operations (Government of Canada 2013). Provided that stormwater is appropriately contained on the site, a short distance to surface water, e.g. 25 m, as has been used in Taranaki, may be appropriate. Further assessment of a suitable distance to surface water should be made on a site-specific basis, taking into account the method of application. Surface run-off from areas receiving surface-application of wastes has the greatest potential impact on nearby surface water if not properly contained, while surface runoff from areas receiving shallow-subsoil application of wastes would be expected to have negligible, if any, impact on nearby surface water, and mix-bury-cover applications would be expected to have no impact on surface water through surface runoff.

When a suitable site is identified, soil sampling of the disposal area should be undertaken to establish the baseline concentrations of the key parameters (pH, salts, electrical conductivity, sodium absorption ratio (SAR), TPH, PAH and metals suite) and soil texture.

It should be noted that application of O&G wastes to land currently falls under category *G5 Waste disposal to land (excluding where biosolids have been used as soil conditioners)* on the Hazardous Activities and Industry List (HAIL) compiled by the Ministry for the Environment (http://www.mfe.govt.nz/land/risks-contaminated-land/my-land-contaminated/hazardous-activities-and-industries-list-hail) for the purposes of managing contaminated land. Thus, these sites should be recorded on Regional Council registers for contaminated land, noting that when soil endpoints have been reached the site is considered to be remediated, and the status on the registers altered accordingly (see also section 3.4.2). It should further be noted, that if sufficient beneficial effects of land application of O&G wastes could be demonstrated then the land application of O&G waste could be excluded from category G5 of the HAIL in the same manner that biosolids have been excluded when used as a soil conditioner.

3.2 Waste management

Many of the practices currently used in the Taranaki region for managing O&G waste include the necessary constraints for providing assurance that land application of solid waste does not present any risks to livestock, products, trade and environment. As outlined in a recent consent (#6236-2.0), this includes requiring that:

- waste is transported from well site to location for land application in an appropriate manner e.g. tankers.
- wastes are stored in pits lined with high-grade synthetic liners or equivalent with the requirement for ongoing monitoring to determine the integrity of the pit liners and requiring repair or replacement as needed

- Groundwater bores are established to enable monitoring of the performance of the pit.

Further, records of any waste application applied to land should be kept, and will enable evaluation of the variability in composition of the waste received and programmes to adequately monitor waste application. Information to be recorded includes:

- the source of the waste (e.g. well)
- the type of waste (e.g. water-based mud)
- the volume and weight or density of the waste to be applied to land
- the concentrations of metals salts, nitrogen and hydrocarbons in the waste
- a list of additives, including amounts used in the drilling process. (This is currently not required to be provided by the Taranaki Regional Council, although it should enable an evaluation of the likely concentration and/or potential toxicity arising from the components to be assessed.)
- verification that NORM are not present (e.g. results of screening for radioactivity of muds or scale, which are expected to have higher radioactivity)

When waste is to be applied to land the proposed loading rate, and calculations of the area required (i.e. taking account of the ratio of mixing of wastes with soils) should be undertaken to ensure maximum limits for conductivity and hydrocarbons will not be exceeded (see section 3.3). If waste has been stored for a period of time the composition of the waste may change, with hydrocarbon concentrations likely reducing. Thus, it may be appropriate to reanalyse the waste closer to the time of application. Obtaining representative samples of waste from storage ponds can be logistically challenging, as is mixing waste to ensure homogeneity. One option, that is starting to occur in Taranaki, is to store wastes of a similar composition, or at least hydrocarbon contaminated waste, in the same pond.

The results from the analysis of pre-disposal samples can be used to estimate the likely heterogeneity of waste from a given storage pond and thus determine what sampling strategy should be applied (see section 3.3). Finally, the site should be managed so that stormwater is contained onsite, and can be reapplied to the waste disposal area.

3.3 Post-application assessment

3.3.1 Visual assessment of homogeneity of waste application

As noted in section 2.2.2 there is potential for applied waste to be inadequately mixed with the sub-soil, leading to patchy waterlogging. It is suggested that visual assessment of the homogeneity of mixing to assess whether adequate mixing has occurred, or whether additional cultivation is required, is undertaken after the drilling mud waste is incorporated into the subsoil. Further assessment should be undertaken within a week of topsoil being placed over the mixed mud/subsoil layer, to confirm the depth to which waste has been mixed. This should inform the depth of post-application sampling. These two steps could be combined if the operator is confident adequate mixing has occurred. For visual assessment, a nominal area of 3 000 m^2 (as specified in Alberta guidance (ECRB 2012) as the sample area) is suggested for use in New Zealand. Within this area, it is suggested that five pits be dug to determine the homogeneity of the mixed waste. If the waste is not adequately mixed, additional cultivation may be required to avoid patchy waterlogging.

3.3.2 Heterogeneity of waste composition

As noted in section 2.3 heterogeneity in the composition of waste applied to land poses challenges to obtaining samples that are representative of the site and/or ensuring that maximum limits of application (see section 3.4.1) are not exceeded. Pre-disposal analysis of the individual wastes comprising the mixed waste can provide a preliminary assessment of heterogeneity of the waste composition. If adequate mixing of wastes can be demonstrated, the waste is considered to be homogenous and the analysis of the mixed waste can be used to determine the area required for disposal. Alternately, where waste is heterogeneous, field screening after waste application would be useful to determine areas with higher hydrocarbon concentrations, which should form the focus for subsequent analysis. Currently the capability and capacity to undertake field screening of hydrocarbons in New Zealand is limited. As an alternative approach, discrete sampling (e.g. five samples within a 3000 m^2 area) could be taken at different locations across the area to which waste has been applied, to identify areas of high hydrocarbon concentrations. Such sampling is important to verify that no areas exceed maximum hydrocarbon at the time of application, and identifies locations for subsequent sampling to verify that soil endpoints have been achieved at all locations across the site (see also next section). However, heterogeneity in waste composition does not pose a risk to food safety or animal welfare from stock, as they graze over a large area.

3.3.3 Post-application sampling

The sampling strategy for post-application sampling depends on the purpose of sampling, although for practical purposes it is likely that only one strategy will be used. From a food safety and animal welfare perspective, as livestock graze over a large area, multiple samples collected along the length of a transect provides an appropriate means to collect samples. The depth of sampling could be as shallow as 7.5cm, which is conventionally considered as the general rooting depth of pasture species, or to 15cm which is conventionally considered to capture the greater rooting depth of other crops. In this case, representative samples should be collected by taking 2.5 cm diameter cores at a spacing of 5 metres along a transect of at least 50m. Samples from two separate transects should initially be collected to account for any significant heterogeneity in the composition of the waste. This sampling is considered sufficiently representative for an area of application of 3,000 m^2 or less and additional samples should be taken where the area of application is greater than 3,000 m^2 on a pro rata basis. If no significant heterogeneity is noted (or expected, based on waste disposal analyses), then the number of transect can be reduced to one per 3,000 m^2. The location of transects should be recorded to enabling resampling during subsequent monitoring, and thus provide a measure over time.

From an environmental perspective, post-application sampling should be based on the depth of incorporation observed during the visual inspection and should include samples taken from 15 cm below the waste zone to enable assessment of leaching, as well as accounting for heterogeneity in waste composition. Surface samples should comprise the mixed waste/soil layer and overlying topsoil. Sampling should be undertaken within a week after application to confirm maximum loadings are not exceeded. Frequency of sampling should be based on the anticipated time for hydrocarbon concentrations to reduce and should be at least annually. More frequent sampling and analysis may help to build a better picture of expected rates of loss under field conditions. Further, as noted above, where the hydrocarbon concentration of the waste is anticipated to be heterogeneous, discrete samples (five samples to every 3,000 m^2) should be taken at different locations across the area to which O&G waste has been applied to identify areas of relatively high hydrocarbon concentrations. These areas with higher concentrations of hydrocarbons should be the focus of subsequent sampling to verify that the entire site has reached the requisite hydrocarbon concentration values.

Analysis of post-application soil samples from a food safety and animal welfare perspective should focus on hydrocarbons. A broader range of components should be considered from an environmental perspective and includes chloride, electrical conductivity, hydrocarbons, pH, sodium adsorption ratio (SAR), sodium and metal suite.

3.3.4 Surface and groundwater sampling

Surface water and groundwater monitoring is required from an environmental perspective and should be undertaken at locations and frequencies pertinent to the specific site, including sites of proposed operations.

3.3.5 Land use prior to soil meeting surrender criteria

As noted earlier, the likelihood of contamination of milk, meat or crops from O&G waste applied to shallow subsoil is extremely low even before any degradation processes, due to the limited potential for plant uptake of the main contaminant, TPH, and low concentrations of contaminants of greater concern, such as PAHs and heavy metals (section 2.1.1). To provide greater assurance, and alleviate potential concerns about exposure of livestock to other contaminants (e.g. biocides or other components present, but typically in very low concentrations), stock should be excluded and crops should not be harvested from areas where O&G waste has been applied until soil endpoints for hydrocarbons have been reached. Similarly, stock should be excluded and crops not harvested from any areas that have received surface application of O&G wastes until soil endpoints for hydrocarbons have been reached. For all sites where O&G solid waste has been applied at depth, i.e. below the root zone, and groundwater from the site is not used for stock drinking water or on-farm use, or where testing has confirmed no contamination, there is no need for stock exclusion as no exposure pathway exists and there is no risk to livestock.

3.4 Soil quality criteria

3.4.1 Maximum application limits

Salts and hydrocarbon concentrations are anticipated to be the key factors limiting the amount of O&G waste that can be applied to land. Maximum limits should be in place to ensure that waste application does not lead to immediate detrimental environmental impacts, acknowledging that concentrations of both these components are expected to reduce over time. These maximum limits are advised for environmental considerations, as opposed to any risk to food safety or animal welfare.

Typically soils with an electrical conductivity (EC) of >4 dS/m (400 mS/m) are considered to be poor (see Table 1), and this is used as an upper limit in salt content for landfarming internationally (e.g. ERCB 2012; Government of Canada 2013) and in Taranaki. It is recommended as a maximum limit for application of O&G waste in New Zealand, recognising that salt concentrations will decrease relatively rapidly under rainfall. It should be noted that while 4.0 dS/m is used as a general threshold (EC) to define saline soils, many sensitive crops, such as some vegetables and ornamentals, will show symptoms and reduced yields at ECs of 2–4 dS/m (Waskom et al. 2012).

Table 1 Soil quality ratings based on soil conductivity (Alberta Environment 2001)

EC dS/m	Rating categories			
	Good	Fair	Poor	Unsuitable
Topsoil	<2	2–4	4– 8	>8
Subsoil (to 1m)	<3	3– 5	5–10	>10

For hydrocarbons, a maximum concentration at time of application of 20 000 mg/kg TPH is currently used in the Taranaki region, which is the same as that used in Alberta for land application of drilling wastes (ERCB 2012). This is lower than maximum concentrations used in landfarming operations for remediating hydrocarbon contaminated soils. For example, 3% or 30 000 mg TPH/kg is suggested in Canadian landfarming guidelines as the upper limit to avoid toxicity to microbial populations (Government of Canada 2013), while Australian Guidelines indicate that wastes containing up to 8% (80 000 mg TPH/kg) can be landfarmed without affecting biodegradation potential (NSW EPA 2014). These higher maximum concentrations appear likely due to the different purpose of landfarming for remediation of hydrocarbon contaminated soil, as opposed to land application of O&G wastes. Pending further investigation of the extent of biodegradation in New Zealand soils, it is suggested that an upper limit of 20 000mg/kg TPH continues to be used as a conservative maximum limit for hydrocarbons.

Table 2 Summary of suggested maximum limits for salts and hydrocarbons

Component	Standard
Conductivity	<4 dS/m
TPH	20 000 mg/kg

3.4.2 Soil endpoints

Soil guideline values (SGVs) are typically developed to provide for protection of the environment and/or human health, as opposed to food safety or animal welfare. In the absence of SGVs developed for the purposes of food safety or animal welfare, SGVs for protection of the environment or human health provide a highly conservative approach to ensuring food safety and animal welfare for the primary components of concern in O&G waste (hydrocarbons, salts).

From an animal welfare perspective, elevated salt concentrations in soil are unlikely to cause toxicity issues at likely post-application concentrations, and may even be beneficial for livestock given salt (typically in the form of salt blocks or "lick") is used to address some mineral deficiencies and improve milk production and herd health (Keyes 2012). For hydrocarbons, risk-based soil screening levels (RBSLs) have been developed to assess the risk associated with livestock exposure to accidental releases of petroleum hydrocarbons at or near exploration and production sites in the United States (Pattanayek & DeShields 2004, Table 3). RBSLs were developed for petroleum hydrocarbons, including crude oil, BTEX and polycyclic aromatic hydrocarbons (PAHs). As these RBSLs are markedly higher than soil hydrocarbon endpoints meeting environmental criteria for hydrocarbons (TPH) (see Table 4), meeting those endpoints assures that animal welfare will also be protected. Risk-based soil screening levels were not developed for metal contaminants, as they were considered to not be found at high enough concentrations in crude oils to be a significant risk to animal welfare (Pattanayek & DeShields 2004).

Table 3 Risk-based soil screening levels for protection of livestock exposed to petroleum hydrocarbons (adapted from Pattanayek and DeShields 2004).

Livestock	**Soil Risk-based Screening Levels (RBSLs);mg/kg**						
	Crude oil[1]	**Benzene**	**Toluene**	**Ethylbenzene**	**Xylene**	**LMW PAH**	**HMW PAH**
Dairy cattle	44 151	1 273	7 946	1 039	6 367	178	35.7
Beef cattle	44 894	1 266	7 901	1 033	6 331	177	35.5
Calves	44 894	2 198	13 715	1 794	10 990	308	61.5
Sheep	20 095	953	5 949	778	4 767	133	26.7

[1] Equivalent to TPH concentration

From an environmental and human health perspective, the key determinant of suitable soil quality endpoints is the intended land use after application of drilling wastes. To ensure land use is not restricted, the soil quality criteria for the most sensitive land use should be used. The most sensitive land use will typically be agricultural land use, to ensure that productivity is not affected, and rural residential land use (which has a higher proportion of assumed home-grown produce intake), to ensure protection of human health. These guideline values should apply to the surface soil and the mixed soil/waste layer. After soil endpoints are met, the site may be considered to be remediated for the purposes of Regional Council classification of contaminated sites based on HAIL activities and may require reporting in accordance with *Contaminated Land Management Guideline No.1* (Mfe 2011c) including that the site investigation has been undertaken in accordance with *Contaminated Land Management Guideline No.5 (*MfE 2011d). The soil guideline value discussed below and provided in Tables 4 and 5 are largely based on what is currently in use in the Taranaki region but have not been comprehensively evaluated from a human health or environmental perspective. This is because these soil guidelines are based on protection of human health and soil biota are conservative with respect to protection of food safety and animal welfare.

The salt concentration of drilling wastes is a key environmental consideration due to the impact of salts on soil structure and quality. Salts may impact soil quality in two respects: salinity, which affects plants, and sodicity, which affects soil structure and water penetrability. Salinity relates to the total salt content of the soil and is measured via EC or total soluble salts. Plants demonstrate different tolerances to salinity (e.g. see http://www.dpi.nsw.gov.au/agriculture/resources/soils/salinity). Sodicity is typically measured as the sodium adsorption ratio (SAR). Sodium is adsorbed to soil particles and the soil then becomes hard and compact when dry and increasingly impervious to water penetration.

The impact of any increase in salinity will also depend on the baseline concentration of the soils to which O&D waste is applied, e.g. soils in coastal environments have a higher baseline conductivity than soils in inland environments – until a critical threshold. Thus a lower limit may be applicable for non-coastal soils.

Soil guideline values for hydrocarbons suggested for use are provided in the *Guidelines for Assessing and Managing Petroleum Hydrocarbon Contaminated Sites in New Zealand* (MfE 2011a) and *Canada-Wide Standard for Petroleum Hydrocarbons (PHC) in Soil: Scientific Rationale* (CCME 2008). The Canadian document provides one of the most recent comprehensive evaluations of the toxicity of petroleum hydrocarbons, and specifically TPH, in the soil environment. As such, it is used in preference to existing New Zealand soil guideline values for TPH, as they are more relevant and mostly lower than TPH soil guideline values for agricultural land-use in MfE[1] (2011a). The Canadian TPH soil endpoints are based on protection for plants and soil biota, which are more sensitive than people to TPH. While the Canadian guidelines use a slightly different fractionation regime (C6–C10, >C10–C16, >C16–C34 and >C34) to that used in New Zealand (C7–C9, >C9–C15, >C15–C36), the values generated are generally applicable to those used in New Zealand for the current purpose. The *Guidelines for Assessing and Managing Petroleum Hydrocarbon Contaminated Sites in New Zealand* (MfE 2011a) provides soil guideline values for aromatic hydrocarbons (BTEX, PAH based on benzo-a-pyrene equivalents) for agricultural land use. This document includes soil guideline values for BTEX, for which Soil Contaminant Standards (SCS) for the *National Environmental Standard for assessing and managing contaminants in soil for the protection of human health* (NES) have not been developed. Further MfE (2011a) includes soil guideline values for agricultural (production) land, which is excluded from the NES (other than in the proximity of residences on production land) although is the primary use of land to which O&G waste has been applied. Future revision of MfE (2011a) may result in the agricultural land use scenario being removed align with the NES, in which case new soil guideline values will need to be considered. Finally, as the hydrocarbon criteria are influenced by soil type, the endpoint concentration will depend on the soil type to which the O&G waste is applied.

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[1] The exception being the soil guideline value for C7-C9 for sandy soils; this is 120 mg/kg in MfE 2011a, but this is based on exposure of a maintenance or excavation worker and so is not relevant.

Table 4 Summary of suggested soil endpoints for salts and hydrocarbons[1]

Category	**Endpoint**	**Petroleum hydrocarbon guidelines[2] (mg/kg)**	**CWS-standards[3] (mg/kg)**	
			Fine	**Coarse**
Conductivity	1.9 dS/m or 1 dS/m above baseline[4]			
Chloride	700 mg/kg			
Sodium	460 mg/kg			
Total soluble salts[5]	2500 mg/kg			
Hydrocarbons				
MAH (benzene, toluene, ethylene, xylenes		See Table 5		
PAH (benzo-a-pyrene-eq)				
TPH				
C7-C9			210	210
C10-C15			150	150
C16-C36			1300	300

[1] These soil endpoints are based on protection of the environment and human health, and are conservative with respect to ensuring protection of food safety and animal welfare; [2] MfE 2011a; [3]CCME 2008 Table 5.3 and 5.3, for fine and coarse soils, soil guidelines are based on slightly different hydrocarbon fractions and are shown for: C6–C10, >C10–C16 and >C16–C34. Fine grained soils are those which contain greater than 50% by mass particles less than or equal to 75 µm mean diameter, while coarse grained soils are those which contain greater than 50% by mass particles greater than 75 µm mean diameter; [4]for soils with a baseline concentration >1 dS/m, ensuring that the maximum limit of 4 dS/m is not exceeded; [5]Total soluble salts are derived from EC according to SS% = EC (mS/cm) x 0.35.

Table 5 Suggested soil endpoints for aromatic hydrocarbons for different soil types (Adapted from MfE 2011a)[1]

Soil Type/Hydrocarbon	Monoaromatic hydrocarbons and polycyclic aromatic hydrocarbons[2]
SAND	
Benzene	1.1 (v)
Toluene	(68) (3,v)
Ethylbenzene	(53) (3,v)
Xylenes	(48) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)
SANDY SILT	
Benzene	1.1 (v)
Toluene	(82) (3,v)
Ethylbenzene	(59) (3,v)
Xylenes	(59) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)
SILTY CLAY	
Benzene	1.7 (v)
Toluene	(210) (3,v)
Ethylbenzene	(110) (3,v)
Xylenes	(160) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)
CLAY	
Benzene	2.7 (v)
Toluene	(320) (3,v)
Ethylbenzene	(160) (3,v)
Xylenes	(250) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)
PUMICE	
Benzene	1.2 (v)
Toluene	(73) (3,v)
Ethylbenzene	(48) (3,v)
Xylenes	(53) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)
PEATS AND HIGHLY ORGANIC SOILS	
Benzene	5.7 (v)
Toluene	(2,500) (3,v)
Ethylbenzene	(2,200) (3,v)
Xylenes	(1,700) (3,v)
Naphthalene	7.2 (p)
Non-carc. (Pyrene)	(160) (3,p)
Benzo(a)pyrene eq.	0.027 (p)

[1] For further detail on the derivation of these soil guideline values refer to MfE 2011a. [2]Letter indicate the limiting pathway for each criterion- Volatilisation, s - Soil Ingestion, d - Dermal, p – Produce consumption; [3]Brackets denote values that exceed threshold likely to form residual separate phase hydrocarbons.

Soil guideline values for metals in *Guidelines for the safe application of Biosolids to land* (NZWWA 2003) consider protection of soil biota as well as human health, and soil contaminant standards for rural residential land use (the most sensitive land use) in the *National Environmental Standard for assessing and managing contaminants in soil for the protection of human health* provide the most recent New Zealand standards for the protection of human health. As metals will not degrade, it is expected that metal concentrations will comply with these limits or standards at all times.

Barium, in the form of barite, is a major constituent of O&G waste (e.g. TRC 2014 b, c), although no New Zealand soil guidelines for barite are available. Soil guideline values for barite have recently been assessed by Alberta Environmental (2009), and values for barium have recently been assessed by CCME (2013). As the toxicity of barium relates to the solubility of the barium compounds and barite is relatively insoluble, Alberta Environmental (2009) developed two soil guideline values, one based on barite and the other based on barium extracted by 0.1M $CaCl_2$ (termed extractable barium), which represents the soil concentration of barium to which soil organisms may be exposed. The soil guideline values for barite and extractable barium for agricultural land use are suggested for inclusion as additional soil quality guidelines to manage any environmental effects; barium does not pose an attributable risk to food safety and animal welfare. A summary of the suggested soil quality guidelines for metals for sites to which O&G wastes are land-applied are shown in Table 6.

Table 6 Summary of suggested soil quality guidelines for metal contaminants

Category	Biosolids soil limit[1] (mg/kg)	SCS-rural residential[2] (mg/kg)	Alberta Environmental (2009)
Arsenic	20	17	
Barium - barite			10,000
Extractable- barium			250
Cadmium	1	0.8	
Chromium	600	NL[3]	
Copper	100	NL	
Lead	300	160	
Nickel	60	-	
Mercury	1	200	
Zinc	300	-	

[1] NZWWA 2003, lowest of protection of human health and ecological receptors; [2] MfE 2011b; [3]NL – no limit.

A Ministry of Business, Innovation and Employment-funded Envirolink Tools project (see http://www.envirolink.govt.nz/ for more details) is currently underway to develop soil guideline values (Eco-SGVs) for protection of ecological receptors, including soil microbiota, soil biota, plants, livestock and wildlife in New Zealand. Eco-SGVs will be derived for a number of priority contaminants, including TPH and selected metals, by June 2016 and will provide updated soil guideline values for the protection of ecological receptors and livestock for use in New Zealand. The soil guideline values discussed in this section could be updated at this time, although it is not anticipated that the new Eco-SGVs will significantly impact on O&G waste application as the currently advised values are considered to be conservative.

4 Additional considerations

4.1 Considerations in selecting disposal method

The relative risks (e.g. livestock exposure, leaching to groundwater) and benefits (e.g. potential for biodegradation of hydrocarbons) of different disposal methods should be considered when selecting a disposal method. For example, surface soils typically contain greater microbial activity and hence will enable more rapid biodegradation of hydrocarbons, although there is greater potential exposure of livestock to the contaminants in the waste if grazed soon after application. Conversely, mix-bury-cover methods pose no risk to livestock or crops, although they may pose greater potential for groundwater contamination and will likely have reduced hydrocarbon degradation potential, depending on what is mixed with the waste.

While there may be considered to be some risks associated with land application of O&G solid waste, there are potential benefits of land application, such as increased water and nutrient retention in selected soils. If the beneficial effects arising from land application of O&G waste can be consistently and robustly demonstrated then it could be considered as a by-product of drilling operations (i.e. not a waste). This also has potential flow-on effect by potentially enabling the exclusion of O&G wastes in category G5 of the Hazardous Activities and Industry list (HAIL) in the same manner that biosolids are excluded (i.e. where used as a soil conditioner). This in turn would remove the requirement to list land that has received O&G waste on Regional Council contaminated land registers. Vermicomposting of the O&G waste also represents a means by which O&G waste is beneficially used, with the benefits demonstrated if appropriate systems are in place to monitor the quality of the compost produced.

Finally, the broader environmental impacts associated with alternative disposal methods also need to be considered relative to those of land application. For example, disposal of the waste to landfill may require transporting greater distances and takes up landfill space that might otherwise be used for more hazardous materials.

4.2 Multiple applications of oil and gas waste

Currently O&G solid waste is applied to land on a single occasion, although there may be future interest in reapplying waste to a site. As noted earlier, accumulation of contaminants is a greater environmental consideration for repeated applications of O&G waste. For example, salts and higher molecular weight organic compounds could increase soil water repellency. An additional consideration is the alteration of the soil drainage characteristics due to the high clay content of O&G waste, which could render soils prone to waterlogging by creating impermeable subsoil layers. If repeated application of wastes is undertaken, testing of soil drainage characteristics should be required from an environmental perspective, in addition to ensuring that endpoints for soil quality are met.

4.3 Application of hydraulic fracturing ('fracking') return wastes

Detailed consideration of land application of return fluids from fracturing operations that are currently largely re-injected back into wells was beyond the scope of this report, however, a brief overview of the aspects that should be considered is provided here. A key initial consideration of the application of these wastes onto or into soil will be the salinity and volume of the liquid wastes and the potential for leaching of salts to groundwater, as well as accumulation of salts in the soil. Further to this, consideration is required of the potential environmental impacts arising from hydrocarbon and chemical additives (e.g. biocides, corrosion inhibitors and used acids) that may also be present in the liquids. While a number of the additives in fracking fluid, and hence in the return fluid, are similar or the same as those used in drilling muds, there appears to be greater public concern over fracking wastes (e.g. DeSmogBlog 2010) and a number of recent studies have examined the composition and toxicity of hydraulic fracturing fluid components (e.g. Stringfellow et al 2014; Lester et al 2015). These studies are typically undertaken from the perspective of potential groundwater contamination, given the nature of fracking operations and are inconclusive with regards to land application of fracking wastes. The greater public concern about land application of fracking wastes appears to be largely due to the nature of fracking operations and the subsequent potential for groundwater contamination (e.g. Godalla et al 2013), which in turn has raised concerns about the land application of fracking return fluids.

5 Summary and next steps

Land application of O&G wastes is considered to pose no attributable risk to food safety or animal welfare, particularly where wastes are incorporated into the shallow subsoil with topsoil overlying the soil/waste layer and the primary pathway of exposure is via plant uptake. This is largely due to the limited plant uptake of the main contaminants of concern in the waste, hydrocarbons. Surface application of O&G wastes is considered to pose minimal risk to food safety and animal welfare before any degradation has occurred, and no attributable risk when stock are excluded and crops are not harvested until agreed soil endpoints are reached. Nonetheless, public and agricultural sector concern, in particular about the potential risks associated with drilling additives such as biocides, may persist. Drilling additives are not of concern to food safety or animal welfare, because they are non-toxic, they are present at concentrations that do not contribute to toxicity, or because they are unlikely to be transferred to livestock either directly or indirectly through plant uptake. To provide greater assurance for the public and agricultural industry that this is the case, information on the types and quantities of the additives used could be required as part of the traceability process for waste disposal. This would provide greater transparency, and enable estimates of the likely concentrations present in muds and soils to be made. It is noted that some compliance reports include information about other components, which may be a useful starting point (e.g. TRC 2014a).

Assurance of the risk that land application of O&G waste poses to food safety and animal welfare is provided by having appropriate management practices in place, and adequate assessment and monitoring of the waste and sites to which the waste is being applied. In practice, these processes are largely driven by environmental considerations (e.g. leaching to groundwater, toxicity to soil biota) although they do also provide assurance from the food safety and animal welfare perspective. In fact many of the practices to manage environmental effects are more than is required to protect food safety or animal welfare. From an environmental perspective, hydrocarbons and salts remain the primary constituents of concern, and many processes currently exist to manage the environmental risk. However, some knowledge gaps exist from an environmental perspective with further monitoring or research required to address these gaps:

- Additional monitoring could assist in providing a better assessment of leaching from drilling mud wastes. In particular, sampling and analysis of soil below the depth of incorporation would indicate whether any significant leaching is occurring, prior to any impacts on groundwater being evident. Desk-top modelling studies could also be used to provide a better perspective on potential groundwater impacts from land application of O&G wastes, particularly in relation to the leaching of salts.
- Heterogeneity in the composition of waste applied to land poses challenges in obtaining samples that are representative of the site and/or ensuring that maximum limits of application are not exceeded. Where pre-disposal analysis has indicated that the waste is likely to be heterogeneous with highly elevated hydrocarbon concentrations in some locations, alternative sampling strategies should be employed. This includes discrete sampling at different locations across a field, or sampling along multiple transects may be appropriate to verify that maximum application limits of hydrocarbons are not being exceeded.

- A key purpose of land application of O&G wastes is to enable biodegradation of hydrocarbons to occur, however, further studies are required to determine the extent to which biodegradation of hydrocarbons is occurring under field conditions in New Zealand.
- Further studies on the benefits (e.g. water and nutrient retention, improved pasture yield) of the land application of O&G waste is required to provide a balanced approach to assessing current and alternative disposal options for O&G waste.

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Appendix 1 – Components of O&G waste

Table A1. Functional categories of materials used in SBM and WBM, scale of use, their functions, and examples of typical chemicals used in New Zealand in each category.

Function category	Mud	Major/minor component	Function characteristics	Typical chemicals
Weighting agents	WBM/SBM	Major	Increase density of mud	Barite
Base fluid	SBM	Major	Base fluid	Distillates, typically C8-C26 branched and linear alkanes
Viscosifiers	WBM	Major	Increase viscosity of mud to suspend cutting and weighting agent in muds	Bentonite, hydroxyethyl cellulose and other polymers, alkanes, plant gums
Shale control materials	WBM	Major	controlling the hydration of shales, including by encapsulation, which causes swelling and dispersion of shales	Soluble calcium and potassium salts, other inorganic salts, organics such as partially hydrolysed polyacrylamides
Lubricants	WBM	Major	Reduce torque and drag on drill bits	Graphites, surfactants, glycols, glycerins,
Lost circulation materials (as needed)	WBM/SBM	Major	Preventing the loss of whole mud to the well bore	organic fibres and materials e.g. sawdust, walnut shells, calcium carbonate
Brine	SBM	Major	Shale/formation stability	Inorganic salts e.g. calcium chloride
Fluid loss reducers	WBM	minor	Plug leaks in wellbore wall, by forming a semi-permeable membrane on the hole wall and prevent the loss of fitrate to the formation	Amorphous silica, cellulose, glycol ethers, polysaccharides
Thinners, temperature stabilizing agents	WBM	minor	Increase stability of mud dispersions	Tannins, chrome-free lignosulfates, polyphosphates, hydrogen peroxide, sodium thiosulphate
Emulsifiers	SBM	minor	Increase stability of mud dispersions	Acrylic or sulfonated polymers or copolymers
pH modifier	WBM	minor	Optimise pH	Caustic soda, citric acid , magnesium oxide
Alkalinity control	WBM/SBM	minor	Optimise alkalinity	Lime (calcium hydroxide)
Calcium reducers	WBM	minor	Reduce hardness in make-up water	Sodium carbonate and bicarbonate, sodium hydroxide, glycols
Biocides	WBM	minor	Prevent biodegradation of organic additives	Glutaraldehyde, isothiazolin, triazine, tetrakis(hydroxymethyl)phosphonium sulphate

Function category	Mud	Major/minor component	Function characteristics	Typical chemicals
Corrosion inhibitors	WBM	minor	Prevent corrosion of the drill pipe or well bore casing by coating pipe or casing	Amines, phosphate, specialty mixtures
Flocculants	Used in dewatering activities	minor	Increase viscocity and gel strength of clays or clarify or de-water low solids muds	Hydrated lime, salts, calcium carbonates, Sodium carbonate and bicarbonate, acrylamide-polymers
Wetting agents	SBM	minor		Pine resin
Defoamers	WBM	minor	Reduce mud foaming	Organic esters, light molecular weight petroleum distillates, selected glycols

Appendix 2 – Estimated concentrations of a selected drilling additive

A mass-balance approach was used to provide indicative concentrations of a selected drilling additive that might form the basis for concern. The substance selected was a triazine tri-ethanol (TTE, CAS: 4719-04-4), the main ingredient of Safe-Cide, a microbiocide currently widely used in New Zealand drilling operations. This was selected because it is a microbiocide, and therefore is toxic to some environmental receptors (bacteria).

The amount of Safe-Cide added and volume of disposed mud was provided by drilling operators. A series of assumptions were used to general the estimated soil concentrations shown in Table 2.1. The assumptions were:

- That TTE was 100% of the product added to the well
- That the volume of disposed mud was the amount of mud into which the product added was mixed
- Where data on the area over which the disposed mud was spread, the area over which the mud was spread was calculated based on application of a 10 cm layer of mud
- The disposed mud was mixed with soil (density 0.9 g/cm3) in a 10cm depth..

Table A2. Estimated soil concentrations of 2,2',2"-(hexahydro-1,3,5-triazine-1,3,5-triyl)triethanol (TTE) arising from disposal of O&G waste.

Well	Disposed mud	SafeCide vol (25 L	Safecide volume	TTE Mass[1] (kg)	Estimated TTE Concentration in disposed mud (kg/m^3)	Area to which mud is applied[2] (m^2)	Total soil[3] (kg)	Estimated soil concentration TTE (g/kg)
Well A	398.6	18	450	531	1.332	3986[4]	358751.7	**1.48**
Well B	1584.0	29	725	855.5	0.540	15840[4]	1425627	**0.60**
Well C	1110.1	28	700	826	0.744	11101[4]	999100.4	**0.83**
Well D	1658.4	22	550	649	0.391	165834[4]	1492550	**0.43**
Well E	1246.8	27	675	796.5	0.639	12468[4]	1122150	**0.71**
Well F	1487.5	21	525	619.5	0.416	14874[4]	1338715	**0.46**
Well G	902.1	19	475	560.5	0.621	9021[4]	811925.9	**0.69**
Well H	1873.9	16	400	472	0.252	18738[4]	1686466	**0.28**
Well I	1490.4	24	600	708	0.475	14904[4]	1341368	**0.53**
Well J	843.6	20	500	590	0.699	9943[5]	894834	**0.66**

[1] based on a density of 1.18 g/cm^3, and assuming SafeCide is comprised 100% TTE (product composition is 60-100% TTE)

[2] estimated or provided

[3] based on mixing with 10cm of soil with a density of 0.9 g/cm^3

[4] Estimated area based on application of a 10cm layer of disposed mud.

[5] actual area of disposal

At the estimated concentrations, the substance should be easily detectable by chemical analysis, although no routine analytical methods are currently available. In reality, concentrations of TTE are likely to be much lower as it is considered to be readily degradable based on testing following OECD guidelines. Further, TTE is considered to have a low potential to bioaccumulate due to it's low octanol-water partitioning coefficient (log K_{ow}) (see http://apps.echa.europa.eu/registered/data/dossiers/DISS-9ebf1bf3-14f9-2d00-e044-00144f67d031/DISS-9ebf1bf3-14f9-2d00-e044-00144f67d031_DISS-9ebf1bf3-14f9-2d00-e044-00144f67d031.html for data on degradability and octanol-water partitioning and more information on TTE). These factors mean the TTE is not considered to pose an attributable risk to food safety and animal welfare.