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Drilling Fluid Design and the use of Vermiculture for the Remediation of Drill Cuttings

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Abstract

A wide variety of hydrocarbon-based drilling fluids are used in drilling operations and while the issues of biodegradability and toxicity have been extensively discussed with regard to the offshore environment, there are also concerns about the impact of these invert emulsion fluids on the terrestrial environment.

In order to address these concerns, new drilling fluids and their associated treatment technologies have been designed that go beyond minimizing impacts of mud and cuttings as waste and move toward using them as a beneficial by-products.

This paper discusses the selection of base fluids, salts, and other components combined with the use of earthworms to remediate the drill cuttings and create a beneficial by-product. Drilling performance of the fluid is reviewed as is biodegradation results from the field test vermiculture studies.

Introduction

While a number of novel drilling fluid systems have been developed in recent years, their design has mainly focused on the technological and environmental challenges of operating in the offshore environment. Even though the same fluid systems can be used to drill wells on land and there has been some work done on the type and amounts of salts used in fluids for land operations, their environmental profile has never been fully optimized. It is generally accepted that, while it is possible to apply various techniques such as bioremediation and thermal desorption to the destruction and removal of hydrocarbons, it is not always as easy to remediate and negate the environmental problems caused by the salts used in the brine phase.

The disposal of the cuttings can be a major issue in land drilling, particularly in remote areas and in most countries; regulatory limits on the electrical conductivity of salts, total oil and grease, and heavy metals make the remediation of cuttings to regulatory approved levels a slow and lengthy process.

The high-performance, synthetic-based, invert emulsion drilling fluid, described in this paper, is engineered with chemicals specifically chosen for their biodegradation and toxicity characteristics. It is designed for cost-effective drilling and gives all the performance benefits of these types of fluids but has been specifically designed to degrade using land-based bioremediation techniques, such as landfarming, composting, slurry phase bioreactors, and biopiles with minimal organic and inorganic residues.

Worm-driven bioremediation, or vermidigestion, is a novel method of treating organic waste. An interesting feature of the process is the generation of a valuable organic-type fertilizer that can be utilized to enhance plant growth.

The aim of this study is to demonstrate that the worms facilitate the rapid degradation of the hydrocarbon base fluid and subsequently process the minerals present in the drill cuttings incorporating them into the worm cast.

Worm-cast material has valuable properties as a fertilizer and it is thought that the process may provide a novel alternative solution to the drill-cuttings-disposal problem.

Optimal benefit is obtained from the synergistic use of the new drilling fluid system and vermiculture technology, the worms being used to add value to the cleaned cuttings and further reduce disposal costs.

Drilling Fluid Design

The original aim of the development of this type of fluid was to design a drilling fluid system that does not negatively impact the soil when the cuttings are spread on land. The fluid should also be readily and rapidly degraded leaving no or minimal organic residues, and not rely upon chloride-type salts for the brine phase.

It is also intended that the fluid generate drill cuttings that actively enhance the soil quality and subsequent plant growth.[1,2] Environmental tests carried out at the University of Calgary on various base fluids and aged drilling fluids formulated using different types of weight materials and internal brine phases[3] indicated that linear paraffin-type base fluids combined with either nitrate or acetate type brine phases would give the best combination of environmental and drilling performance. The technical performance of all the drilling fluids were evaluated and then thoroughly tested prior to environmental testing which included the following tests:

1. Alfalfa seed emergence and root elongation.
2. Earthworms (*Eisenia fetida*) toxicity
3. Springtail (*Folsomia candida*) toxicity.
4. Microtox toxicity
5. Biodegradability (Respiration rate and hydrocarbon loss in moist soil.)

Technical Performance During Field Trials

The primary selection criteria for the drilling fluid was enhancement of production from tight gas sands, an additional criteria being the increased shale inhibition available from the use of synthetic-based drilling fluids (SBM) when compared to water-based fluids (WBM). This reduced the risk of well bore stability problems that had been experienced in previous wells. Additional benefits include increased rates of penetration (ROP) and fluid stability for high-pressure formations and subsequent high-weight requirements.

Field Trial 1

The synthetic-based drilling fluid used in New Zealand employed a linear paraffin as the base fluid, calcium ammonium nitrate as the internal phase and barite as the weight material. The technical performance of the new fluid system was assessed in the laboratory prior to the field trial. The results obtained in the laboratory tests and the technical performance is discussed in more detail by Curtis, *et al*.[1] and Norman, *et al*.[4]

The fluid was introduced in a field where high weight WBM ranging from 16 – 19 lb/gal was traditionally used at depths around 1000 m with hole problems experienced, including but not limited to:

- Extremely reactive plasticene clays, squeezing up the inside of the casing,
- Formation of “mud rings”
- Significant borehole ballooning
- High background gas and gas kicks
- Numerous hole packoffs due to tectonics, *e.g.* 3 – 4-in. pieces of wellbore popping off into the annulus
- Minimal hole tolerance to formation pressure balance, *i.e.* a fine line between gains and losses
- Fluid rheology problems at high weights
- Induced fractures due to high equivalent circulating density (ECD)
- Water flows
- No logs successfully run
- Difficulty in running casing
- Resultant fluid cost contributed to 30% of the AFE total well budget

Eleven wells had previously been drilled in the area with WBM and all experienced extensive hole problems. Alternative systems were considered and the newly engineered “bioremediation-friendly” SBM was chosen based on the selection criteria discussed previously.

The previous well was originally drilled using a WBM which resulted in three stuck pipe incidents, two sidetracks, significant torque and overpull, ballooning from plastic clays, numerous packoffs, high rheologies due to high Methylene Blue cation exchange capacities, and difficult wiper trips. The well never reached TD and had to be plugged and abandoned due to poor hole conditions. It took 28 days to drill to 1150 m.

The next well was drilled with the new synthetic system. The results surpassed expectations. A depth of 2544 m was achieved in only 34 days. No drilling problems were experienced and torque and drag was reduced. The hole was successfully logged with the caliper indicating gauge hole, and hole integrity was maintained during a five-day, open-hole testing program. This had not been achieved in previous wells.

Additional wells have since been drilled in this area using the same fluid and with minimal hole problems and cheaper overall drilling fluid costs compared to the previous WBM wells. The paleontology results are the best the operator has seen and all holes have reached TD with efficient casing runs and logging. Hole conditions are still difficult but the combination of experience, good drilling practice, and the “bioremediation-friendly” synthetic mud system has contributed to a successful ongoing drilling program. Skin-irritation levels are very low by comparison with other synthetic- and oil-based systems that have been used in other countries – the first incidence of skin irritation was reported 22 days into the program. Strict adherence to a good occupational hygiene program including barrier cream, nitrile gloves, and disposable coveralls greatly reduces the chances of irritations.

Field Trial 2

Field Trial 2 incorporated the use of worm-driven waste management to remediate the drill cuttings. An advantage of this field trial was the fact that the fluid was used in an 8½-in. sidetrack of a wellbore, originally drilled with a KCl/Glycol water-based mud, thus conditions for comparison were ideal.

Traditional drilling fluid weights for wells in this area are 9.2 – 11 lb/gal using highly inhibitive WBM’s. Although hole problems are generally less in this area as compared to the area drilled in the first Field Trial, there were still a few challenges such as:

- Highly reactive, tectonically stressed shale bands, causing excessive cavings

- Interbedded clays dispersing into the system and creating concerns with rheology
- Slow ROP's through the lower section of the hole
- Considerable borehole breakout due to openhole exposure time.
- Seepage losses to limestone
- Coal stringers
- Excessive trip times due to reaming and back reaming of open hole sectioning

The 8½-in. hole was drilled in 47 days using a WBM, including a four-day fishing run, with a section length of 3005 m. Average ROPs through the lower section of the hole were 2 – 4 m/hr. Hole washout was extensive and difficult trips were experienced. The logs could not be run to the bottom. The high MBT of the system required increased dilution requirements.

After plugging back and displacing to the synthetic fluid, the hole was drilled ahead with cuttings transported to the worm farm. Drilling was fast and 22 days into drilling, the depth was greater than that of the original well, reducing 26 days off the previous time curve. By day 25, the well had reached a depth of 4800 m with no hole problems experienced, minimal overpull and drag, and no logging or tripping incidents. The logs revealed an in-gauge hole. The system was stable and only one incidence of skin irritation was reported. The cuttings were collected in a direct collection bin at the base of the auger outlet and transferred to a tip truck after blending with bulking material (sawdust) to facilitate transport.

Although the drilling fluid and the handling of cuttings associated with the running of SBM were costly, the resultant reduction in rig downtime considerably offset these costs. The only negative aspect, noted to date, of this type of fluid system is the ammonia smell generated by the calcium nitrate, which contains trace amounts of ammonia as a result of the manufacturing process. This results in an uncomfortable emission of ammonia as it dissipates at the shakers. Other internal phase salts are being considered at this time to eliminate this effect.

Drill Cuttings Waste Management

Drill cuttings were mixed with sawdust (45% w/w; **Fig. 1a and b**) to facilitate transport and then delivered to the vermiculture site near New Plymouth, New Zealand where they were blended (**Fig. 2a and b**) with paunch waste (undigested grass) from a slaughterhouse before being fed to the worm beds using an agricultural feed-out wagon of the sort used for feeding silage to livestock (**Fig. 3**).

Preparation of the Feed Mixture

Successful degradation of organic materials by worms is dependent upon maintaining optimal environmental conditions for the worms, the most important parameters being the carbon/nitrogen ratio (25:1) and moisture content (75%).

The drill cuttings were blended and mixed with the paunch material at variable ratios and then combined with water giving a 50:50 v/v water:solids slurry that could be evenly distributed from the feedout wagon. Blending and mixing of the drill cuttings, paunch wastes, green wastes and water was performed on a bunded concrete pad that is approximately 30 m by 15 m in diameter, giving 450 m^2 for controlled waste mixing. The mixing and was carried out in a Marmix combined mixing and feed-out wagon, the three internal augers of the trailer being used to ensure thorough mixing.

Application to the Worm Beds

Once the blended material had been prepared it was loaded into a watertight feed-out wagon for application as feedstock for the worms to process in mounds referred to as windrows (**Fig. 4**). The windrows were 88 m in length by 3 m wide. There are two meter-wide access tracks between each of the windrows for access of the feed-out wagon to apply the mixed material, and also to allow for ongoing maintenance of the windrows and the subsequent vermiculture production processes.

The blended material was applied to the center/top of the windrows, usually once a week at an average depth of 15-30 mm. The exact application rate depends upon climatic conditions and is higher in summer than winter. The worms "work" the top 100 mm of each windrow, consuming the applied material over a five- to seven-day period. Once the test materials had been applied, the worm beds were fed on a weekly to 10-day basis with unamended paunch material as part of the normal worm-driven waste-management routine carried out at the site.

Maintenance of the Worm Beds

Each of the windrows is covered completely by a polypropylene-backed felt mat which excludes light from the worm bed and, although semi-permeable to water, the polypropylene backing deflects heavy rainfall away from the surface of the bed and prevents the windrow from becoming waterlogged. This is important as it maintains an optimal aerobic environment for the worms to work in.

The windrows were also fitted with a controlled irrigation system that could be used to keep the covers moist and maintain the correct moisture content during periods of low rainfall.

As the use of worms for degradation of the mixture is an aerobic process, the windrows are aerated prior to each feeding procedure to ensure aerobic conditions within all of the beds and maintain optimal conditions for the worms and their associated microbial processes. The aerator is attached to the power take-off linkage on the tractor and side arms guide any material (vermicast) back onto the beds, ensuring no windrow exceeds the width to be covered by the felt mat.

Harvesting the Vermicast

Once the worms have degraded the waste and converted the applied material into vermicastings (worm castings), the vermicast organic fertilizer is harvested using an industrial digger and is then packaged for distribution and use on agricultural and horticultural land as a beneficial fertilizer and soil conditioner.

Vermicast Applications

Vermicast is well known for its fertilizer properties[5,6] and has applications within both agriculture and horticulture, but it still remains to be seen what effect the inclusion of drill cuttings has on the fertilizer properties of the final product.

Experimental Design

Currently three experiments have been performed to evaluate the effect of worm farming on the remediation of drill cuttings.

The first experiment was a relatively simple feasibility study, which looked for evidence of a decrease in hydrocarbon concentration in samples taken from a worm bed to which drill cuttings had been applied.

Norman, *et al.*[4] discussed the results of this initial test but it will also be reviewed in this paper to put the results in full context. Following on from the first experiment, it was decided to perform a number of more comprehensive experiments to further study the process. Two subsequent experiments have been carried out, the first during the antipodean winter, the second during the New Zealand summer months.

The primary aim of the second experiment was to repeat the initial work under more defined conditions and study the effect of different cuttings application rates on the process (**Table 1**).

In addition to monitoring hydrocarbon concentrations within the worm beds, a wide variety of soil chemistry parameters were also measured. As the barite weight material contains a number of heavy metals and earthworms are known to be liable to bioaccumulate such materials,[7-9] it was also decided to evaluate the fate of the heavy metals from the drilling fluid in the worm beds.

As the second experiment was carried out during the New Zealand winter, under environmental conditions which do not favor high rates of activity by the earth worms, it was decided to repeat the experiment a third time under more favorable (summer) environmental conditions.

Because the two highest application rates used in the previous experiment did not favor efficient remediation of the drill cuttings, the experiment was repeated using only the two lower application rates; 30% w/w drill cuttings and 50% w/w drill cuttings.

Sampling and Analytical Procedures

Initial Experiments

50-mL grab samples were taken at time zero and then at approximately weekly intervals throughout the course of the experiment. Samples were transported by overnight courier to the analytical laboratory in Hamilton, New Zealand where they were stored at 4°C prior to analysis. The samples were analyzed for total petroleum hydrocarbons (TPH) content according to the New Zealand Oil Industries Environmental Working Group (OIEWG) guidelines and recommendations.[10]

Once in the laboratory, the samples were ground with dry ice (Cryogrinding) prior to sub-sampling and subsequent analysis. Samples for TPH determination were extracted using dichloromethane and sonication. The extracted samples were then dried with silica prior to analysis by GC-FID,[10] the detection limit of the procedure used by the laboratory being 60 mg/kg.

Second Experiment

Triplicate core samples were taken randomly and on an approximately weekly basis from a (6-m x 3-m) sub-section of each of the 5 research windrows using 60-mm diameter plastic core tubes. The core tubes were screwed all the way to the base of the windrow to ensured the sample contained any hydrocarbon material that might have migrated vertically down through the windrow, either as a result of leaching or mechanical or biological movement and transport

All samples were analyzed for TPH content with more detailed soil chemistry and heavy metal analysis (**Appendix 1**) being performed on the time zero and 60-day (termination) samples to study the effect of the process on nutrient and heavy metal concentrations.

Seasonal variations in temperature were recorded, as they are climatic factors that could influence rates of hydrocarbon degradation in the worm beds.

Third Experiment

Initially six core samples were taken from each of the treatment areas (total sample weight approx 1 kg), and combined together at the test site in large mixing container. The samples were then thoroughly mixed prior to removal of a 250 – 300-g composite sub-sample, which was sent for analysis. After five days, the applied material appeared to be well distributed across the windrow and the number of core samples was reduced to four. The mixing and sub-sampling procedure remained the same.

All samples were analyzed for TPH content with more detailed soil chemistry and heavy metal analysis (Appendix 1) being performed on the time zero and termination samples to study the effect of the process on nutrient and heavy metal concentrations.

Seasonal variations in temperature were also recorded.

Results

First Experiment

In the initial experiment discussed in Norman, *et al.,*[4] the hydrocarbon concentrations decreased from 4600 mg /kg (dry wt) to less than 100 mg/kg (dry wt) in under 28 days with less than 200 mg/kg (dry wt) remaining after 10 days in what appears to be a fairly typical exponential-type degradation curve (**Fig. 5**).

The bulk of the hydrocarbons detected were comprised of C_{10} – C_{14} aliphatic hydrocarbons (**Table 2**), which is in good agreement with the carbon-chain-length distribution of the C_{12} – C_{17} linear paraffin blend used in this drilling fluid and indicates that there were no external sources of contaminating hydrocarbons.

There was no detectable excess mortality amongst the worms that were fed the drill cuttings and although the numbers were not quantified, there appeared to be a definite preference among the worms for the area where the cuttings and paunch feed had been applied. It is not clear if this was due to the hydrocarbons attracting the worms or the increased availability of easily assimilated organic carbon/microbial biomass that would be associated with the highly biodegradable linear paraffins of the drill cuttings.

It was also noted that there was complete physical degradation of the cuttings by the vermidigestion process and none of the original intact cuttings could be found, the original cuttings size being 5 –10 mm in diameter.

Second Experiment

Again there was no visual mortality among the treated earthworms and the hydrocarbon “fingerprint” matched the applied base fluid. It was also apparent that the applied drill cuttings mix caused the worms to actively seek out the clumps on material containing drill cuttings (**Fig. 6**).

Total Petroleum Hydrocarbons

From the results shown in **Fig. 7**, it can be seen that the background hydrocarbon samples were around the detection levels for the method for the duration of the experiment indicating that there were no significant external sources of hydrocarbons being added to the worm beds apart from the test material

Due to the heterogeneous way in which the cuttings were applied to the worm bed, some of the initial samples taken were very variable and this is reflected in the data points for the TPH results shown in **Fig. 7**. However taken overall, a number of general trends can be seen.

The hydrocarbons in the cuttings applied at 30% w/w decreased from an average of 1900 mg/kg to less than 60 mg/kg within 45 days

The hydrocarbons in the cuttings applied at 50% w/w decreased from an average of 2100 mg/kg to the detection limit within 45 days but then showed a slight increase for some, unknown reason, although it may be related to the heterogeneity of the worm bed and sampling variation.

The hydrocarbons in the cuttings applied at 70% w/w showed quite a clear trend and decreased from an average of 20,000 mg/kg to 1500 mg/kg within 45 days but there was no subsequent reduction in the hydrocarbon concentration after this time.

After the initial degradation of the cuttings applied at 70% w/w, it was found that the clumps of cuttings and feed mixture within the worm bed had dried out and become compacted making them unpalatable to the worms. As the worms were no longer breaking down the cuttings, it is thought that the remaining degradation is microbially driven and is not expected to be particularly fast given the unfavorable conditions for bacteria and lack of moisture within the cutting/feed mix clumps. It also means that as the worm beds continued to be fed with unamended paunch material, the worms feeding zone moved away from the cuttings. This further reduced the rate of hydrocarbon degradation, as the process is no longer being facilitated and accelerated by the worms.

The hydrocarbons in the cuttings applied at 100% w/w (i.e. without any paunch amendments) did not show any obvious degradation throughout the course of the experiment (60 days). It is thought that this is because the consistency of the cuttings (mixed with sawdust to facilitate transport) combined with that lack of paunch material (which constitutes a large part of the worm “normal” diet) makes the unamended mixture of cuttings and sawdust very “unappealing” to the worms. This means that the worms don’t eat the cuttings and the rates of hydrocarbon degradation are much reduced.

Overall the rates of hydrocarbon degradation were slower in the second experiment than in the first and this is thought to be due to the prevailing weather and climatic conditions.

The importance of the worms in enhancing the rates of hydrocarbon degradation is shown by the much slower rates of decrease in hydrocarbon concentration (**Table 3**) in samples of cuttings blended with paunch material that were in parts of the windrow that were inaccessible to the worms and were not tilled and aerated.

Soil Chemistry

Looking at the pH data shown in **Fig. 8**, it can be seen that there is slight increase in pH as more cuttings are applied to the worm bed and that the pH tends to be slightly higher at the end of the experiment. This would be caused by the slightly alkaline nature of the drill cuttings and base fluid and the release of the lime from the drilling fluid emulsion as it is broken down. The increase in pH is not sufficiently high as to adversely affect the earthworms.

The remaining soil chemistry results (**Figs. 9 – 14**) are not quite as easy to interpret.

Electrical conductivity is a measure of the total salt or ion content within the sample and can have significant effects on soil properties such as the cation exchange capacity, etc. From time zero on, the electrical conductivity can be seen to generally increase (**Fig. 9**) as more cuttings are applied. This probably reflects the use of calcium ammonium nitrate in the brine phase of the drilling fluid; the more cuttings added the higher the electrical conductivity. At the end of the experiment the electrical conductivity is constant for all the windrows to which drill cuttings were applied. This suggests that either the bacteria or earthworms have utilized the calcium ammonium nitrate in the remediation process. It is not clear why the electrical conductivity in the control (no added drill cuttings) should differ at the start and finish of the experiment. This trend is confirmed by the other soil chemistry data for nitrogen-containing materials (**Figs. 11, 12 and 13**).

As mentioned previously, the nitrogen- and phosphorous-containing compounds, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen and phosphate phosphorous do not show readily discernable individual trends (**Figs. 11, 12, 13 and 14**). However, taken overall, it can be seen that the concentration of these elements, which are essential for microbial degradation and growth[11] decrease over the course of the experiment as they are consumed by the bacteria and converted into microbial and earthworm biomass as part of the degradation process.

Heavy Metals

The barium concentrations shown in **Figs. 15 and 16** reflect the amount of drilling fluid and cuttings added to the windrows (the barium is present as barium sulfate in the drilling fluid weight material) and were used as a conservative marker to ensure that the hydrocarbons were being degraded within the cuttings pile and that there was no loss of the cuttings through physical removal.

Looking at the time zero barium concentrations in **Fig. 15**, it can be seen that, as would be expected, as more cuttings are added to the worm bed, the barium concentration increases. It is not clear why, after a single application of drill cuttings, the barium concentration at the end of the experiment (T=60 days) should be higher than the initial starting concentration. Currently we do not have an explanation for these phenomena, although it may be caused by improved sample homogeneity as the worms broke down the paunch and cuttings materials.

Whilst the barium concentrations for each of the windrows remained broadly comparable at the start and finish of the experiment, the hydrocarbon concentrations in all but the 100% w/w cuttings addition showed a marked decrease in TPH concentration (**Fig. 16**) indicating degradation of the hydrocarbons but no physical loss of the drill cuttings from the windrows. This indicates that the cuttings were being degraded in the worm beds.

Heavy metal bioaccumulation

As earthworms are known to accumulate heavy metals within their tissues,[7-9] 3-g samples of earthworms were analyzed for heavy metal content at the end of the experiment. Most of the metal concentrations remain fairly constant at the different cuttings application rates (**Fig. 17**). However, there is a slight increase in the lead concentration within the earthworm tissues coupled with a more obvious increase in the barium concentration in the 30%, 50% and & 70% w/w additions. It is interesting to note that the barium and lead levels show a slight decrease at highest rate of addition (where there was very little biological "working" of the cuttings), presumably because the worms were not ingesting the cuttings in large amounts therefore there was less bioaccumulation. This reduced rate of activity in the 100% addition may also explain some of the other variations in nutrient levels, etc.

Third Experiment

As the climatic conditions for the winter experiment did not favor maximum rates of degradation in the worm beds and there were concerns about the variability of some of the TPH samples it was decided to repeat the experiment a third time under more favorable environmental conditions using a composite sampling procedure as discussed above.

Again there was no visual mortality of the worms and they appeared to actively seek out the clumps of drill cuttings.

Total Petroleum Hydrocarbons

As in previous experiments no significant background hydrocarbon concentrations were found (**Fig. 18**), whilst the 30 and 50% application rates showed significant degradation of hydrocarbons to background levels within 30 days (**Fig. 18**). The initial results for the cuttings applied at 30% w/w are somewhat misleading due to incorrect analytical procedures being used for these samples. The original samples from this treatment were incorrectly air dried at 35°C, resulting in the loss of some of the volatile hydrocarbon fractions. However, in spite of this anomaly, a clear decrease in hydrocarbon concentration can still be seen.

The increased rate of degradation for the third experiment compared to the second experiment (**Fig. 19**) show the advantages of favorable environmental conditions, specifically the effect of the temperature in the worm beds (**Fig. 20**), which is considerably higher in the New Zealand winter.

Soil Chemistry

The soil chemistry parameters for the third experiment were also somewhat inconclusive (data not shown). There did appear to be similar trends to those observed in the second experiment, *i.e.*, a general decrease in the nitrogen- and phosphorous-containing compounds as they are used up in the microbial degradation process.

Heavy Metals

As in the second experiment, barium concentrations in the samples increased when drill cuttings were applied, but the limited number of samples analyzed for barium at the start and finish of the experiment make it difficult to draw any firm conclusions.

The worms did show an increase in a number of heavy metals after feeding on material containing drill cuttings and barite weight material (**Table 4**) but it is not clear if the heavy metals were found in the worms gut or tissues even though the worms were fasted for 24 hours before sampling in an attempt to remove the internal castings before sampling. This length of time might not be sufficient to purge the gut contents.

Conclusions

- Results indicate, that under the correct conditions, there is substantial degradation of the hydrocarbons within the worm bed, although at this point in time it is not yet clear exactly what the biological mechanism is.
- Factors such as temperature are known to have significant effects on worm husbandry and were shown to effect rates of hydrocarbon degradation.
- As might be expected from our knowledge of the microbial degradation of hydrocarbons, a number of the more bioavailable soil nutrients such as nitrate and phosphate decreased as the hydrocarbons were degraded.
- Heavy metal concentrations in the resulting worm cast increased at higher application and feeding rates and there is some indications of heavy metal bioaccumulation, which requires further study, or the use of alternative weighting materials.
- Good husbandry of the worms appears to be the key to success of the process
- Cuttings additions of 30 — 50% appear to be optimum. Any higher and the cuttings and hydrocarbons are less available to the worms or are unpalatable (100% w/w) and are not degraded.
- Cuttings which are unpalatable to the worms will eventually become buried in the worm cast as more food is applied to the worms beds and move out of the feeding zone, forcing the degradation to be purely microbial and hence slower if the conditions within the cuttings "pats" are unfavorable for microbial degradation.
- Given the amount of worms available for treating organic wastes at the treatment site, the approximate amount of cuttings that can be treated at a 30% w/w feeding regime equates to about 800 tonnes per month depending upon the time of year.
- Optimum benefit is obtained from the synergistic use of drilling fluids designed for bioremediation and vermiculture technology, the worms being used to add value to the cleaned cuttings and further reducing disposal costs.

Future Work

The worm farm in New Zealand is now routinely adding 20% w/w drill cuttings to their worm beds and there has not been any evidence of decline in consumption rates or volumes with the combination of cuttings, and no apparent detriment to the worm population at this point in time

Although it can be seen from these results that hydrocarbons are degraded in the worm bed there still remain a number of important questions to be answered so that we can better understand the degradation process and fate of the heavy metals associated with the drill cuttings.

We need a better knowledge of the way in which the hydrocarbons are degraded in the worm beds. Possible hypothesis include microbial degradation within the worm beds, favorable aerobic conditions being generated by the burrowing and mixing activities of the worms; metabolism of the hydrocarbons by the worms; a symbiotic relationship between the bacteria in the earthworm gut degrading the hydrocarbons on the ingested cutting particles, or perhaps a combination of these mechanisms.

We need to better understand the effect of the process on the fate of the heavy metals associated with the cuttings and their impact on the final quality of the worm cast.

It is also important that we further develop our sampling and analysis procedures so as to better confirm degradation of the hydrocarbons and fully understand their fate.

As worm cast has been shown to have beneficial properties as an agricultural fertilizer, we also propose to perform further studies to determine the role of the clays and minerals present in the cleaned drill cuttings may have on the horticultural properties of the worm cast.

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Table 1 Experimental design, second experiment

Treatment 1	Bed #4	Control, no drill cuttings, Paunch only
Treatment 2	Bed #2	30:70 (w/w) drill cuttings: paunch material
Treatment 3	Bed #3	50:50 (w/w) drill cuttings: paunch material
Treatment 4	Bed #5	70:30 (w/w) drill cuttings: paunch material
Treatment 5	Bed #1	100% drill cuttings; no paunch

Table 2 - Initial results rate of degradation and hydrocarbon chain length distribution

Carbon No	Days						
	0	4	10	13	19	21	28
C7-C9	<80	<50	<8	<7	<7	<20	<20
C10-C14	4600	2700	140	127	82	<30	<40
C15-C36	<300	<200	<30	40	<30	<60	<80
Total	4600	2700	150	170	110	<100	<100

Table 3 - TPH concentrations (OIEWG carbon banding; mg/kg) in cuttings amended samples not degraded by worms

	30% cuttings	70% cuttings	100% cuttings
Day 1	33000	81000	120000
Day 46	19000	34000	71000

Table 4 - Background heavy metal concentrations

	Background concentration			Concentration in worms fed 50% w/w cuttings after 35 days	
Zinc (mg/kg)	27.6	27.6	28.5	23.7	23.6
Copper (mg/kg)	3.0	2.7	3.3	6.1	5.5
Arsenic (mg/kg)	3.6	3.6	3.6	3.1	3.5
Mercury (mg/kg)	<0.04	<0.03	<0.05	<0.03	<0.03
Barium (mg/kg)	2.31	0.79	1.39	256	243
Cadmium (mg/kg)	0.19	0.36	0.15	0.19	0.21
Chromium (mg/kg)	<0.2	<0.2	<0.3	1.4	1.3
Nickel (mg/kg)	<0.4	<0.3	<0.5	0.8	0.7
Lead (mg/kg)	<0.1	<0.09	<0.2	0.4	0.36

Fig. 1a - Collecting the drill cuttings.

Fig. 1b - The drill cuttings mixed with sawdust ready for transportation.

Fig. 2a - Organic feed material (paunch) prior to blending with the cuttings.

Fig. 2b - Mixing the cuttings, organic buffer and water in the feed-out wagon.

Fig. 3 - Feeding the cuttings mixture onto the worm beds.

Fig. 4 - The covered windrows.

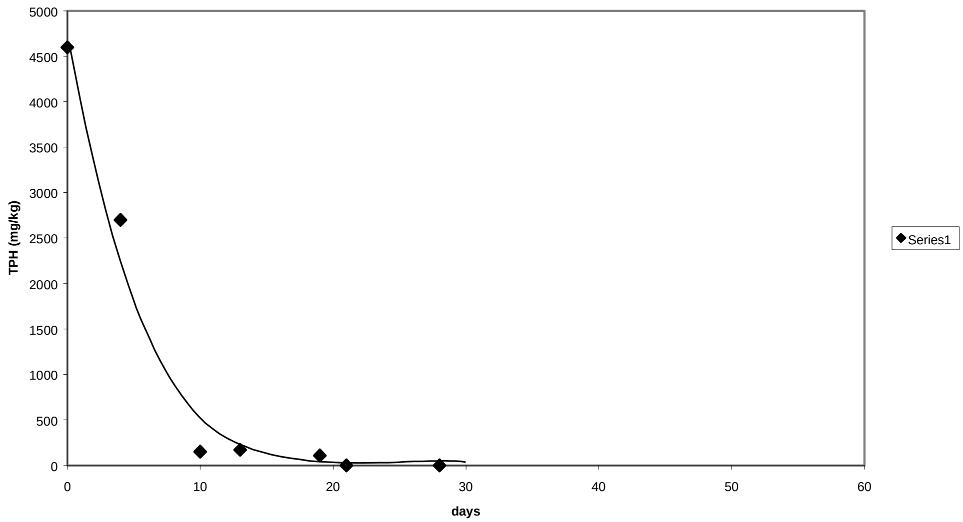

Fig. 5 - Total hydrocarbons by GC-FID (OIEWG carbon bands; mg/kg dry wt) – Initial Experiment.

Fig. 6 - Worms feeding on the drill cuttings and organic ammendments mix.

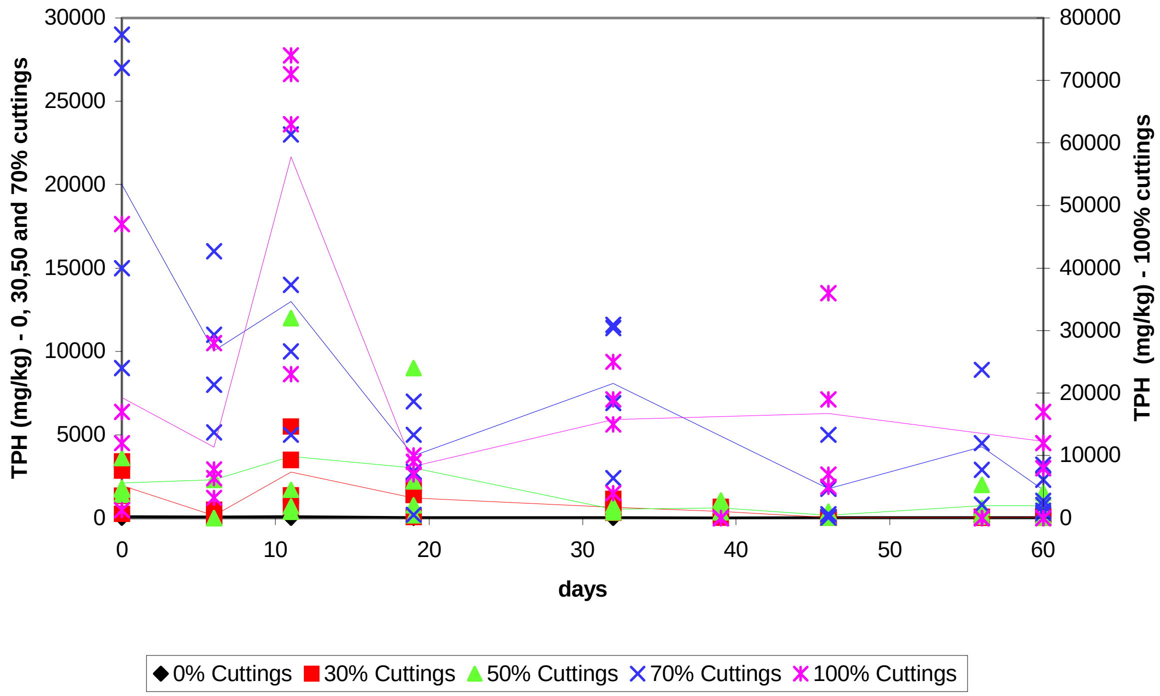

Fig. 7 - Average hydrocarbons concentrations by GC-FID (OIEWG carbon bands; mg/kg dry wt) for all application rates – Second Experiment.

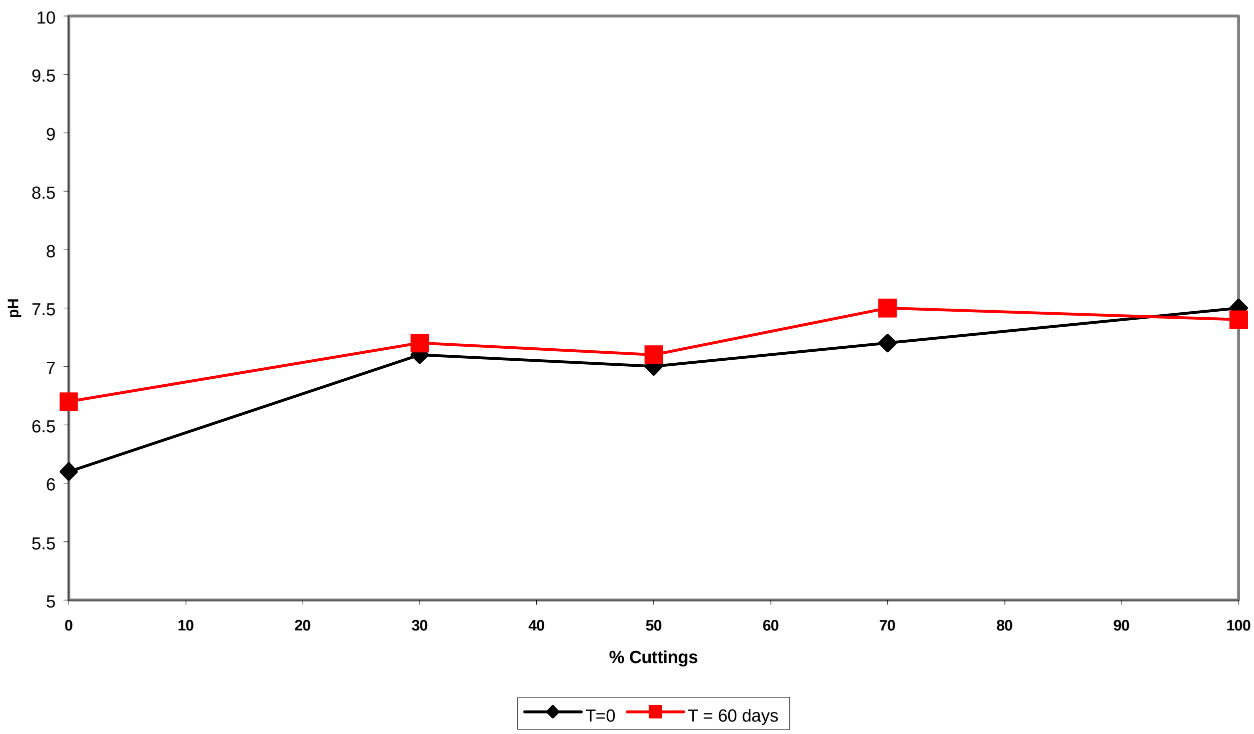

Fig. 8 - pH – Second experiment.

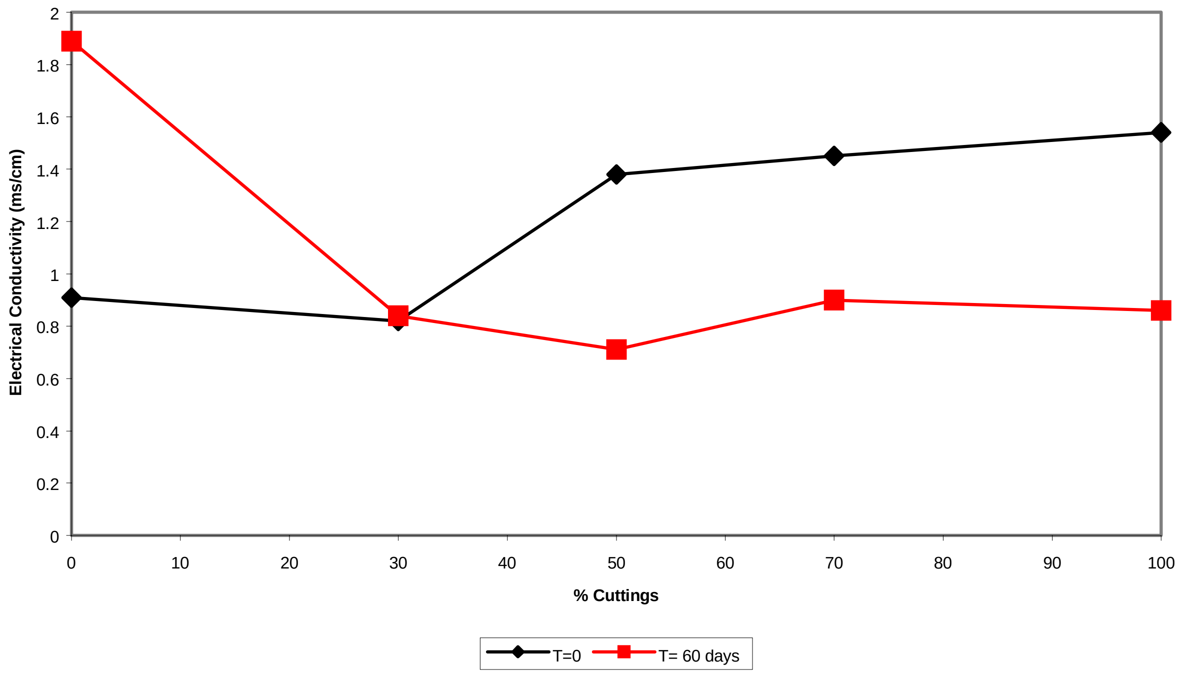

Fig. 9 - Electrical Conductivity – Second experiment.

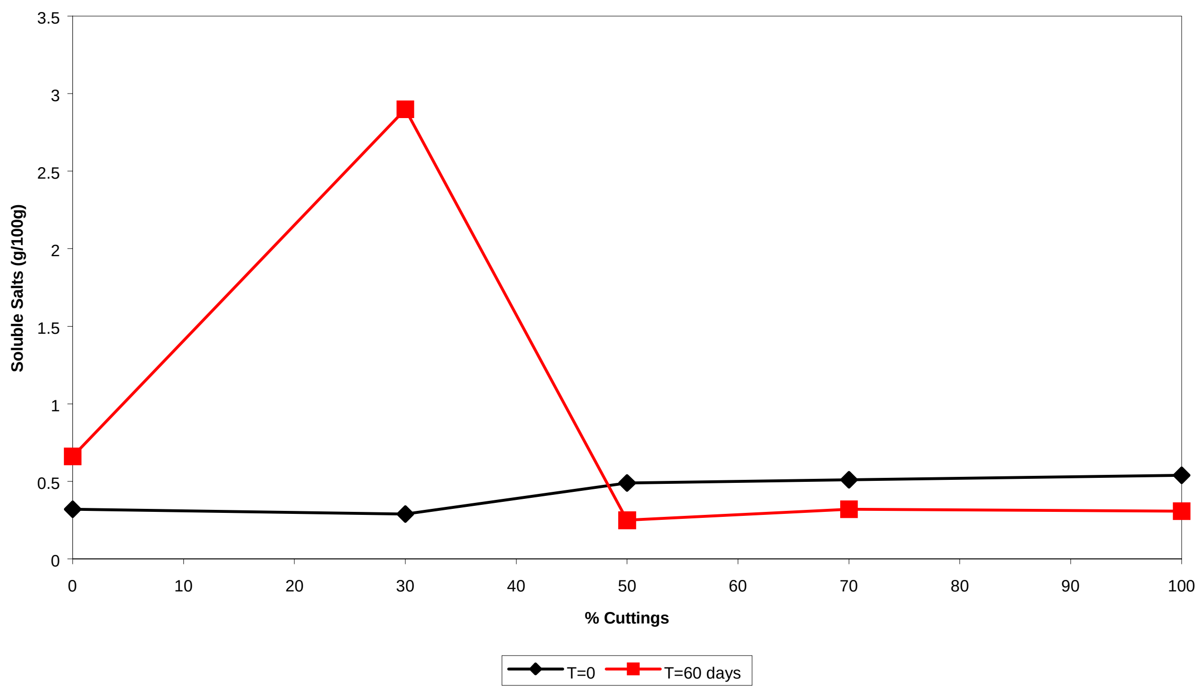

Fig. 10 - Soluble Salts Concentration – Second experiment.

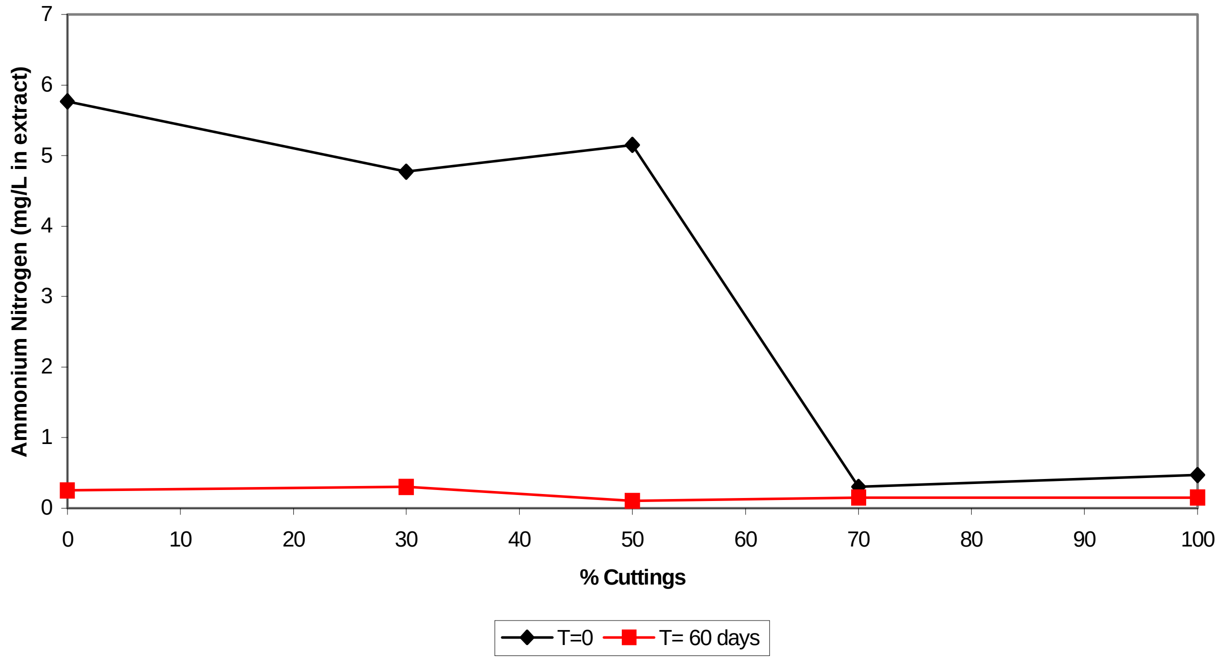

Fig. 11 - Ammonium Nitrogen Concentration – Second experiment.

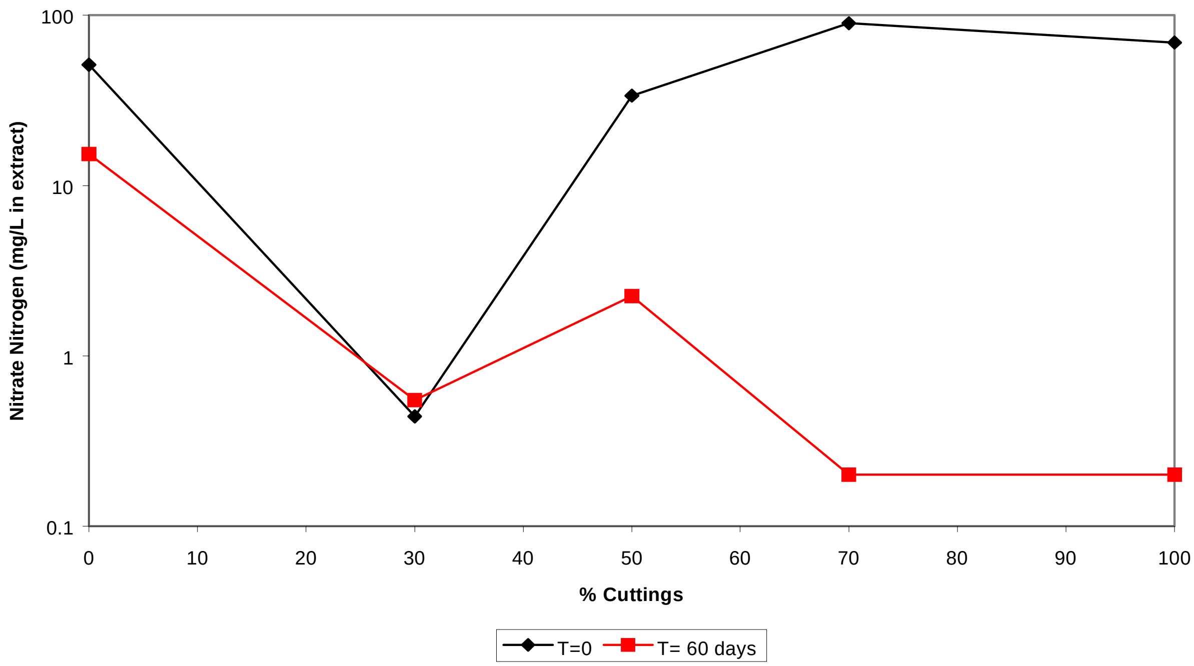

Fig. 12 - Nitrate Nitrogen Concentration – Second experiment.

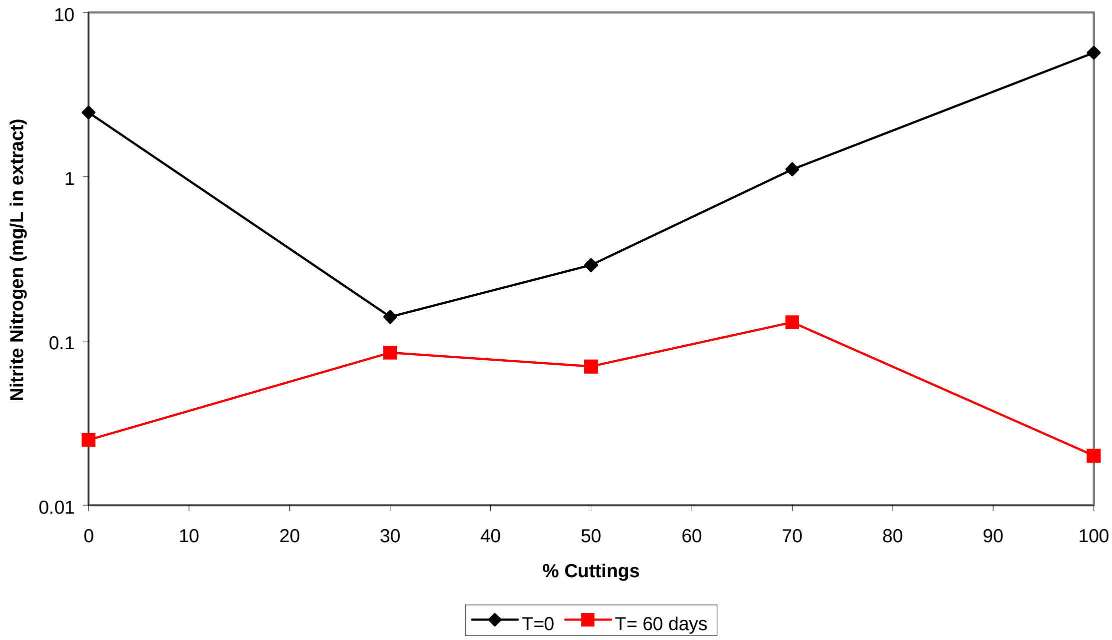

Fig. 13 - Nitrite Nitrogen Concentration – Second experiment.

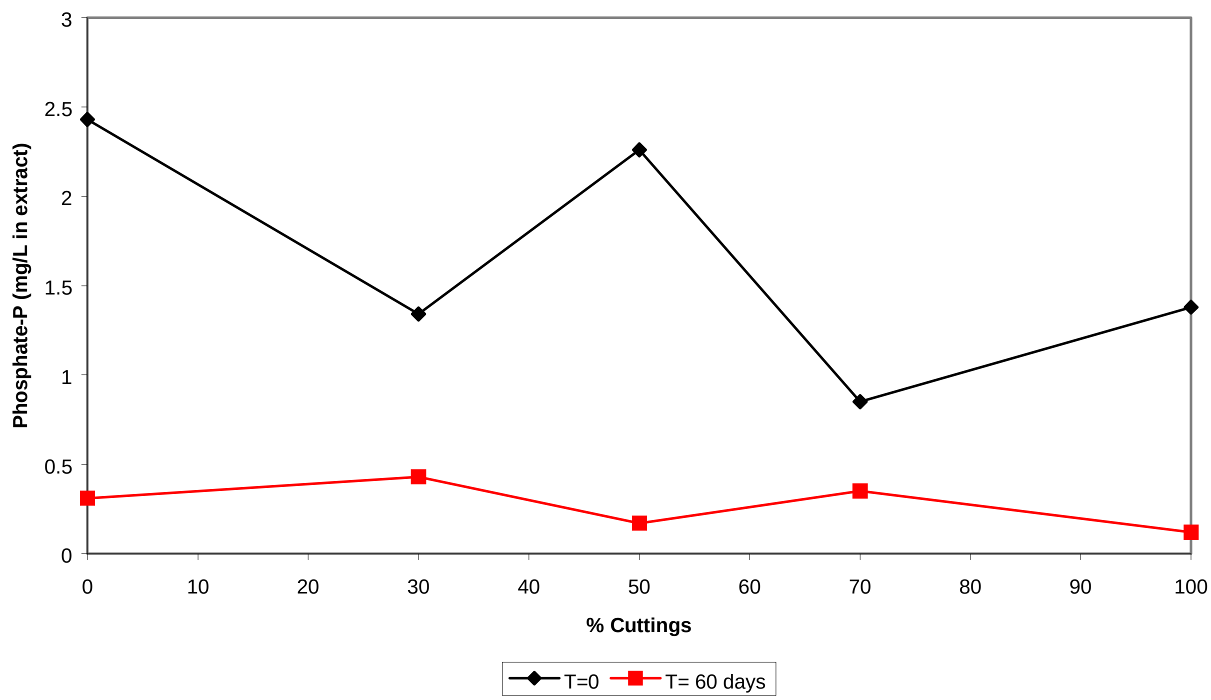

Fig. 14 - Phosphate Phosphorous Concentration – Second experiment.

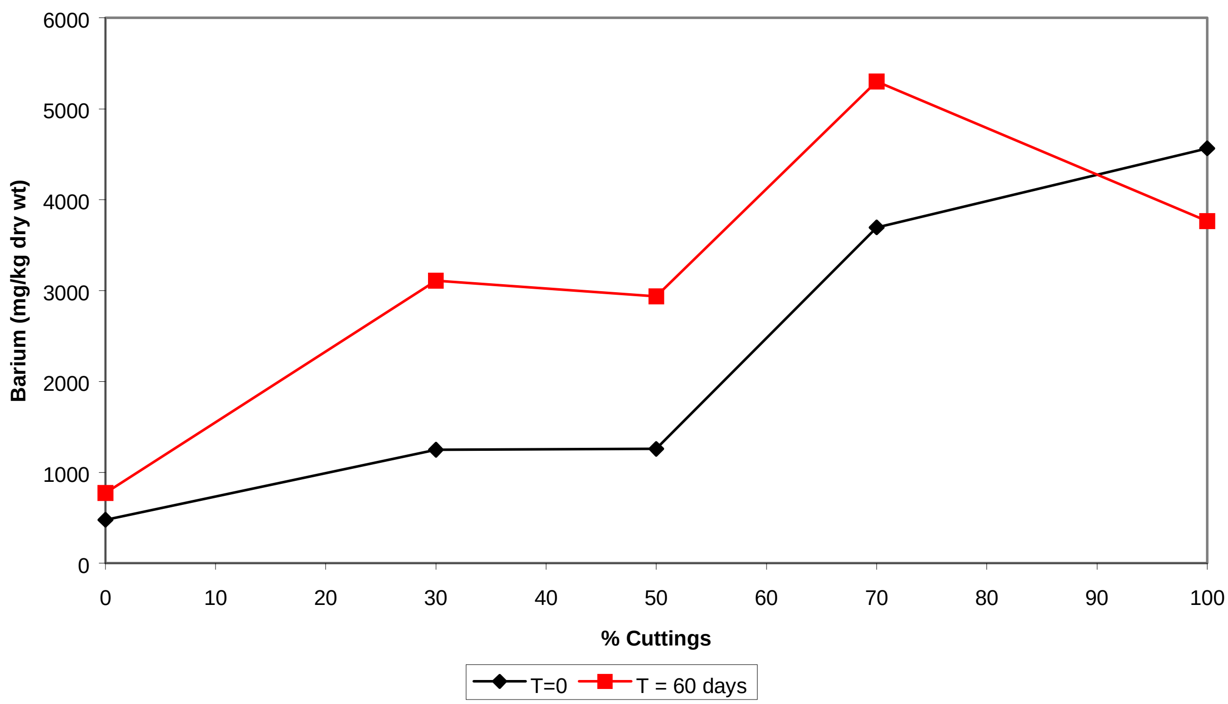

Fig. 15 - Barium Concentration in Soil Samples at the Start and Finish of the Experiment - Second Experiment.

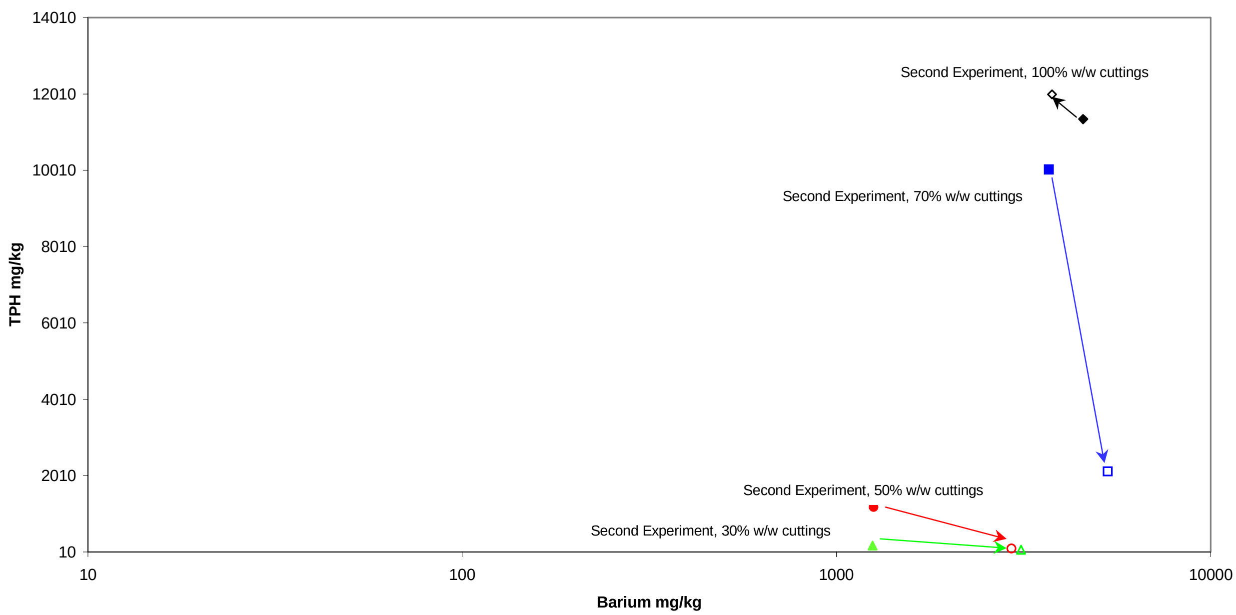

Fig. 16 - Barium and hydrocarbon concentrations at the start and finish of the second experiment. Solid symbols represent samples taken at the start of the experiment; hollow symbols samples taken at the end of the experiment.

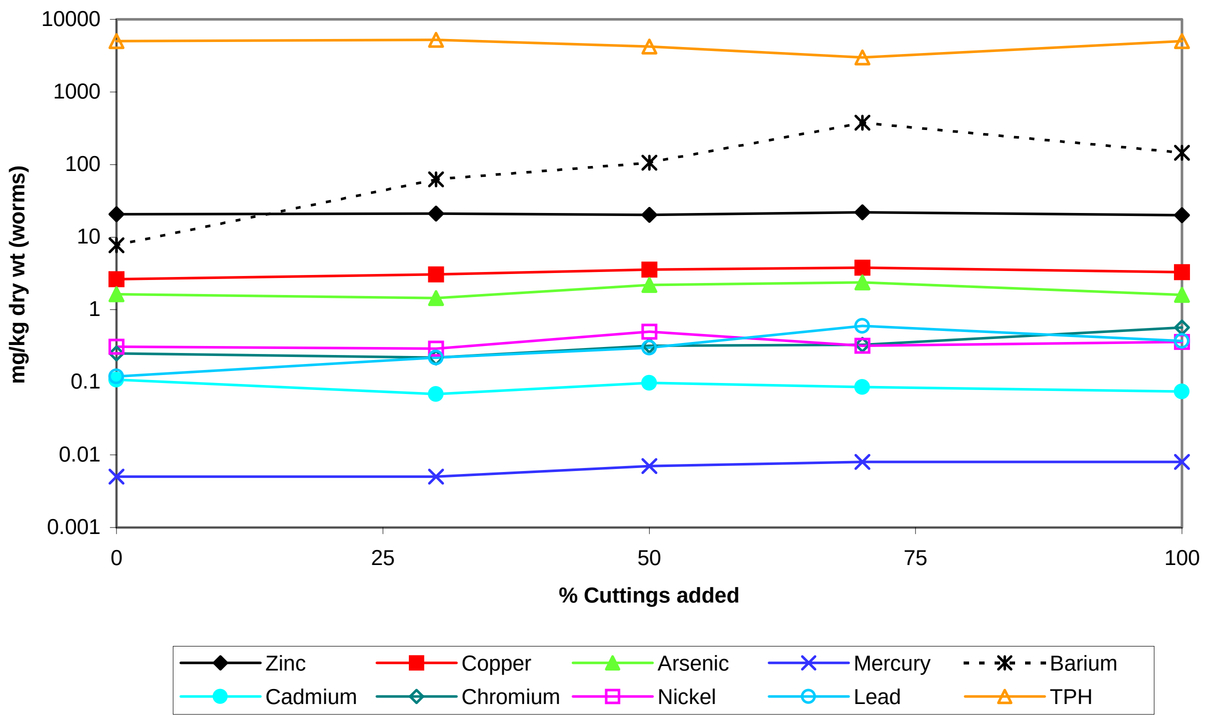

Fig. 17 - Heavy Metal Concentration in Earthworms Fed at Different Application Rates – Second Experiment.

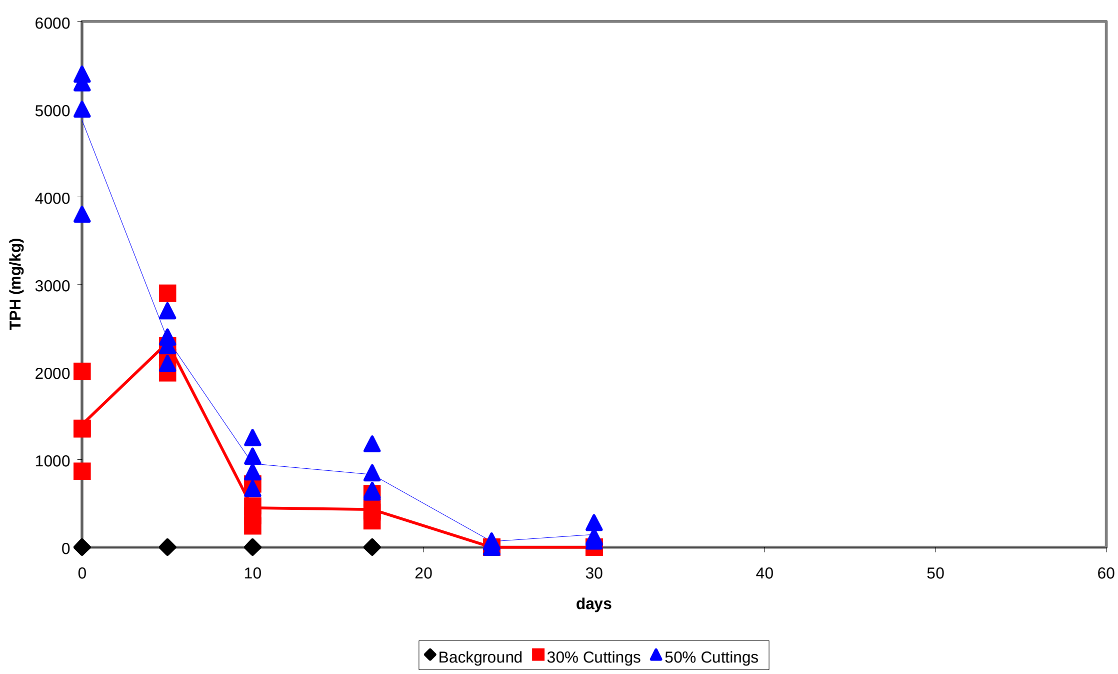

Fig. 18 - Hydrocarbon concentrations by GC-FID (OIEWG carbon bands; mg/kg dry wt) – Third Experiment.

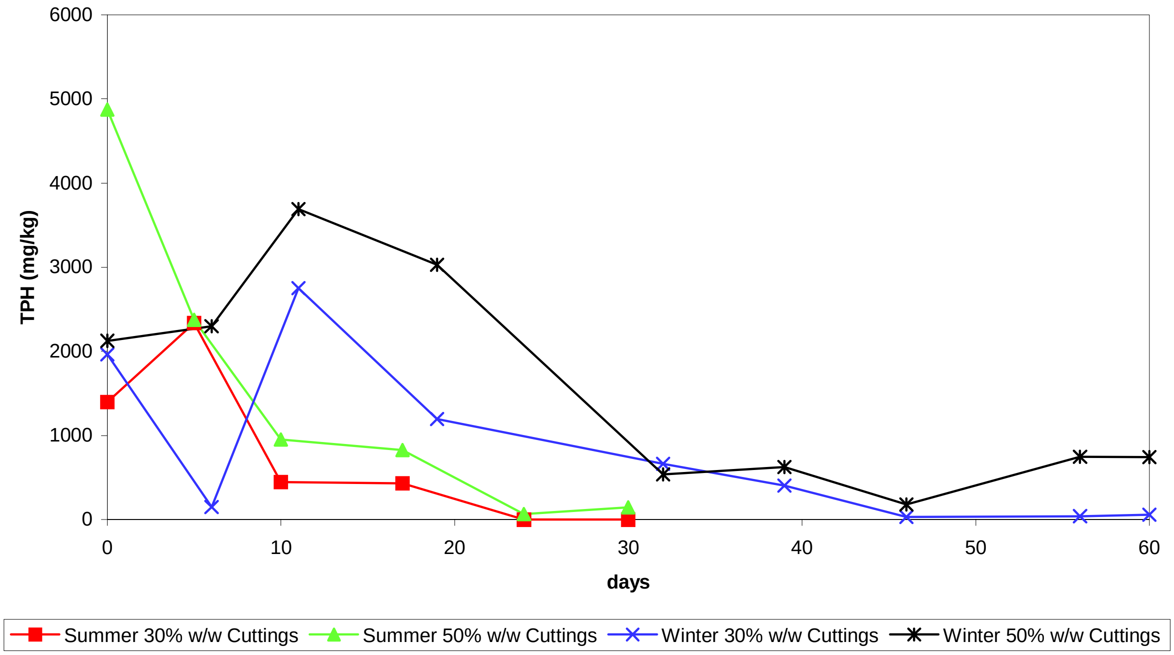

Fig. 19 - Mean hydrocarbon concentrations by GC-FID (OIEWG carbon bands; mg/kg dry wt) comparison of second and third experiments performed under summer and winter conditions respectively.

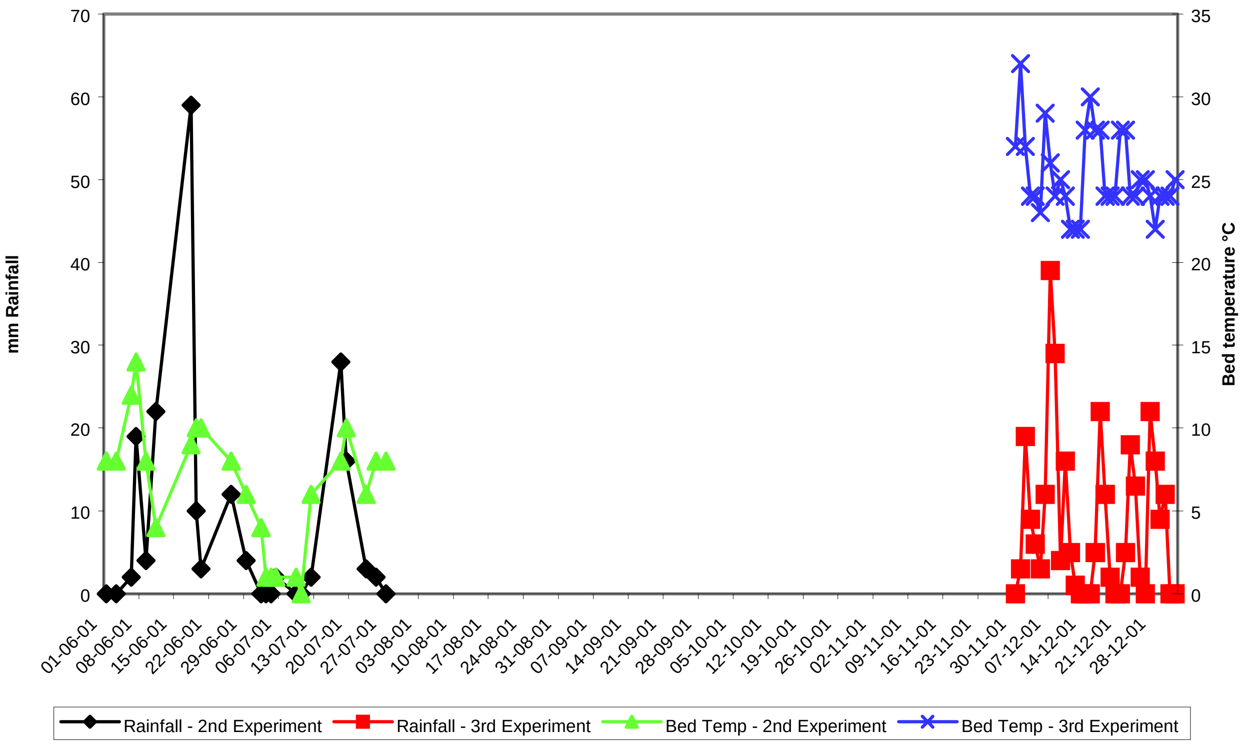

Fig. 20 - Worm bed temperatures and rainfall during Experiments two and three.

Appendix 1 - Summary of Methods Used and Detection Limits

The following table(s) gives a brief description of the methods used to conduct the analyses for this job.
The detection limits given below are those attainable in a relatively clean matrix. Detection limits may be higher for individual samples should insufficient sample be available, or if the matrix requires that dilutions be performed during analysis.

Parameter	Method Used	Detection Limit
pH	1:2 water extraction of dried sample. pH read directly.	0.1 pH Units
Electrical Conductivity	1:2 water extraction of dried sample. Measured conductivity at 25 °C	0.05 mS/cm in extract
Soluble Salts	Calculation: measured EC (mS/cm) x 0.35.	0.02 g/100 g
Total Nitrogen*	Determined by Dumas combustion procedure using Elementar VarioMAX instrument.	0.02 g/100 g dry wt
Total Carbon*	Determined by Dumas combustion procedure using Elementar VarioMAX instrument.	0.05 g/100 g dry wt
Zinc	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.1 mg/kg dry wt
Copper	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.05 mg/kg dry wt
Ammonium-N*	1:2 water extraction on dried sample. FIA colorimetric determination.	0.1 mg/L in extract
Nitrate-N	1:2 water extraction on dried sample. FIA colorimetric determination.	0.2 mg/L in extract
Nitrite-N	1:2 water extraction on dried sample. FIA colorimetric determination.	0.02 mg/L in extract
Phosphate-P	1:2 water extraction on dried sample. FIA colorimetric determination.	0.04 mg/L in extract
Arsenic	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.1 mg/kg dry wt
Mercury	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.01 mg/kg dry wt
Barium	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.01 mg/kg dry wt
Cadmium	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.005 mg/kg dry wt
Chromium	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.1 mg/kg dry wt
Nickel	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.1 mg/kg dry wt
Lead	Nitric/hydrochloric acid digestion. ICP-MS determination.	0.03 mg/kg dry wt
Total Hydrocarbons by GC-FID [OIEWG carbon bands]	ASE or Sonication Extraction, GC-FID Quantitation	N/A