Land farming of drilling wastes: Impacts on soil biota within sandy soils in Taranaki (Year 1 of 3)

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Executive summary

Land spreading (also known as landfarming, land disposal and land treatment) is the process whereby drilling wastes (cuttings and mud) are disposed of via application to land. Landfarming is a form of bioremediation, which allows the soil's naturally occurring microbial population to degrade drilling waste constituents (particularly hydrocarbons, other organic compounds and nitrogen). This report details the methods and results for year one of a three year bio-monitoring project investigating the effects of landfarming on nematode and microbe populations and pasture yield in coastal Taranaki pastures. In particular, the effects of high chloride and petroleum hydrocarbon loadings on nematode community structure and abundance as well as microbe community structure and activity were investigated.

Hydraulic fracturing or "fracking" is an extraction method for petroleum and gas products, which involves injecting chemicals, sand, and water under high pressure directly into shale deposits deep underground. Fracking has a high media profile at present, due to concerns over the toxicity of fracking wastes and groundwater contamination from fracking by-products. Although fracking wastes have been applied to soils in Taranaki on several occasions, fracking wastes were not a component of the wastes applied to the landfarms assessed during this study.

Overall, there were very few statistical differences in the parameters investigated for assessing the health of soil biota communities and soil chemical composition among control and treatment areas. However, this may be due to the relatively small samples' sizes and replicate numbers, and differences in site management after drilling waste application (e.g. differences in tilling regimes, fertiliser application rates etc). Therefore, it is difficult to reach definitive conclusions from the results of this study, and further research in years 2 and 3 of this project is required to elucidate some of the patterns emerging from this study. Initial results suggest changes to nutrient levels (C, N & P in particular), and microbial biomass and respiration, after the application of drilling wastes to some treatment areas, with these differences becoming more apparent in areas where synthetic-based muds had been applied (water-based muds have less impact). Nematode abundances and pasture yield were largely unaffected by drilling waste application. Additionally, no resource consents were breached at any of the sites surveyed for this study. Monitoring of these sites will continue throughout years 2 and 3 of this study (in 2011/2012 and 2012/2013) to ensure that no negative impacts on soil biodiversity arise over time due to landfarming practices, or emerge as low-level chronic effects.

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1. Introduction

1.1 Scope & structure

The application to land of drilling wastes arising from hydrocarbon exploration drilling activities in Taranaki has become an established method for disposing of such wastes in an environmentally acceptable and beneficial manner. The Taranaki Regional Council routinely monitors the disposal sites for compliance with resource consents and for evidence of any adverse effects. A number of studies of the benefits generated in subsequent utilization of sites for productive pastures have established, to the extent of the scope of the studies, that the activity of land spreading has minor effects, and in some case has beneficial effects (e.g., on pasture yield), when conducted according to Council guidelines.

The Council has now extended the scope of its investigations into a review of the consequences of land spreading for soil ecology. This report covers the background of land spreading operations and their possible effect on soil biota and pasture growth, the methodology used for gathering data on land spreading in Taranaki, results and recommendations, and future project requirements.

Hydraulic fracturing or "fracking" is an extraction method for petroleum and gas products, which involves injecting chemicals, sand, and water under high pressure directly into shale deposits deep underground. The shale deposits are fractured during this process and natural gas is released from them. Fracking has a high media profile at present, due to concerns over the toxicity of fracking wastes and groundwater contamination from fracking by-products. However, laboratory analyses of fracking wastes from Taranaki wells indicate that the chemical concentrations and composition of fracking wastes are similar to those that have been used in landfarming thus far (see 'Landfarm Results – Self Monitoring' spreadsheet, FRODO document # 360675, and FRODO documents # 929999 and # 930001). Although fracking wastes have been applied to soils in Taranaki on several occasions, fracking wastes were not a component of the wastes applied to the landfarms assessed during this study, and further research is required to address this gap in knowledge.

This document is divided into 4 sections:

- Section 1 introduces the purpose, scope and structure of the report, along with a brief description of land spreading techniques and Taranaki Regional Council's Guidelines for land spreading applications.
- Section 2 outlines the objectives and methodology of the project.
- Section 3 provides an overview of the results of the soil biota monitoring project, a map showing site locations, and an analysis of the information gathered.
- Section 4 presents conclusions and recommendations, with possible information gaps identified.
- The glossary contains definitions for technical terms used throughout this document.
- The appendices present site details (Appendix I), details of the soil analyses performed by Landcare Research (Appendix II), photos of stock exclosure plots (Appendix III), additional results for nematodes (Appendix IV), and chloride and hydrocarbon loadings/concentrations for treatment and control areas (Appendix V).

1.2 Purpose

Soils are populated by a multitude of microorganisms and invertebrates, which play an important role in the decomposition of organic matter, cycling of nutrients, energy and elemental fixation, soil metabolism and overall soil health. Among the microorganisms found in the soil are bacteria, actinomycetes, fungi, micro-algae, protozoa, nematodes, and other invertebrates (mostly arthropods) (Dindal, 1990).

This report details methods and results for year one of a three year bio-monitoring project investigating the effects of land spreading/farming on nematode and microbe populations as well as pasture yield in coastal Taranaki pastures. More specifically, this study examines the effects of high chloride and petroleum hydrocarbons loadings on nematode community structure and abundance as well as microbe community structure and activity.

Nematodes are the most numerous multicellular animals on earth and a handful of soil will contain thousands of these microscopic worms. Many nematodes are parasites of insects, plants or animals although free-living species are also abundant, including nematodes that feed on bacteria, fungi, and other nematodes. Thus, they are an important component of soil ecosystems and food-webs (Dindal, 1990), and can therefore provide useful information on soil health and biodiversity.

1.3 Background

Land spreading (also known as landfarming, land disposal or land treatment) is the process whereby drilling wastes (cuttings and mud) are disposed of via application to land. Oil and gas wells may be drilled with either synthetic based mud (SBM) or water based mud (WBM), and more than one type may be used to drill an individual well. In the past, oil based muds (diesel/crude oil based) have also been used. Their use has declined since the 1980s due to their ecotoxicity, and they have been replaced by SBM, which is synthesised from diesel that has had the aromatic chemicals (chemicals with six carbon molecules in a ring formation) removed. Barium sulphate is added to most drilling muds as a wetting and weighting agent.

Applying drilling wastes to the land is a form of bioremediation – it allows the soil's naturally occurring microbial population to degrade the waste constituents (particularly hydrocarbons, other organic compounds and nitrogen) that drilling cuttings and muds contain. Optimal land spreading techniques balance waste additions against a soil's capacity to assimilate waste constituents. This is important to avoid detrimental effects on soil integrity, subsurface soil contamination problems, or other adverse environmental impacts.

Taranaki loading limits and maximum application rates are dictated by resource consents. The preparation of these consents is informed by national and international guidelines and criteria for soil and water quality, along with local research into biodegradation and attenuation rates and environmental effects associated with drilling wastes. Taranaki Regional Council has granted consents for land spreading of drilling wastes at several locations around the region, with conditions stipulating maximum loading limits and application depths for various contaminants based on Canadian standards, which have been modified for conditions in Taranaki.

In Taranaki to date, land spreading has consisted only of single applications of drilling wastes at a particular locality within a disposal site (a consented site will generally have space for a number of disposal operations).

Basic steps in the land treatment process include;

- Drilling waste is transported from wellsites by truck (cuttings) or tanker (liquids), and may be discharged directly to land or placed in a dedicated storage pit (for individual well and mud type).
- Required area is prepared by removing any existing pasture/topsoil and leveling out uneven ground.
- Waste may be blended with additional materials such as sawdust to reduce initial concentrations or stabilize liquid fractions.
- Waste is transferred to prepared area by excavator and truck and spread out with a bulldozer. Liquids may be discharged by tanker or spray system.
- Waste is allowed to dry sufficiently before being tilled into the soil to the required depth with a tractor and discs.
- Area is leveled with chains or harrows.
- Removed topsoil/clay is applied to aid stability and assist in grass establishment. Fertiliser may be applied and the area is sown in crop or pasture at a suitable time of year.

Studies elsewhere have indicated that if wastes are applied correctly, land spreading does not adversely affect soils. Furthermore, some studies as well as anecdotal evidence have suggested that land spreading may even benefit certain sandy soils by increasing their water-retaining capacity and reducing fertilizer losses, and hence enhancing productivity.

Taranaki Regional Council guidelines relating to land spreading in Taranaki suggest that land spreading operations should ideally be located on relatively flat sandy country prone to wind erosion as this is where the greatest environmental benefits are likely to be obtained, through reducing susceptibility to wind erosion. Additionally, Council Monitoring Programme Technical Reports for land spreading operations in Taranaki have stated that such operations are being used to assist the conversion of unstable shifting sands to productive pasture.

In the past however, monitoring of bioremediation at contaminated sites has usually been limited to chemical analysis of pollutants in the soil (Wilson & Jones 1993, Hubalek *et al* 2007). However, chemical analysis is not enough to evaluate the impacts of soil contamination on soil biota, nor the efficiency of clean up techniques (Molina-Barahona *et al* 2005, Paton *et al* 2005, Smith *et al* 2006), and cannot provide a full picture of the bioremediation process (Hubalek *et al* 2007).

At present, there is a paucity of information on "safe" concentrations and practices for land spreading in relation to soil ecosystems and biodiversity under different field conditions. Some studies have been carried out assessing the effects of hydrocarbons on soil biota but these have predominantly been conducted in a laboratory setting and do not account for site specific factors such as soil characteristics, environmental conditions and species. Another reason why chemical analysis is inadequate for assessing the impacts of land spreading on soil biota is that factors beside toxicity of contaminants can have negative effects on biota at land spreading sites. For example, the method of incorporating or applying drilling wastes to the soil may in some cases be more important than the contaminants within the waste. In Taranaki, the extent to which drilling wastes are tilled into the soil is variable. Studies have shown that tillage can sometimes negatively impact on earthworm abundance. Such impacts are most likely to result from mechanical damage to individuals or damage to habitats but the exact processes responsible have seldom been investigated (Chan 2001). Additionally, reduction in contamination is not always accompanied by reduced soil toxicity. In fact, in some cases, incomplete degradation and the formation of intermediary metabolites can lead to increased soil toxicity (Hubalek *et al* 2007). For example, a study by Hubalek *et al* (2007) found that inhibition of earthworm reproduction in hydrocarbon contaminated soil remained reasonably steady across the study period (17 months) despite total hydrocarbon concentrations decreasing by 65.5%.

Investigations of the impacts of land spreading on soil organisms and ecosystems has been rated overall as a very high priority by the National Science Strategy Committee in their "*Sustainable Land Management Strategy*" (1997). Additionally, the MAF report *"Towards Safeguarding New Zealand's Agricultural Biodiversity: Research gaps, Priorities and Potential Case Studies"* states that: *"In New Zealand, little is known about…the influence of waste/sewage spreading on ecosystems"*. Thus there is a lack of information to inform local authorities' decisions regarding the granting of resource consents, the surrender of consents and the formulation of consents.

Therefore, for the above reasons, and because biodiversity in agricultural ecosystems is important for maintaining essential ecosystem goods and services (nutrient cycling, maintenance of soil structure and fertility, degradation of pollutants, soil carbon sequestration, pollination), studies of the effects of land treatment of drilling wastes on soil ecology and biodiversity in Taranaki are prudent and valuable.

2. Methodology

2.1 Project objectives

This project was particularly motivated by a need to examine the potential implications of recent changes to consent conditions relating to chloride loading limits at some landfarms. This project also builds upon and complements previous projects undertaken by the Council which have investigated the effects of land spreading on earthworm populations (as an indicator taxon for the effects on soil biota in general). These previous investigations suggested that earthworm populations had been impacted upon by drilling waste application but that they were making a slow recovery.

Nematodes and microbes, being much smaller than earthworms, are likely to be substantially less vulnerable to the effects of tillage. Thus, they may be more sensitive indicators of the effects of contaminants on soil biota, regardless of what tilling practices were utilised. Additionally, monitoring these taxa will allow for a more comprehensive understanding of the effects of landfarming on soil biota and ecosystems.

2.2 Sample sites

Monitoring and sampling for this project was/is being undertaken at sites being landfarming under the following consents:

Held by BTW for Brown Road Landfarm

6867-1 To discharge drilling wastes [consisting of drilling cuttings and drilling fluids] from hydrocarbon exploration activities with water-based muds and synthetic-based muds, and oily wastes from hydrocarbon exploration and production activities, onto and into land via landfarming.

Held by Origin Energy Resources New Zealand Limited for Schrider landfarm:

6135 – 1 To discharge drilling cuttings and fluids from drilling operations with water-based muds, drilling cuttings from wells drilled with synthetic-based muds, and drilling cuttings and oily wastes from wells drilled with oil based muds, onto and into land via landfarming.

No resource consents were breached at any of the sites surveyed for this study (Origin Energy Resources NZ Limited, Drilling Waste Landfarms Annual Report, 2009-2010, FRODO# 829868).

Both sample sites are located on the coast. The Schrider landfarm is located on Lower Manutahi Road (unformed) in Manutahi, South Taranaki (N1719058, E5605067). The predominant soil type in sampled areas was sand. The Brown Road landfarm is located on Brown Road, Waitara in North Taranaki (N1703999, E5683454). The soil type in areas where sampling was undertaken was sand but this site also includes some areas of New Plymouth black loam at its southern end.

2.3 Sample design

2.3.1 Effects of landfarming on soil biota, soil chemistry and pasture yield over time

To examine the effects of landfarming on nematodes, microbes, soil chemistry and pasture yield, effect sizes (the magnitude of difference between treatment and control areas) were investigated by comparing pastures treated with water-based and synthetic-based drilling muds with control areas where tillage but no spreading of drilling wastes had occurred. Comparisons were undertaken within rather than between sites.

The effect of landfarming on microbe and nematode communities/populations over time was investigated by comparing areas where drilling muds had only recently been applied with results from the same areas one and two years later (sampled in 2010), and with results from areas where land spreading had been used 3 and 4 years previously (sampled in 2006 and 2007).

2.3.2 Effects of high chlorides after three to four years

To examine the effect of chlorides on nematodes, microbes, pasture yield and soil chemistry, effect size (the magnitude of difference between treatment and control) was compared between an area subject to a high chloride loading (water-based mud at Brown Road) and an area subject to a low chloride loading (water-based mud at Schrider) for both 2006 (August-October) and for 2007 (January/February).

2.3.3 Effects of high hydrocarbons after three to four years

To examine the effects of petroleum hydrocarbons on nematodes, microbes, pasture yield and soil chemistry, effect size (the magnitude of difference between treatment and control areas) was compared between an area subject to a high total petroleum hydrocarbon loading (synthetic-based mud spread at Brown Road in January/February 2007) and an area subject to a low total petroleum hydrocarbon loading (synthetic-based mud at Schrider in 2007).

2.4 Soil samples and analysis methods

2.4.1 Soil chemistry and microbes

Four 5x5m plots were set up at 5 metre intervals along transects within each of the treatment and control areas. 25 soil cores (75mm in length and 28 mm in diameter) were collected within each of these plots on August 9 and 10, 2010, and composited to form one sample per plot. The soil corer was cleaned with alcohol between treatments. Samples were sent to Landcare Research for analysis.

Samples were analysed for soil chemistry parameters, microbial biomass and microbial community composition by Landcare Research (see Appendix II for detailed analytical methodology and information on how microbial community composition is determined).

2.4.2 Nematodes

Within the same plots described for microbes and soil chemistry, plus an additional 5x5m plot, 10 soil cores (75mm in length and 28 mm in diameter) were collected and composited to form one sample per plot on August 9 and 10, 2010. Samples were sent to Lincoln University where they were analysed by Nicole Schon (PhD). Nematodes were extracted by the modified tray method described by Yeates (1978). Nematodes were counted, fixed by adding boiling 8% formaldehyde and mounted onto temporary slides for identification. Nematodes were identified to nominal genera and allocated to feeding groups following Yeates et al. (1993a; 1993b).

2.4.3 Pasture yield

Pasture yield was measured within the same 5x5metre plots used for microbes and soil chemistry (four plots per treatment). Plots were mown using a petrol lawnmower (mower blade was set at 60mm above the ground) and pasture mass (kilograms of dry matter per hectare) measured using an analogue Jenquip folding plate pasture meter (forty samples per plot) (Figure 1). Plots were then fenced with electric wire to exclude stock and left for 33-34 days before pasture mass was again measured using the rising plate meter (forty samples per plot) (Figure 2).

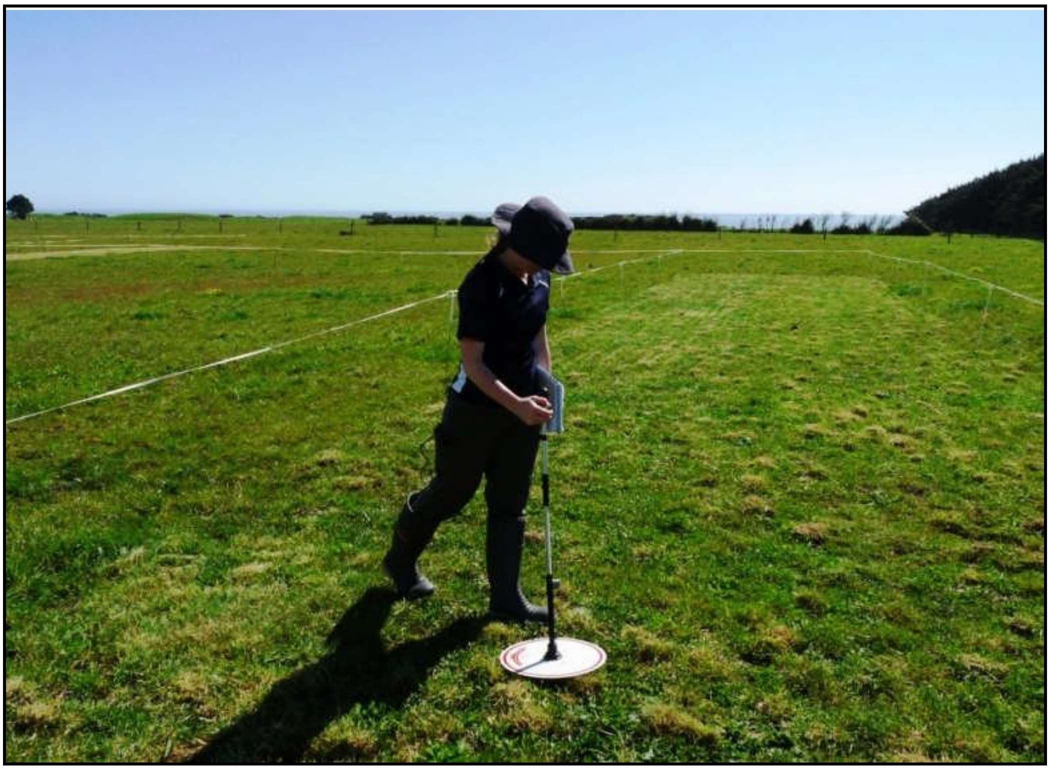

Figure 1 Council Officer measuring pasture mass using a folding plate metre within mown exclosure plots at the Brown Road landfarm

Figure 2 Exclosure plot at the Schrider landfarm after one month of stock exclusion

2.4.4 Bulk density

Soil bulk density provides a measure of soil moisture, water content, porosity, compaction, and structure, all of which influence the potential for plant growth and oxygen and water movement within the soil. One soil core (of a standard 418.5 cm^3 volume) was collected and analyzed for soil bulk density in each of the four 5x5metre plots used for microbes and soil chemistry, in both treatment and control areas. This provided four cores per treatment. Core contents were emptied into individual foil trays of known weight and dried in an oven at 105˚C for more than 24 hours.

2.5 Data analysis

Pasture yield in kg dry matter/hectare was calculated using a standard equation for Taranaki dairy pasture. A dry weight/volume formula was then used to calculate mean bulk density for each pasture sample. Soil chemistry, microbe and nematode results were compared between treatment and control plots at the landfarming sites to assess whether landfarming was having an impact on overall soil health and biodiversity. All results from the analyses of soil chemistry, microbes and nematodes were converted to a per m^2 basis using the pasture bulk densities calculated above. Additionally, for nematodes, mean nematode abundances were calculated, along with various population indices used to describe nematode community composition and diversity (see Appendix III for a more detailed data analysis methodology).

3. Results

3.1 Soil chemistry

At the Brown Road site, there were no statistically significant differences in soil moisture (water % v/v) between any of the control and treatment areas (Table 1). Additionally, pH levels in synthetic based mud treatment areas and control areas were not significantly different. However, there were statistically significant differences in pH between water based mud areas and both tilled and untilled control areas for both 2006 and 2007. In 2006, pH was significantly higher than the control areas, whereas in 2007 pH was significantly lower than the control areas. This may indicate that the fluctuation in soil pH may have varied due to natural processes rather than being influenced by the application of drilling wastes, as there was no distinct pattern in the changes occurring to pH in these areas across years. Soil pH has a strong influence on soil biota, including the community composition of macro-invertebrates and microbes. There were significant differences in electrical conductivity (EC) between synthetic based mud and water based mud areas in comparison to the untilled control area for both 2007 and 2010, but this difference was not apparent when compared with the tilled control area (Table 1). A difference in electrical conductivity would demonstrate that the salinity of the drilling wastes was having a negative impact on soil chemistry, but as this result was only apparent for the untilled control, it could be that tilling practices have a greater impact on soil salinity than the application of drilling wastes.

Organic carbon (C) levels in synthetic based mud (SBM) areas were significantly lower than untilled control areas for both 2007 and 2010. However, although 2007 SBM levels were not significantly different to the tilled control areas, C levels in 2010 had significantly decreased, resulting in a C level of almost half that of the tilled and untilled control areas (Table 1). Carbon levels at water based mud (WBM) treatment areas did not differ significantly from control areas. Total nitrogen (N) levels were also significantly less than both tilled and untilled control areas in the SBM areas for 2007 and 2010, although this difference was not apparent at WBM treatment areas (Table 1). The soil C/N ratio was significantly greater compared to the control area for the synthetic based mud 2007 area and water-based mud 2007 area, although this varied across sampling years and did not show a consistent pattern for different treatment areas (Table 1). A reduction in C or N generally leads to a reduction in soil quality, and thus it appears that carbon and nitrogen are being negatively affected by the application of synthetic based muds to the soil. However, water based muds do not appear to negatively affect carbon and nitrogen levels in the soil (Table 1).

Potassium chloride (KCl) was significantly lower in synthetic based mud areas compared to both tilled and untilled controls, and this was also the case for water based mud treatment areas in 2006, but not in 2007. Additionally, ammonium (NH_4) was significantly lower compared to the control area in synthetic-based mud areas in 2007, but levels of this chemical had increased in these areas in 2010 and were no longer significantly different from the control areas (Table 1). There were also some significant differences in phosphorus (P) across years in both synthetic based mud and water based mud treatment areas, and these differences appeared to increase with time (Table 1). Thus, it appears that the application of drilling wastes to soil may be negatively affecting the concentrations of these three chemicals (potassium chloride, nitrates and phosphorus) at the Brown Road landfarm, all of which are essential for healthy pasture growth. However, further soil analyses at this site (being undertaken in 2011/2012) should provide further clarification of these results.

At the Schriders site, there were no statistically significant differences in any of the measured chemical properties between water based mud 2006, water based mud 2007, synthetic based mud 2007 and the control area, with the exception of an increased pH and electrical conductivity for water-based mud in 2007 (Table 1). These results were the opposite to what was observed at the Brown Road site (higher pH and electrical conductivity at treatment areas compared to controls at Schriders landfarm). This may indicate that these differences occurred due to natural fluctuations in soil salinity, rather than due to the application of drilling wastes, although further sampling (being undertaken in 2011/2012) should elucidate these patterns.

Table 1 Mean soil chemistry results (± standard error) for treatments (SBM = synthetic-based mud, WBM = water-based mud) and controls at the Brown Road and Schrider landfarms across years. Differences in soil chemistry parameters were only assessed within each site and not compared across sites. Additionally, results were not compared between WBM and SBM treatments, but only between each treatment type and it's corresponding control plot.

Parameter (Unit of Measurement)	Water (%v/v)	pH	EC (Electrical Conductivity in mS/cm)	Organic C (Carbon in kg C/m^2)	Total N (Nitrogen in kg N/m^2)	C/N ratio (Ratio of carbon to nitrogen)	KCl (Potassium chloride in mg/m^2)	NH4 (Ammonium in mg/m^2)	P (Phosphorus in mg/m^2)
Brown Road Landfarm									
Untilled Control	48.6 (± 3.5)a	6.46 (± 0.03)b	0.09 (± 0.01)b	4.04 (± 0.36)c	0.39 (± 0.04)c	10.5 (± 0.1)a	1.68 (± 0.22)b	0.06 (0± .01)a	0.86 (± 0.03)a
Tilled Control	42.3 (± 10.9)a	6.73 (± 0.11)b	0.07 (± 0.01)a	3.02 (± 0.93)bc	0.28 (± 0.1)bc	11.2 (± 0.3)a	1.14 (± 0.22)b	0.03 (± 0.01)ab	1.63 (± 0.32)b
SBM 2007	39.3 (± 5.6)a	6.49 (± 0.02)b	**0.06 (± 0.01)a***	**2.00 (± 0.15)ab***	**0.16 (± 0.01)a***	**12.5 (± 0.3)b***	**0.20 (± 0.11)a***	**0.01 (± 0.01)b***	**2.11 (± 0.20)bc***
SBM 2010	33.3 (± 1.2)a	6.60 (± 0.04)b	**0.05 (± 0.00)a***	**1.51 (± 0.09)a***	**0.13 (± 0.01)a***	11.4 (± 0.1)a	**0.06 (± 0.01)a***	0.06 (± 0.06)a	**3.09 (± 0.10)c***
WBM 2006	42.3 (± 5.2)a	**6.95 (± 0.04)c***	**0.06 (± 0.01)a***	2.42 (± 0.37)c	0.22 (± 0.04)c	11.3 (± 0.2)a	**0.21 (± 0.09)a***	0.05 (± 0.01)a	**2.32 (± 0.15)b***
WBM 2007	38.5 (± 1.0)a	**6.09 (± 0.07)a***	**0.05 (± 0.00)a***	3.75 (± 0.31)c	0.26 (± 0.02)c	**14.4 (± 0.9)c***	1.25 (± 0.11)b	0.03 (± 0.01)a	**4.12 (± 0.85)c***
Schrider Landfarm									
Untilled Control	-	-	-	-	-	-	-	-	-
Control	21.6 (± 1.7)a	5.99 (± 0.03)a	0.04 (± 0.00)a	1.58 (± 0.33)a	0.14 (± 0.02)a	11.4 (± 0.4)a	1.65 (± 0.21)a	0.08 (± 0.04)a	3.34 (±0.11)a
SBM 2007	22.6 (± 1.8)a	5.95 (± 0.07)a	0.04 (± 0.00)a	1.16 (± 0.10)a	0.10 (± 0.01)a	11.4 (± 0.1)a	2.10 (± 0.09)a	0.31 (± 0.12)a	3.7 (± 0.63)a
SBM 2010	-	-	-	-	-	-	-	-	-
WBM 2006	23.7 (± 2.1)a	6.20 (± 0.08)a	0.04 (± 0.00)a	1.43 (± 0.25)a	0.12 (± 0.02)a	11.7 (± 0.2)a	2.13 (± 0.16)a	0.15 (± 0.09)a	2.46 (± 0.31)a
WBM 2007	26.3 (± 0.6)a	**6.97 (± 0.34)b***	**0.09 (± 0.02)b***	1.51 (± 0.04)a	0.13 (± 0.01)a	12.0 (± 0.3)a	1.89 (± 0.15)a	0.32 (± 0.02)a	3.10 (± 0.45)a

* Statistically significant differences between SBM treatments and controls, and WBM treatments and controls are highlighted in bold. The letters after each result indicate whether these treatments were different from tilled or untilled controls; where results share a letter they are not significantly different.

3.2 Microbes

At the Brown Road landfarm, mineralization of nitrogen (N) through microbial reactions in the synthetic based mud 2007 area was significantly lower than in both tilled and untilled control areas. However, nitrogen mineralization had increased in the 2010 samples and was at similar levels as the control (Table 2). Mean basal respiration was significantly lower for both years (2007 and 2010) in the synthetic-based mud areas, compared to the untilled control areas, but not the tilled control areas (Table 2). This indicates that tilling of the soil has a greater influence on microbial respiration than the application of drilling wastes *per se*. However, microbial biomass (MBC) was significantly lower in the synthetic based mud plots for both years compared with both tilled and untilled control plots, although this was not the case for water based muds. Thus, the application of synthetic based muds appears to have a negative effect on soil microbial biomass. Nitrogen mineralization and basal respiration were not different between water based mud and control areas at Brown Road. However, the ratios of microbial biomass to total carbon (MBC/TC) were significantly different in 2007 and microbial biomass to respiration (MBC/Respiration) were significantly different in 2006, although no definitive trends were apparent for these data (Table 2).

At the Schriders landfarm, there were no statistically significant differences between water-based mud areas and any of the soil parameters measured at the control areas (Table 2). However, the synthetic-based mud areas (2007) had significantly lower microbial biomass (MBC), MBC/TC and N mineralisation rates compared with the control areas. Respiration/MBC was significantly higher in synthetic-based mud areas compared to controls, but there were no significant differences for basal respiration rates between synthetic-based mud and control areas.

At Brown Road, virtually all measures of microbial community composition (i.e., total phospholipid fatty acid microbial biomass, fungal biomass, bacterial biomass, actinomycetes, Gram+ and Gram– bacteria), except for the fungal/bacterial ratio, were significantly lower in the synthetic-based mud area compared with the control area, for both years (Table 3). All elements of the microbial community appeared to be equally affected by the synthetic-based mud and this probably represents a dilution effect from the drilling mud application. The only parameter affected for both years at the water-based mud areas was the fungal/bacterial biomass ratio which was significantly higher in 2006 (but not 2007) than the control (Table 3).

However, it is important to note that the untilled control areas had significantly higher PLFA, bacterial biomass, fungal/bacterial ratio, Gram + and Gram -, and Actinomycete biomass compared to the tilled control areas (Table 3). This suggests that while the application of synthetic based mud appears to have a negative effect on microbial community composition, tilling practices may also be having a negative impact on soil microbes.

At the Schrider landfarm, almost all parameters of the microbial community structure (Total PLFA microbial biomass, bacterial biomass, actinomycetes, Gram + and Gram – bacteria) were lower in synthetic-based mud areas (Table 3). However, there were no significant differences between synthetic-based mud and control areas for fungal and protozoan biomass, and the fungal/bacterial biomass ratio (Table 3). Meanwhile, the only significant differences between control areas and water-based mud areas were significantly lower Actinomycete biomass in 2006, and a significantly higher Protozoan biomass for both years, in control areas (Table 3).

Changes in bacterial biomass will have impacts on soil decomposition rates, nutrient cycling and other processes important to soil health and viability. Overall, it appears that synthetic based mud application has a greater detrimental effect on soil microbial communities compared to water based mud application. However, further research in years 2 and 3 of this study will elucidate whether the fluctuations in microbial community composition observed in this preliminary study persist for several years, or whether physical parameters such as tilling practices are more influential than drilling waste application *per se*.

Table 2 Mean values (± standard error) for the microbial analysis of samples collected from treatment (WBM = water-based mud, SBM = synthetic-based mud) and control areas at the Brown Road and Schrider landfarms. Differences in soil chemistry parameters were only assessed within each site and not compared across sites. Additionally, results were not compared between WBM and SBM treatments, but only between each treatment type and it's corresponding control plot.

Parameter (Unit of Measurement)	56-day nitrogen mineralization (mg N/m^2)	Basal respiration (mgC/m^2/hr)	Microbial biomass (MBC) (mg/m^2)	Ratio of microbial biomass (MBC) to total carbon (TC) (x10^{-5})	Respiration/MBC
Brown Road Landfarm					
Untilled Control	5.07 (± 0.65)b	76.3 (± 6.3)b	61.8 (± 6.1)b	1.57 (± 0.22)b	1.30 (± 0.23)a
Tilled Control	4.13 (± 1.49)b	62.6 (± 12.8)ab	52.9 (± 15.2)b	1.78 (± 0.20)b	1.34 (± 0.24)a
SBM 2007	**1.37 (± 0.40)a***	**38.8 (± 6.7)a***	**25.2 (± 1.6)a***	1.28 (± 0.11)b	1.52 (± 0.21)a
SBM 2010	2.99 (± 0.42)b	**46.6 (± 5.0)a***	**20.8 (± 1.9)a***	1.38 (± 0.11)b	**2.23 (± 0.07)b***
WBM 2006	5.23 (± 0.24)b	88.3 (± 6.1)b	34.1 (± 3.4)b	1.46 (± 0.13)b	**2.62 (± 0.16)b***
WBM 2007	5.57 (± 0.44)b	54.2 (± 8.7)b	36.9 (± 0.7)b	**1.01 (± 0.10)a***	1.47 (± 0.23)a
Schrider Landfarm					
Untilled Control	-	-	-	-	-
Tilled Control	8.94 (± 0.81)b	67.6 (± 10.5)a	36.3 (± 3.5)b	2.44 (± 0.26)b	1.85 (± 0.20)a
SBM 2007	**6.39 (± 0.22)a***	57.1 (± 4.3)a	**19.9 (± 2.0)a***	**1.74 (± 0.14)a***	**2.88 (± 0.08)b***
SBM 2010	-	-	-	-	-
WBM 2006	7.10 (± 1.08)b	55.8 (± 13.7)a	29.3 (± 1.7)b	2.29 (± 0.46)b	1.93 (± 0.91)a
WBM 2007	8.41 (± 0.47)b	101.6 (± 2.0)a	34.9 (± 2.8)b	2.32 (± 0.18)b	2.97 (± 0.25)a

* Statistically significant differences between SBM treatments and controls, and WBM treatments and controls are highlighted in bold. The letters after each result indicate whether these treatments were different from tilled or untilled controls; where results share a letter they are not significantly different.

Table 3 Mean values (± standard error) for the results of Phospholipid Fatty Acid Analysis (PFLA) and microbial biomass analyses of samples collected from treatment (WBM = water-based mud, SBM = synthetic-based mud) and control areas at the Brown Road and Schrider landfarms.

Parameter (Unit of Measurement)	Total PLFA (mmol/m²)	Fungal biomass (mmol/m²)	Bacterial biomass (mmol/m²)	Fungal/Bacterial biomass Ratio	Actinomycete Biomass (mmol/m²)	Gram + Bacteria Biomass (mmol/m²)	Gram – Bacteria Biomass (mmol/m²)	Protozoan Biomass (mmol/m²)
Brown Road Landfarm								
Untilled Control	13.86 (± 1.07)c	0.20 (± 0.03)b	6.37 (± 0.51)c	0.032 (± 0.004)a	1.06 (± 0.08)c	3.57 (± 0.26)c	2.15 (± 0.20)c	0.042 (± 0.009)b
Control	9.08 (± 1.90)b	0.17 (± 0.03)b	3.93 (± 0.91)b	0.044 (± 0.004)b	0.64 (± 0.16)b	2.26 (± 0.50)b	1.30 (± 0.29)b	0.034 (± 0.007)b
SBM 2007	**5.01 (± 0.26)a***	**0.09 (± 0.02)a***	**2.07 (± 0.11)a***	0.043 (± 0.009)ab	**0.36 (± 0.02)a***	**1.27 (± 0.07)a***	**0.65 (± 0.03)a***	**0.011 (± 0.003)a***
SBM 2010	**5.02 (± 0.54)a***	**0.07 (± 0.01)a***	**2.00 (± 0.21)a***	0.037 (± 0.002)ab	**0.34 (± 0.04)a***	**1.24 (± 0.14)a***	**0.61 (± 0.06)a***	**0.008 (± 0.001)a***
WBM 2006	**7.01 (± 0.95)b***	0.19 (± 0.03)b	**2.73 (± 0.38)b***	**0.070 (± 0.002)c***	**0.39 (± 0.07)b***	**1.56 (± 0.22)b***	**1.01 (± 0.14)b***	0.034 (± 0.005)b
WBM 2007	**7.83 (± 0.56)b***	0.13 (± 0.01)b	**3.56 (± 0.30)b***	0.039 (± 0.005)ab	**0.58 (± 0.06)b***	**2.18 (± 0.19)b***	**1.05 (± 0.07)b***	0.022 (± 0.002)b
Schrider Landfarm								
Untilled Control	-	-	-	-	-	-	-	-
Control	4.59 (± 0.52)b	0.11 (± 0.01)a	2.01 (± 0.24)b	0.058 (± 0.007)a	0.33 (± 0.04)b	1.21 (± 0.15)b	0.61 (± 0.07)b	0.007 (± 0.000)a
SBM 2007	**3.15 (± 0.07)a***	0.08 (± 0.01)a	**1.36 (± 0.02)a***	0.058 (± 0.006)a	**0.19 (± 0.12)a***	**0.78 (± 0.01)a***	**0.45 (± 0.02)a***	0.010 (± 0.002)a
SBM 2010	-	-	-	-	-	-	-	-
WBM 2006	3.66 (± 0.44)b	0.09 (± 0.02)a	1.59 (± 0.19)b	0.054 (± 0.008)a	**0.20 (± 0.02)a***	0.87 (± 0.10)b	0.59 (± 0.08)b	**0.014 (± 0.006)b***
WBM 2007	4.66 (± 0.29)b	0.11 (± 0.02)a	2.00 (± 0.11)b	0.055 (± 0.007)a	0.23 (± 0.01)ab	1.05 (± 0.06)b	0.78 (± 0.05)b	**0.026 (± 0.005)b***

* Statistically significant differences between SBM treatments and controls, and WBM treatments and controls are highlighted in bold. The letters after each result indicate whether these treatments were different from tilled or untilled controls; where results share a letter they are not significantly different.

3.3 Nematodes (see appendix 2 for additional results)

Differences in mean nematode abundance between treatment and controls were much greater at the Brown Road landfarm (high chloride and high total petroleum hydrocarbons) than those at the Schrider landfarm (low chloride, low total petroleum hydrocarbons) (Table 4). Furthermore, all treatment areas at the Brown Road landfarm had lower mean nematode abundances compared with the control area (Figure 3). However, the large confidence intervals on Figure 3 suggest that differences between treatments areas and the control area were not statistically significant.

Table 4 Percent difference in mean nematode abundance (per m^2) between treatment (WBM = water-based mud, SBM = synthetic-based mud) and control areas (tilled) at the Brown Road and Schrider landfarms.

Site Type	Percentage difference between treatment and control	
	Brown Road	Schriders
WBM 2006	75.41	4.55
WBM 2007	40.06	35.83
SBM 2007	64.23	-8.44

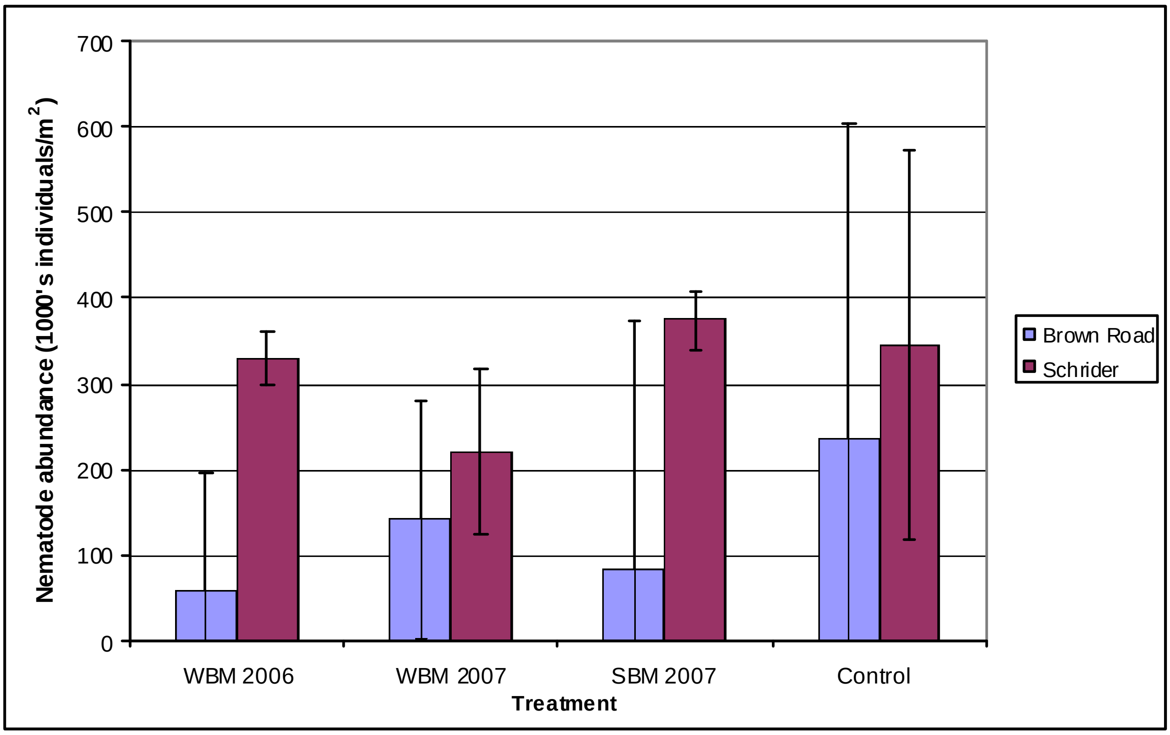

Figure 3 Mean abundance of nematodes (per m^2) in treatment (WBM = water-based mud, SBM = synthetic-based mud) and control areas (tilled) at the Brown Road and Schrider landfarms (N=5)

3.4 Pasture yield

There were no significant differences in pasture yield between treatment and control areas at both the Brown Road and Schrider sites, although the synthetic-based mud areas at both sites had relatively lower mean yields compared to the controls and water-based mud areas (Figures 4 and 5). However, it is important to note that plots at the Schrider landfarm site appeared to differ little in their floral species composition (primarily rye grass and clover), while results at the Brown Road landfarm may have been affected by differences species composition among treatment and control areas.

In particular, the tilled control and synthetic-based mud areas were observed to have a greater abundance of low growing weed species such as cape daisy and a greater abundance of oats as opposed to ryegrass and clover (see photos in Appendix 2).

Pasture yield was generally higher at the Schrider landfarm, despite this site having higher bulk density, a lower water content and lower concentrations of organic carbon (C), and total nitrogen (N) (Figures 4 and 5).

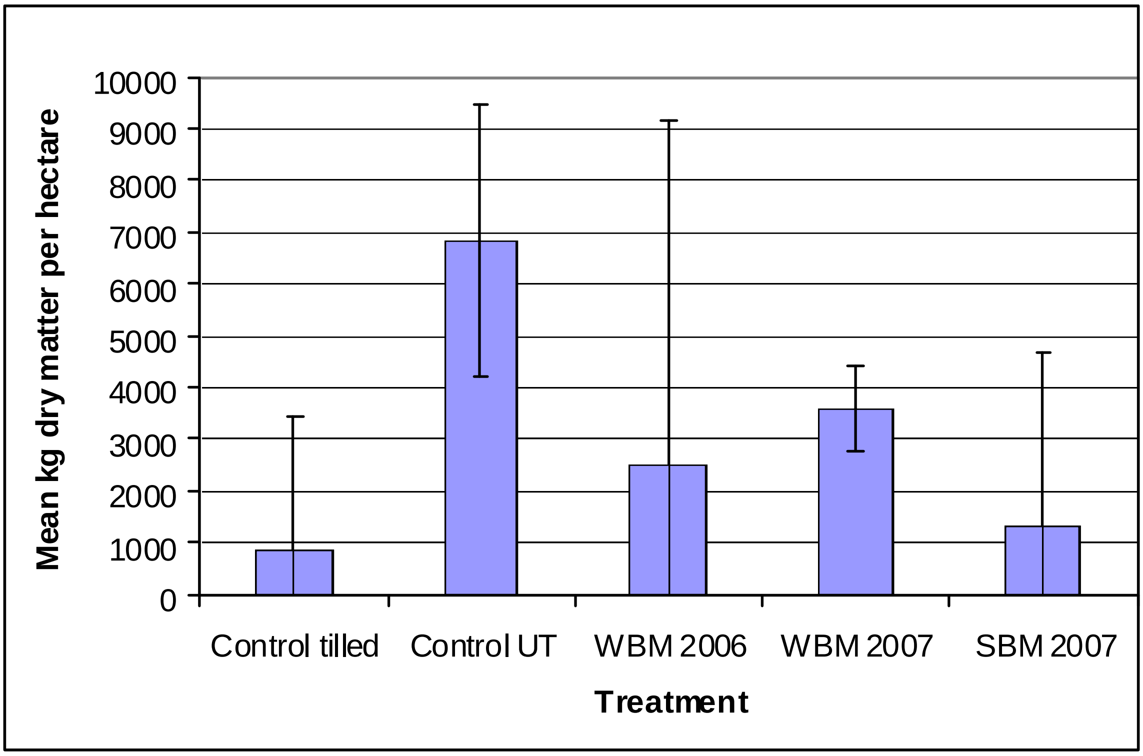

Figure 4 Mean pasture yield (kg dry matter per hectare) within treatment (WBM = water-based mud and SBM = synthetic-based mud) and control (control UT = control Untilled) areas at the Brown Road landfarm (N=4)

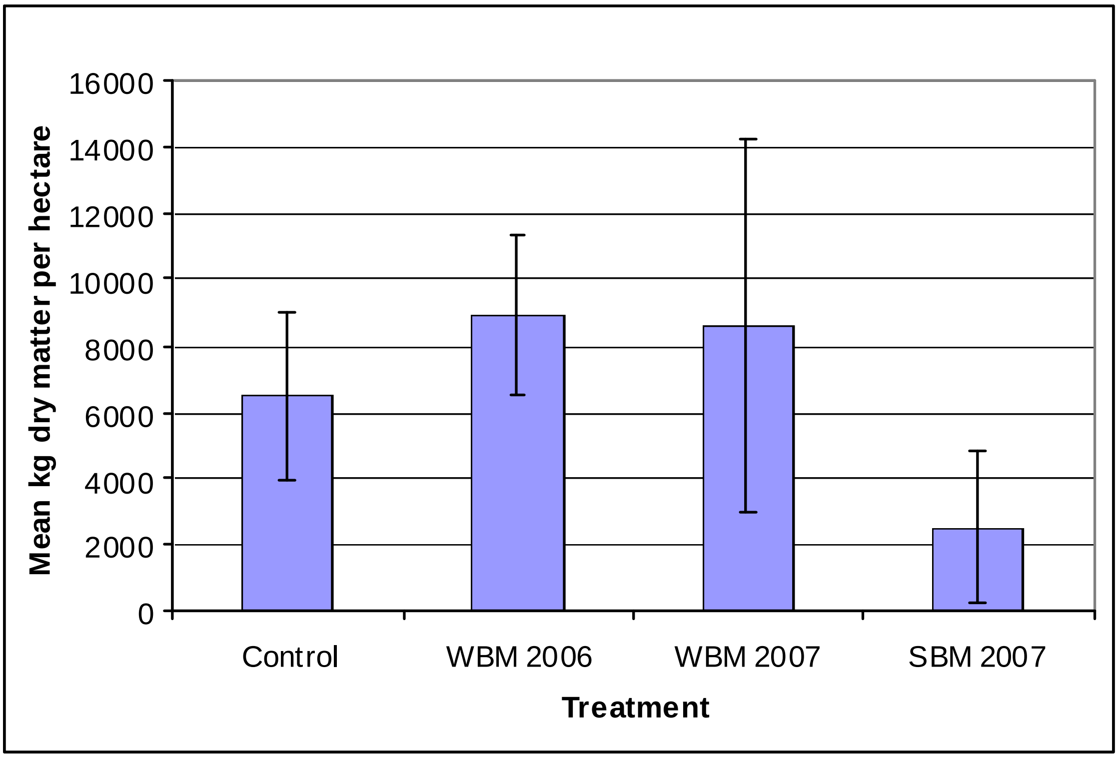

Figure 5 Mean pasture yield (kg dry matter per hectare) within treatment (WBM = water-based mud and SBM = synthetic-based mud) and control (untilled) areas at the Schrider landfarm (N=4)

3.5 Bulk density

Mean bulk density differed very little between treatments or between treatments and tilled controls for both the Brown Road and Schrider landfarms (Table 5). The untilled control at the Brown Road landfarm had a lower bulk density than both the treatment areas and the tilled control area, indicating that tillage has resulted in loss of soil structure and subsequent soil compaction (Table 5). Standard deviations (S.D.) are small for all areas, indicating that bulk density varied little across samples within treatment and control areas.

With the exception of the untilled control, bulk densities at both landfarms appear to be a lot higher than those typically found for Taranaki ring plain top soils (typically 0.7 - 0.8 T/m^3) (Table 5). Bulk density target ranges from Hill and Sparling (2009) suggest that tilled treatments and controls at these landfarms are *'very compacted'*.

Figure 6 Mean bulk density (T/m^3) (± S.D.) for treatment (WBM = water-based mud, SBM = synthetic-based mud) and control areas at the Brown Road and Schrider landfarms.

Site	Treatment	Bulk Density (± S.D.)
Brown Road	Untilled Control	0.95 (± 0.23)
	Tilled Control	1.31 (± 0.36)
	WBM 2006	1.33 (± 0.09)
	WBM 2007	1.29 (± 0.12)
	SBM 2007	1.30 (± 0.04)
Schriders	Control	1.80 (± 0.09)
	WBM 2006	1.70 (± 0.13)
	WBM 2007	1.80 (± 0.08)
	SBM 2007	1.82 (± 0.06)

4. Discussion and conclusions

Prior to discussing the results of these experiments, it is important to note that comparisons of effect sizes for soil biota and soil chemical parameters between areas subject to low chloride/hydrocarbon loadings should ideally have been made within landfarm sites (i.e. within Brown Road) rather than across landfarms sites (i.e. between Brown Road and Schrider). Unfortunately, a lack of available data on loading rates, differing disposal activities and tilling practices at each site, as well as lack of areas that were suitable for analyses meant that comparison within landfarm sites was not always possible or preferable. Soil compaction due to tilling at each site was higher than expected, and thus the changes observed in nutrient levels and microbial community composition may have been biased by this. Additionally, another sampling bias was introduced by the fact that it was impossible to determine whether drilling wastes had been spread evenly across the entire surface of the study site, or whether there were some areas within sites with differing levels of drilling waste application. As such, care must be taken in interpreting the results of this study, as this data only summarises the findings from the first of three sampling periods, the treatment effects (drilling mud type and date of application) were not replicated and sample sizes were low. Thus, significant differences in treatments could reflect differences in site characteristics or management differences between sites, rather than differences due to the effects of drilling waste application. Further research is required to elucidate any patterns emerging from these results, with more stringent controls for site-level variability. This project is due to run for a further 2 years, with samples being taken in both 2011/2012 and 2012/2013, which will provide further evidence for the patterns emerging from this study.

This study suggests that total carbon (C), nitrogen (N) and phosphate (P) levels in soil are affected by the application of synthetic-based muds from drilling wastes, and these changes persist 3 to 4 years after synthetic-based mud application. However, the fluctuations in levels of these nutrients varied over time, suggesting that synthetic-based mud application may be affecting nutrient cycling at different temporal scales, depending on the nutrient investigated. Carbon levels decreased with time post synthetic-based mud application, and were initially not significantly different from the tilled control areas (in 2007), although by 2010 carbon levels were almost half that in the tilled control areas. The untilled control areas had significantly higher carbon levels compared to synthetic based mud treatment areas in both 2007 and 2010. Nitrogen levels were significantly decreased immediately after mud application in 2007, and remained significantly lower than both tilled and untilled control areas throughout the study period. Phosphate, on the other hand, increased significantly immediately after synthetic-based mud application in 2007, compared to untilled controls, although again there was no difference between tilled control and treatment areas in 2007. However, phosphate levels remained elevated 3 to 4 years after landfarming, so that in 2010 phosphate levels in treatment areas were significantly higher than those in both tilled and untilled control areas. This pattern was also evident for phosphate levels in water-based mud application areas, but these differences may reflect management changes (e.g. liming or phosphate fertilisation) rather than any direct effects of drilling mud application. It is widely known that tilling practices result in the alteration of soil nutrient levels, regardless of whether areas subsequently undergo landfarming. The differences in nutrient levels between tilled and untilled control areas suggest that the fluctuations in nutrient levels observed in this study were confounded by the differing tilling practices at sites. Further research is required to provide definitive results as to whether drilling waste application (without the influence of differing tilling regimes) is causing changes in soil nutrient levels.

From this study, there appears to be little evidence that water-based muds with higher hydrocarbon and chloride concentrations have negative effects on microbe communities. However, synthetic-based drilling muds do appear to have negative effects on soil biota compared to control areas, for at least 3 to 4 years post mud application. The differences in the soil microbial community between synthetic-based mud sites and controls were greater than between water-based mud sites and controls, at both the Brown Road and Schrider sites, and these differences appear to persist for longer periods of time (although differences were more pronounced at Brown Road). The more pronounced differences in basal microbial respiration rates and microbial biomass carbon (MBC) in synthetic-based mud areas at Brown Road could be due to either a heavier rate of application or a specific characteristic of the synthetic-based mud, either of which could be diluting the microbial biomass upon application and inhibiting microbial recolonisation within the drilling mud particles over time.

Basal microbial respiration and MBC were both significantly negatively affected by the application of synthetic-based muds, but total N, nitrate-N and N mineralisation were also generally lower in synthetic-based mud sites, suggesting that nitrogen cycling may have been impacted by landfarming practices in these areas. However, there has been very little research on the levels of disturbance required to cause significant change to ecosystem function in microbial communities. Therefore, it is difficult to assess whether the above changes in the microbial community reflect changes in ecosystem functionality.

Significant negative effects arising from drilling waste application on soil nematode populations were not apparent from this study. Differences between treatment and control areas were greater at the high hydrocarbon/high chlorides landfarm (Brown Road), but there were no statistically significant differences between treatments and controls within landfarms. In general, there were more significant changes in soil characteristics on drilling mud sites in comparison to the control at Brown Road Landfarm than at Schriders Landfarm. However, these results are based on nematode abundances only, and this study did not assess whether nematode community structure and function is affected by drilling mud application.

Decreased pasture yield in synthetic-based mud areas would be an indication that changes to the microbial community and/or soil biota were affecting ecosystem functioning and nutrient cycling, but definitive trends were not apparent from this study, as the time between drilling waste application and pasture yield analyses may be too short-term to identify long-term patterns. However, initial results suggest no negative effect on pasture yield due to landfarming practices, for either water- or synthetic-based muds.

In conclusion, it appears that there may be some statistically significant differences in soil characteristics and soil biota between untreated control areas and areas with synthetic-based muds applied, for carbon, nitrogen and phosphate levels, and microbial respiration and biomass in particular. At present, pasture yield and nematode abundances do not appear to be affected by landfarming practices. Therefore, in ecological terms, the effects on soil biodiversity due to landfarming practices may be subtle rather than substantial. However, further research, with increased replication at both site- and treatment-levels is required to elucidate any long-term trends arising from the application of drilling wastes to pasture.

5. Recommendations

It is clear from this study that tilling is having a major negative effect on soil biota, as all soils surveyed in this study were heavily compacted. This is to be expected in highly modified pasture land, and it is difficult to assess whether tilling or drilling waste application are the main contributing factors to the changing soil nutrient levels, and/or soil biota, or whether a combination of both is causing the changes observed. Water based mud application appears to have relatively minor effects on soil, within the short timeframes and limitations of this study, which have been discussed above. However, synthetic based mud application appears to be having relatively larger subtle and ongoing effects. Notably, pasture yield was not negatively affected by drilling waste application.

It therefore appears that the Council's controls on such activities, via resource consent conditions, are well-judged. However, pending the results of years 2 and 3 of this study, the council may need to review the consent conditions imposed thus far on synthetic based mud application at landfarms, which would most likely involve reducing the current spreading levels, and/or measures to ensure that drilling waste application is equally spread across treated areas. Thus, it is recommended that the sampling at these sites scheduled for 2011/2012 and 2012/2013 continue (years 2 and 3 of the study), in order to monitor and assess the long-term patterns and effects on soil post-landfarming operations. Years 2 and 3 of this study should focus on increasing the replication levels in tilled and untilled control and treatment areas, and more detailed assessments of the management practices at each site, so that the sampling biases identified thus far can be reduced in the future.

It is also recommended that research be carried out on the application of fracking wastes at landfarming sites, as the chemical composition of these wastes compared to synthetic and water based muds needs to be clarified, as does their effect on soil nutrient levels, biodiversity and health. A project brief has been completed for this work (FRODO # 930194), and sampling of these sites will begin in due course. It should be noted that initial laboratory analyses suggest that fracking wastes have much lower hydrocarbon loadings compared to those found in the synthetic and water based muds applied during this study (see 'Landfarm Results – Self Monitoring' spreadsheet, FRODO document # 360675, and FRODO documents # 929999 and # 930001).

Glossary

Aromatic hydrocarbons A large class of organic compounds whose molecular structure usually includes six carbon atoms bound together tightly in a ring, the most well known compound of which is benzene (C_6H_6). Crude oil, diesel and conventional mineral oils contain high proportions of aromatic hydrocarbons.

Bulk density Bulk density is a measure of soil compaction. Compacted soils will not allow water or air to penetrate, do not drain easily, restrict root growth and can have adverse effects on plant growth. Compact soils increase the potential of run-off and nutrient losses to surface waters.

Control plot An untreated sample plot or area which is used as a baseline to compare with treated areas in scientific studies

Drilling muds Oil and gas wells may be drilled with oil based mud (OBM), synthetic based mud (SBM) or water based mud (WBM). More than one type may be used to drill an individual well. Barium sulphate is added to most drilling muds as a wetting and weighting agent.

Exclosure plot An area or plot that has had stock excluded from it so that no grazing can occur.

Fracking Hydraulic fracturing or "fracking" is an extraction method for petroleum and gas products, which involves injecting chemicals, sand, and water under high pressure directly into shale deposits deep underground. The shale deposits are fractured during this process and natural gas is released from them.

Mean The average value of a set of values, which is derived statistically

Microbial biomass The mass of microbial life in a given sample or area.

Mineralisable N Organic nitrogen potentially available for plant uptake and activity of soil organisms. Not all nitrogen can be used by plants; soil organisms change nitrogen to forms that plants can use. Mineralisable N gives a measure of how much organic nitrogen is available to the plants, and the potential for nitrogen leaching at times of low plant demand. Mineralisable nitrogen is also used as a surrogate measure of the microbial biomass.

Nematode Nematodes are a type of roundworm belonging to the phylum Nematoda. They are the most numerous multicellular animals on earth and a handful of soil will contain thousands of these microscopic worms. Many .nematodes are parasites of insects, plants or animals although free-living species are also abundant, including nematodes that feed on bacteria, fungi, and other nematodes. Thus, they are an important component of soil ecosystems and food-webs, and can therefore provide useful information on soil health and biodiversity.

Oil based mud Oil based mud is composed primarily of non-aqueous fluids with high aromatic hydrocarbon levels. These fluids are refined from crude oil, diesel and other mineral oils, and typically contain aromatic hydrocarbon levels of 5-35%. The use of oil based muds (diesel/crude oil based) has declined since the 1980s due to their ecotoxicity, and they have been replaced by synthetic based mud.

Olsen P Phosphorus (P) is an essential nutrient for plants and animals. Plants get their P from phosphates in soil. Many soils in New Zealand have low available phosphorus, and P needs to be added to soils used for agricultural purposes. Depletion of nutrients shows that soils are being `mined' and, if so, current land use may require maintenance applications of fertiliser.

Phospholipid Fatty Acid (PLFA) Analysis is widely used in microbial ecology as indicators for the presence of bacteria and other organisms. Phospholipids are the primary lipids composing cellular membranes. Once the phospholipids of an unknown sample are analyzed, the composition of the resulting PLFA can be compared to the PLFA of known organisms to determine the identity of the sample organisms.

Soil pH Most plants and soil animals have an optimum pH range for growth. Indigenous species are generally tolerant of acid conditions but introduced pasture and crop species require a more alkaline soil. Some heavy metals may become soluble and bioavailable at low pH.

Standard deviation The estimated error in a series of measurements, which is derived statistically.

Synthetic based mud Synthetic based mud is composed primarily of non-aqueous esters and processed mineral oils, which contain less than 0.5% aromatic hydrocarbons and less than 0.001% polycyclic aromatic hydrocarbons.

Total C & N Total carbon (C) is a measure of organic matter content. Organic matter helps soils retain moisture and nutrients, and gives good soil structure for water movement and root growth. Nitrogen (N) is an essential nutrient for plants and animals. Most N in soil is in organic matter and total N gives a measure of those reserves. The ratio of C to N can indicate the type of organic matter returned to the soil.

Treatment plot A sample plot or area which has undergone a specific treatment, and which is then compared with an untreated control area in scientific studies

Water based mud Water based mud is composed primarily of brine or water, with clays and other chemical components making up less than 25% of the total by weight. Oil and gas wells may be drilled with oil based mud (OBM), synthetic based mud (SBM) or water based mud (WBM). More than one type may be used to drill an individual well. Barium sulphate is added to most drilling muds as a wetting and weighting agent.

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Appendix I

Site details

Table 1.1 Site details, treatments and GPS co-ordinates for exclosure plots

Site	Treatment	Area	Plot	Northing	Easting
Brown Road[1]	Control tilled		1	1703928	5683315
Brown Road	Control tilled		2	1703923	5683325
Brown Road	Control tilled		3	1703920	5683334
Brown Road	Control tilled		4	1703915	5683342
Brown Road	Control un-tilled		1	1703919	5683293
Brown Road	Control un-tilled		2	1703916	5683304
Brown Road	Control un-tilled		3	1703912	5683313
Brown Road	Control un-tilled		4	1703909	5683324
Brown Road	WBM 2006	B1	1	1704202	5683434
Brown Road	WBM 2006	B1	2	1704198	5683442
Brown Road	WBM 2006	B1	3	1704195	5683451
Brown Road	WBM 2006	B1	4	1704190	5683459
Brown Road	WBM 2007	B3	1	1704251	5683435
Brown Road	WBM 2007	B3	2	1704198	5683442
Brown Road	WBM 2007	B3	3	1704229	5683446
Brown Road	WBM 2007	B3	4	1704227	5683455
Brown Road	SBM 2007	B4	1	1703997	5683340
Brown Road	SBM 2007	B4	2	1703995	5683350
Brown Road	SBM 2007	B4	3	1703991	5683360
Brown Road	SBM 2007	B4	4	1703988	5683369
Schrider[2]	Control tilled		1	1719171	5605372
Schrider	Control tilled		2		
Schrider	Control tilled		3	1719181	5605378
Schrider	Control tilled		4 (up)	1719184	5605381
Schrider	WBM 2006	H30	1 (south)	1719354	5605157
Schrider	WBM 2006	H30	2	1719357	5605193
Schrider	WBM 2006	H30	3	1719349	5605200
Schrider	WBM 2006	H30	4 (north)	1719342	5605209
Schrider	WBM 2007	H41	1 (south)	1719205	5605309
Schrider	WBM 2007	H41	2	1719198	5605319
Schrider	WBM 2007	H41	3	1719195	5605327
Schrider	WBM 2007	H41	4 (north)	1719191	5605339
Schrider	SBM 2007	H39	1 (south)	1719247	5605210
Schrider	SBM 2007	H39	2	1719244	5605220
Schrider	SBM 2007	H39	3	1719239	5605227
Schrider	SBM 2007	H39	4 (north)	1719235	5605233

[1]Average yearly rainfall recorded at the hydrological monitoring station nearest to the Brown Road site (Motunui) for the previous five years (2005 - 2010) was 1339.2 mm. Total rainfall for September 2009 to September 2010 and the period 10 August to 10 September was 1566.0 mm and 144.0 mm respectively. Average soil moisture for the period September 2009 to September 2010 and the period 10 August to 10 September was 31.27% and 35.67% respectively, while average monthly soil temperature for the period September 2009 to September 2010 and the period 10 August 2010 to 10 September 2010 13.57 °C and 10.75 °C respectively.

[2]Average yearly rainfall recorded at the hydrological monitoring station nearest to the Schriders site (Patea) for the previous five years (September 2005 – September 2010) was 1058.8 mm. Total rainfall for September 2009 to September 2010 and the period 10 August to 10 September was 1074.5 mm and 120.0 mm respectively. Average soil moisture for the period September 2009 to September 2010 and the period 10 August to 10 September was 28.02% and 33.47% respectively, while average monthly soil temperature for the period September 2009 to September 2010 and the period 10 August 2010 to 10 September 2010 was 13.83 °C and 10.43 °C respectively.

Appendix II

Details of soil analyses conducted by Landcare Research

Soil chemistry

Landcare Research used standard methods for soil analyses, as presented in Blakemore *et al.*, (1987) to determine a range of physical and chemical characteristics of the soil sampled. In brief, the following chemical parameters were examined:

1. pH was determined from a 1:2.5 soil to water extract
2. Electrical conductivity (EC) was determined from a 1:5 soil to water extract.
3. Ammonium (NH_4) and nitrate (NO_3) were analysed from a 2-molar (2M) potassium chloride (KCL) extract.
4. Phosphorus (Olsen P) was determined from a 0.5-molar sodium bicarbonate extract at pH8.5.
5. Total Carbon (C) and Nitrogen (N) were analysed by combustion on a Leco CHN analyser (Leco Laboratory Equipment Corporation, St. Joseph, Michigan, USA).
6. Aerobic net mineralisable N was determined by subtraction of initial minus final NH_4 and NO_3 after incubation of soil at -10kPa moisture at 20°C for 56 days.

More specific details can be found at
http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabtest_list.asp

Microbes

Samples analysed for soil chemistry were also used by Landcare Research in assessing the microbial parameters within the soil, including basal microbial respiration and microbial biomass. The composition of the microbial community was also assessed by phospholipid fatty acids analysis (PLFAs), using the method of Bligh and Dyer (1959), as modified by White *et al.* (1979) and used by Bardgett *et al.* (1996). Phospholipid fatty acids (PLFA) are a main component of the cell membrane of all microbes. PLFA's can be separated from one another using chemical analyses, and each microbe has a slightly different PLFA signature (almost like DNA), so that a picture of the differing microbes in a sample can be formed, which gives information on microbial community composition.

In brief, the following protocols were utilised to examine soil microbes:

1. Microbial biomass carbon (C) was determined by the chloroform fumigation extraction method and used a K_{ec} of 0.41 to convert extractable C to microbial biomass C.
2. Lipids were extracted from 1.5 g of fresh soil, fractionated, methylated, and the resulting fatty acid methyl esters analysed using GCMS (Agilent 7890A GC with Agilent 5975C VL MSD). Resulting peaks were identified using retention times relative to two added internal standards (C13 and C19) and a bacterial methyl ester standard mixture (Supeloc Bacterial Acid Methyl Esters CP Mix 47080-U). Peak size was quantified using the FAME 19:0 internal standard and the abundance of each of the individual phospholipid fatty acids (PLFAs) extracted expressed as relative ηmoles per g of dry soil using standard nomenclature (Tunlid *et al.*, 1989; Frostegård *et al.*, 1993a, b).
3. Certain PLFAs from (2) above were then used to calculate bacterial biomass. PLFA markers used for this purpose were: i-15:0, a-15:0, 15:0, i-16.0, i-17:0, cy-17:0, and 18:1ω7c.

4. The 18:2ω6 marker (Parekh and Bardgett 2002) was used as an indicator of fungal biomass.
5. The ratio of fungal PLFA to bacterial PLFAs was used as an estimate of the relative dominance of bacterial and fungal biomass (Bardgett *et al.* 1996, Parekh & Bardgett 2002). Gram positive bacteria were considered i-15:0, a-15:0, i-16.0, i-17:0, a-17:0; Gram negative bacteria cy-17:0, and 18:1ω7c, actinomycetes 10Me16:0 and 10Me18:0 (O'leary & Wilkinson, 1988; Zak *et al.*, 1996). Additionally, the 20:4 marker has been suggested as an indicator of protozoa (Lechevalier & Lechevalier, 1988), but it has not been verified to reflect abundance in soil as opposed to pure culture. It has been included since the study involved counts of mesofauna but should be treated with caution.

Appendix III

Data analysis

Data were log transformed when necessary. The synthetic-based mud and water-based mud plots were analyzed by one-way ANOVA separately with control and treatment plot means compared by protected Least Significance Difference (LSD) testing ($P < 0.05$).

Pasture yield (in kg dry matter/hectare ± 95% confidence intervals) was calculated using the following standard equation for Taranaki dairy pasture:

$$[(Y-X)/Z]*158 + 1000 = \text{Kg Dry Matter per Hectare}$$

Where Y = final reading, X = initial reading and Z = the number of samples taken per paddock.

Mean bulk density (± standard deviation) for each sample was then calculated using mass of oven dried soil/total soil volume. All results from the analyses of soil chemistry, microbes and nematodes were converted to a per m^2 basis using the soil bulk densities calculated.

Additionally, for nematodes, mean nematode abundances (± standard errors or 95% confidence intervals) were calculated, along with the following population indices used to describe nematode community composition and diversity: the Nematode Channel Ratio (NCR), Maturity Index (MI), Plant Parasitic Index (PPI) and Σ Maturity Index (ΣMI) (Bongers 1990; Yeates 1994; 2003). The Shannon-Wiener diversity index (H') was also calculated to describe the diversity of soil fauna (Ludwig and Reynolds 1988; Yeates 1984).

Appendix IV

Photos of exclosure plots

Photo Exclosure plot in water-based mud 2006 area treatment area at Brown Road landf arm after stock exclusion for a period of one month

Photo Exclosure plot in water-based mud 2006 area treatment area at Brown Road landf arm after stock exclusion for a period of one month.

Photo Exclosure plot in the synthetic-based mud 2007 treatment area at the Brown Road landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the synthetic-based mud 2007 treatment area at the Brown Road landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the control (tilled) area at the Brown Road landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the control (tilled) area at the Brown Road landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the control (un-tilled) area at the Brown Road landfarm after stock exclusion for a period of one month

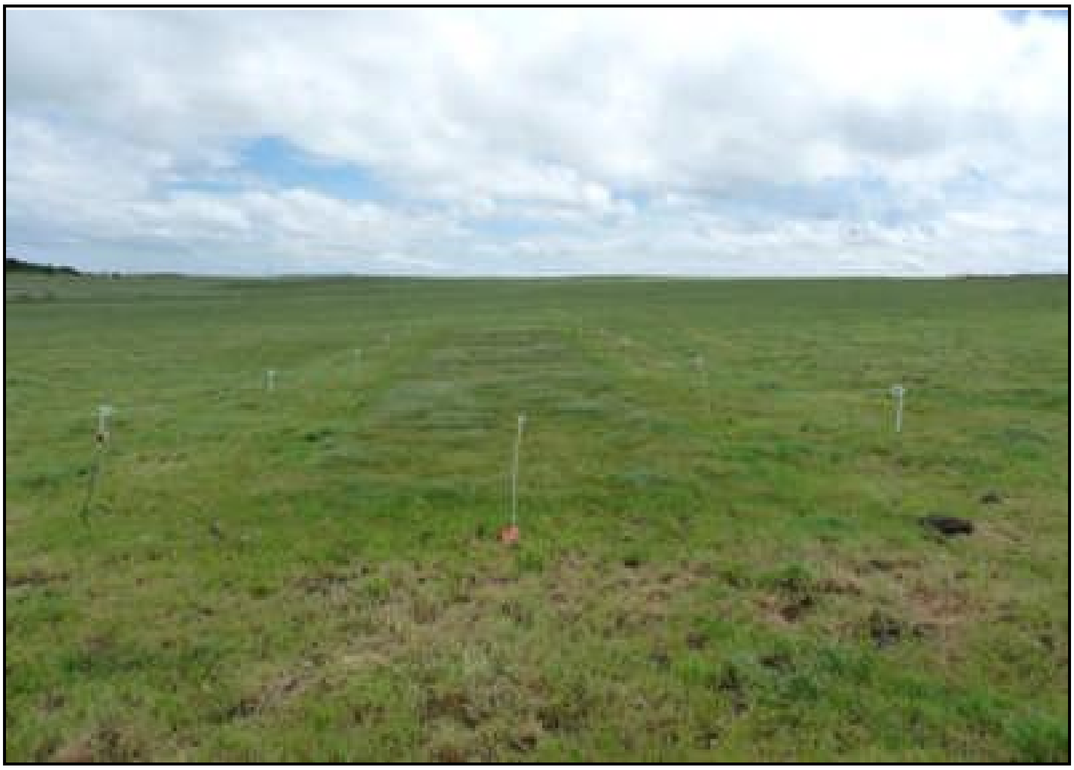

Photo Exclosure plot in the synthetic-based mud 2007 treatment area at the Schrider landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the water-based mud 2006 treatment area at the Schrider landfarm after stock exclusion for a period of one month

Photo Exclosure plot in the water-based mud 2006 treatment area at the Schrider landfarm after stock exclusion for a period of one month

Appendix V

Additional nematode results

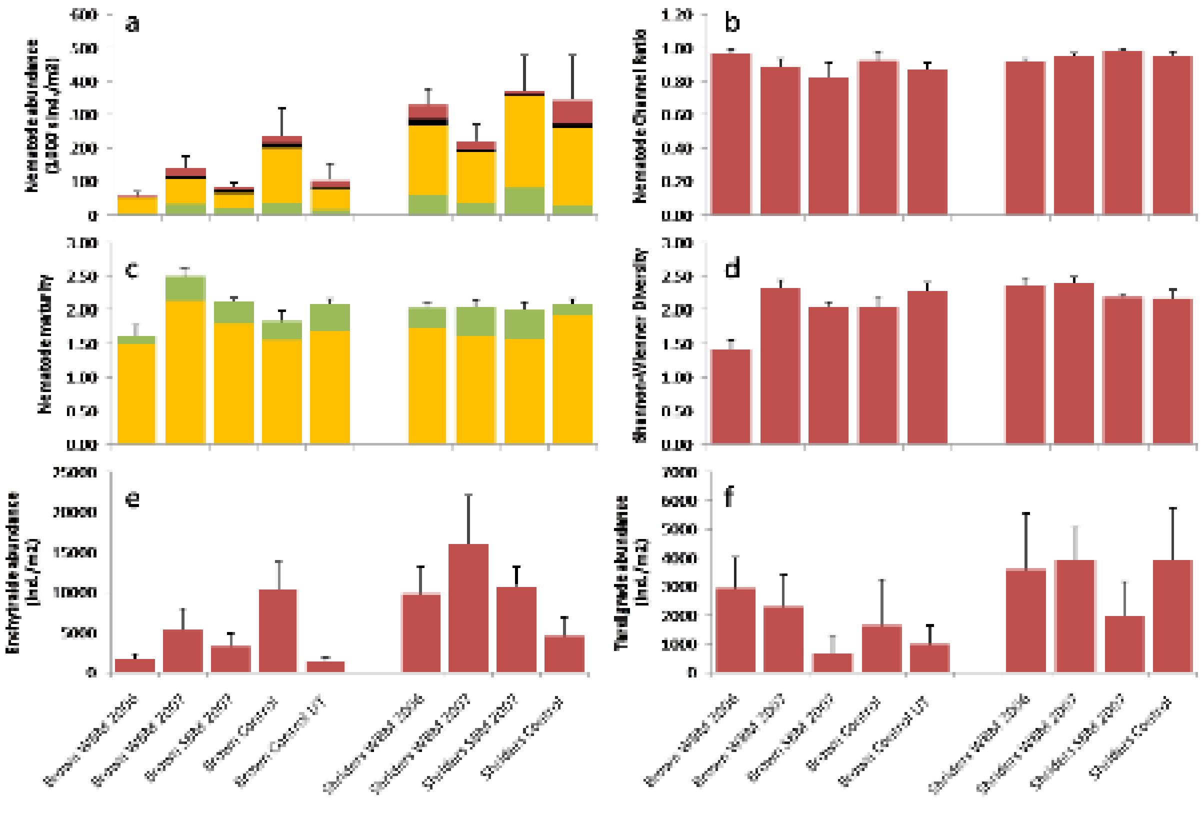

Figure 3.1 Features of the invertebrate community: (a) Abundance of nematode trophic groups; green: plant, yellow: bacterial, black: fungal, red: predator; (b) Nematode Channel Ratio; (c) Nematode ∑Maturity Index; yellow: Maturity Index, green: Plant Parasitic Index; (d) Nematode Shannon-Wienner diversity index; (e) Enchytraeidae abundance; (f) Tardigrada abundance.

Appendix VI

Chloride & hydrocarbon loadings/concentrations in treatment and control areas

Table 4.1 Chloride loadings, Chloride soil levels 2 months post spreading, total petroleum hydrocarbon (TPH) loadings and total petroleum hydrocarbon (TPH) soil levels 2 month after spreading for sampling areas

Date spread	Mud	Parameter	Units	Brown Road	Schrider
Control	n/a	Chloride load	kg/ha	n/a	n/a
		Chloride soil	mg/kg dry wt	est. 5	est. 5
		TPH load	kg/ha	n/a	n/a
		TPH soil	mg/kg dry wt	est. < 50	Est. < 50
Aug/Oct 2006	WBM	Chloride load	kg/ha	38,408 (B1)	7550 (H30)
		Chloride soil	mg/kg dry wt	341 (B1)	38 (H30)
		TPH load	kg/ha	807.6 (B1)	? (H30)
		TPH soil	mg/kg dry wt	90 (B1)	? (H30)
	SBM	Chloride load	kg/ha	n/a	n/a
		Chloride soil	mg/kg dry wt	n/a	n/a
		TPH load	kg/ha	n/a	n/a
		TPH soil	mg/kg dry wt	n/a	n/a
Jan/Feb 2007	WBM	Chloride load	kg/ha	38,408 (B3)	938 (H41)
		Chloride soil	mg/kg dry wt	248 (B3)	78 (H41)
		TPH load	kg/ha	807.6 (B3)	31182.12 (H41)
		TPH soil	mg/kg dry wt	820 (B3)	320 (H41)
	SBM	Chloride load	kg/ha	2750 (B4)	? (H39)
		Chloride soil	mg/kg dry wt	995 (B4)	23 (H39)
		TPH load	kg/ha	65882.1 (B4)	? (H39)
		TPH soil	mg/kg dry wt	17100 (B4)	230 (H39)
Jan Feb 2010	WBM	Chloride load	kg/ha	n/a	n/a
		Chloride soil	mg/kg dry wt	n/a	n/a
		TPH load	kg/ha	n/a	n/a
		TPH soil	mg/kg dry wt	n/a	n/a
	SBM	Chloride load	kg/ha	tbd	n/a
		Chloride soil	mg/kg dry wt	tbd	n/a
		TPH load	kg/ha	tbd	n/a
		TPH soil	mg/kg dry wt	tbd	n/a
May 2010	WBM	Chloride load	kg/ha	n/a	tbd
		Chloride soil	mg/kg dry wt	n/a	tbd
		TPH load	kg/ha	n/a	tbd
		TPH soil	mg/kg dry wt	n/a	tbd
	SBM	Chloride load	kg/ha	n/a	n/a
		Chloride soil	mg/kg dry wt	n/a	n/a
		TPH load	kg/ha	n/a	n/a
		TPH soil	mg/kg dry wt	n/a	n/a