

RESEARCH RELATIVE TO LAND APPLICATION OF DIESEL INVERT DRILLING WASTES

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ABSTRACT

Diesel invert wastes are one of the more difficult types of drilling mud wastes to dispose of due to the presence of hydrocarbons and salts. In 1989 a joint research program funded by the Alberta Research Council (ARC) and the Alberta Land Conservation and Reclamation Council was initiated to develop environmentally acceptable land application rates of diesel invert wastes for soils in Alberta and to model the fate of these wastes. The work was undertaken as four individual but closely linked experiments. This paper emphasizes the work related to the field study.

The characterization experiment included the sampling and analysis of the waste materials and indigenous soils from the field site. The degradation experiment was undertaken to determine degradation rates of the oil, organic carbon and three targeted PAH's (fluorine, phenanthrene, and pyrene) when applied to soil under laboratory conditions. The objective of the greenhouse pot experiment was to measure the relative impact of the oily materials and salts present in the invert wastes on soil quality and plant growth and quality.

The field plot experiment was undertaken to validate and calibrate the results of the degradation and greenhouse experiments. It was established adjacent to the wellsite which was reclaimed using conventional management practices. The oil application rates achieved in the field plots were 0% (control), 1.0%, 2.0%, 3.0%, and 4.0%. Frequency of application included single applications with and without a vegetation cover and multiple waste application plots. Waste was applied and incorporated in October 1990 and again in September 1991 for the multiple application plots. Each treatment (4 m x 5 m plot) was replicated three times and a grass or grass and legume vegetation cover was established. Each of the 54 plots was sampled in 15 cm intervals to the 250 cm depth prior to waste application, 15 days after application, and again in the fall of 1992, 1993, 1994, 1995, and 2003. Tissue samples were collected and biomass was determined.

The extent of chloride movement was greatest in year 1 and declined thereafter. By year 5 the highest chloride values were in the 150 to 180 cm depth interval and by 2003 (year 13) the chloride had all been leached beyond the 3 m depth. None of the 2%, 3%, or 4% vegetated or non-cultivated treatments achieved the 0.5% oil content limit by the end of year 5 whereas all of the non-vegetated treatments did achieve the 0.5% target by

the end of year 5. For the treatments that did exhibit some level of hydrophobicity, the levels were dominantly slight with only a few in the moderate category.

The vegetation cover established at the wellsite where operational reclamation practices were employed was comprised mainly of grasses in 2003. Trees and shrubs were much more common in the adjacent plot area. Overall neither the salt content nor oil content had any long-term effect on vegetation cover establishment and growth.

In 2004, the ARC initiated a bench scale experiment to assess the effectiveness of raw and composted mechanical pulp mill sludge for degrading hydrocarbons. The results indicated that both materials have significant potential for use as a soil amendment for remediating hydrocarbon contaminated sites.

INTRODUCTION

Invert mud drilling wastes or residues present significant problems relative to disposal due to the presence of hydrocarbons and salts. The soil offers an opportunity for assimilation of these wastes by land treatment which involves landspreading or landfarming operations.

In 1990 the Alberta Research Council initiated a study to determine environmentally acceptable rates of invert mud drilling waste application for soils in Alberta. The term “acceptable” meant an agreed upon level of limitation to soils, plants, animals, water, air, etc. based on the literature.

OBJECTIVE

The objective of this research was to develop environmentally acceptable land application rates of invert mud drilling wastes for soils in Alberta and to model the fate of these wastes.

The objective was accomplished by:

- a) Measurement of the rates of degradation of the invert mud drilling wastes in soil at different waste concentrations, frequencies of application and soil temperature under controlled growth chamber conditions.
- b) Measurements of the relative impact of oil materials and salts present in the wastes on soil quality and plant growth and quality (greenhouse pot experiment).
- c) Assessment of the impact of different application rates and frequencies of application of invert mud drilling wastes on soils and vegetation in a field experiment.

The characterization experiment was undertaken to determine the characteristics of the invert waste and the indigenous soil for implementing the degradation, greenhouse and field experiments. The degradation experiment was undertaken to assess the fate of organic wastes on soils and to provide some basis for the treatments to be utilized in the field experiment. Modelling of the soil assimilation of organic wastes affords an

opportunity to enhance the applicability of both laboratory and field acquired data beyond site specific situations.

The greenhouse pot experiment was undertaken to measure the relative impact of oily materials and salts that individually can prove limiting to plant growth. The field experiment was established to test the model developed in the degradation experiment and to verify and enhance the results of the greenhouse work.

MATERIALS AND METHODS

The field experiment was located immediately adjacent to a wellsite lease area southwest of Edson, Alberta.

Site Preparation

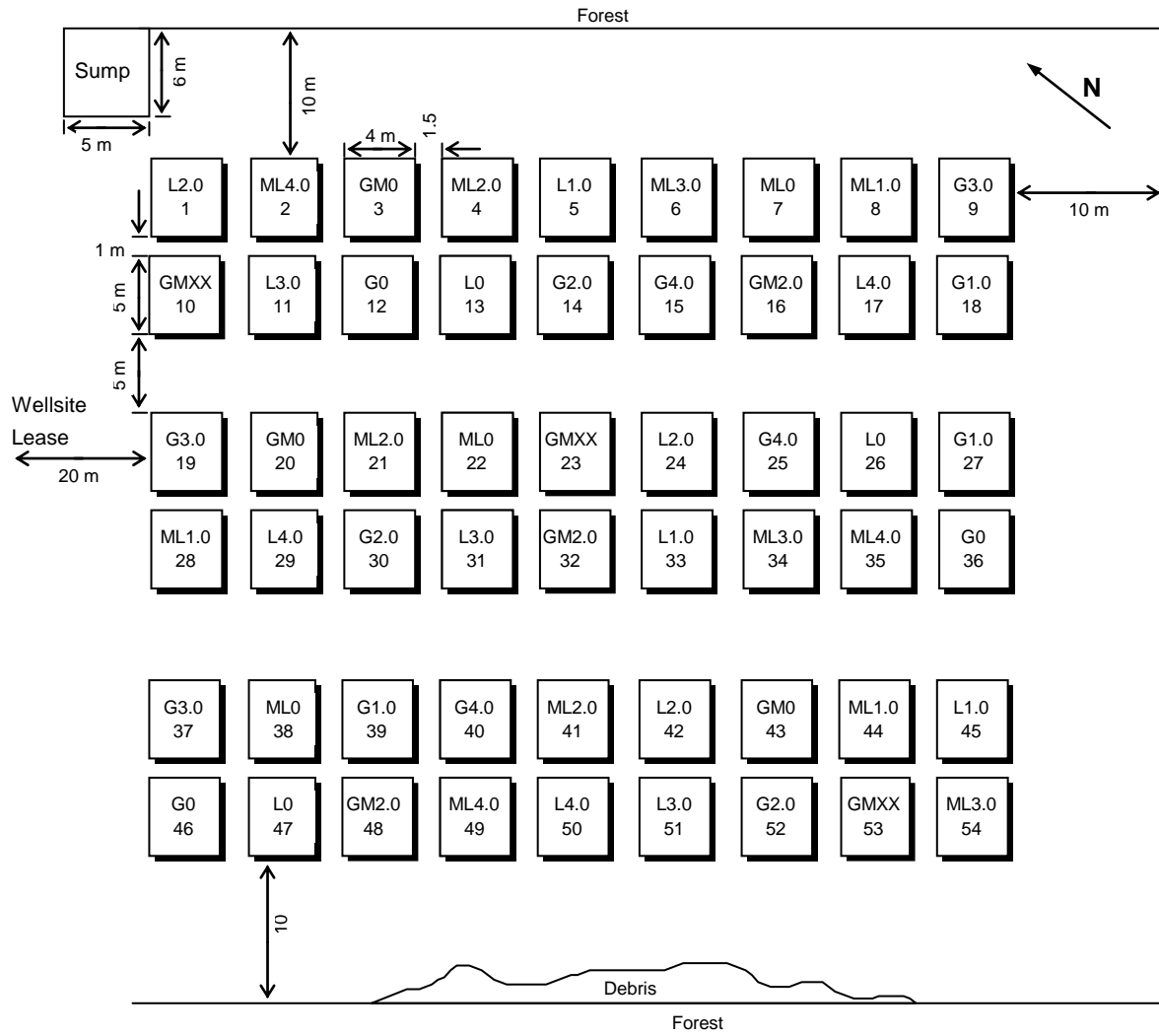
The site was cleared of existing poplar, spruce and understory cover and then cleaned and rototilled. The site was staked (Figure 1) and baseline sampling was undertaken to provide analytical information for each of the plots including the control plots so that comparisons could be made with the results of subsequent sampling events. A composite sample from five sample locations was obtained for the 0 to 15 cm depth interval at each of the plots. Additional samples were obtained from the 15 to 30 cm, 30 to 45 cm, 45 to 60 cm, and 60 to 90 cm depth intervals at selected plots to represent the baseline conditions of the whole site.

Waste Application

The waste application was completed on October 1 and 2, 1990. The waste material was transported from the storage sump to the respective plots by a tractor model backhoe unit. Spreading was done by the backhoe unit and supplemented by the use of hand tools resulting in a uniform application of the invert material.

Application rates were based on the equivalent oil content of the waste. The treatments (Figure 1) included:

- a) Oil application rates of 0%, 1%, 2%, 3% and 4%.
- b) Frequency of application
 - single application with vegetation cover
 - single application with no vegetation cover
 - multiple application where an initial rate of 1% oil was applied in 1990 and a second application of 1%, 2%, and 3% oil was applied one year later.
- c) Selected plots were seeded with either brome grass or a grass mixture
- d) Three replicates



- L2.0 1 - Treatment (no vegetation, single oil application of 2.0%)
 - Plot number
- G - Brome grass, single oil application
- GM - Grass mixture, single oil application
- GMXX - Grass mixture, no oil application
- L - No vegetation, single oil application
- ML - No vegetation, multiple oil application

Figure 1. Invert landspreading field site.

Plot Fertilization

Nitrogen and phosphorus fertilizers were applied annually to all single and multiple amended plots on the basis of the amount of waste applied measured in terms of an equivalent oil content. The following amounts per plot were applied initially:

- a) 0.0% oil rate – no fertilizer added
- b) 1.0% oil rate – 250 g 34-0-0 + 200 g 34-17-0 (77 kg N/ha + 7.5 kg P/ha)
- c) 2.0% oil rate – 500 g 34-0-0 + 400 g 34-17-0 (153 kg N/ha + 15 kg P/ha)
- d) 3.0% oil rate – 1000 g 34-0-0 + 800 g 34-17-0 (306 kg N/ha + 28 kg P/ha)
- e) 4.0% oil rate – 1500 g 34-0-0 + 1200 g 34-17-0 (459 kg N/ha + 45 kg P/ha)

In the following year (1991), 500 g of 35-15-0 (88 kg N/ha and 16 kg P/ha) were applied to all the plots. Fertilizer was also applied to the multiple oil application plots after the second addition of waste. The following amounts were applied:

- a) ML2.0 – 250 g 34-0-0 + 200 g 34-17-0 (77 kg N/ha and 7.5 kg P/ha)
- b) ML3.0 – 500 g 34-0-0 + 400 g 34-17-0 (153 kg N/ha and 15 kg P/ha)
- c) ML4.0 – 750 g 34-0-0 + 600 g 34-17-0 (230 kg N/ha and 22 kg P/ha)

The following amounts were applied two years later in 1992:

- a) all vegetated plots – 200 g 34-17-0 (34 kg N/ha and 7.5 kg P/ha)
- b) 2.0% oil rate - 250 g 34-0-0 + 200 g 34-17-0 (77 kg N/ha and 7.5 kg P/ha)
- c) 3.0% oil rate – 500 g 34-0-0 + 400 g 34-17-0 (153 kg N/ha and 15 kg P/ha)
- d) 4.0% oil rate – 750 g 34-0-0 + 600 g 34-17-0 (230 kg N/ha and 22 kg P/ha)

Fertilizer application in 1993 was the same as in 1992. In 1994 and 1995, all plots received 500 g of 34-17-0 fertilizer.

Plot Tilling

Following the initial waste and fertilizer applications all plots were rototilled to a depth of 15 cm to incorporate the waste with the soil material. A minimum of four passes were completed in each plot to ensure adequate mixing of the materials. Rototilling was also completed on the multiple application treatments after the second application of invert waste. The plots designated as controls (no vegetation and no waste applied), 'no vegetation, single oil application' and 'no vegetation, multiple oil application' were tilled from one to four times annually. To prevent cross-contamination, tilling was initiated with plots that received no waste and ended with plots containing higher application rates of waste.

Plot Seeding

The plot seeding was completed on May 29, 1991. The seed was applied at the rate of 150 g of forestry mix per GM (Grass Mix) plot and 180 g of brome grass per G (Grass) plot. The forestry mix was comprised of the following:

	<u>% by weight</u>
Creeping red fescue	40
Timothy (Climax)	20
Crested wheat grass	20
White clover	20

The plots were hand raked following the application of seed.

Plots designated as G3.0 and G4.0 in which grass had not become established after the initial seeding were re-seeded in the spring of 1994. These plots received 180 g of brome grass and were hand raked.

Plot Sampling

Plots were sampled two weeks after the initial waste application and then once annually. Sampling also occurred after the second waste application at the multiple application plots. For most plots, one composite sample based on five subsamples was obtained for the 0 to 15 cm and 15 to 30 cm depth intervals. For selected plots, five individual samples per plot were obtained to assess the extent of variability within each plot. Post-application sampling involved the collection of samples from the 0 to 15 cm depth interval only. In 1991 all plots were sampled in 15 cm intervals to the 105 cm depth. In the second year of the field experiment, most plots were sampled as described above and the additional depth intervals of 105 to 120 cm, 120 to 135 cm and 135 to 150 cm were also sampled. In the third year of the study (1993), most plots were sampled to a depth of 150 cm as described above. Selected plots were also sampled to a depth of 240 cm including the 150 to 180 cm, 180 to 210 cm and 210 to 240 cm depth intervals. In 1994, samples were obtained for the 0 to 15 cm surface depth interval from most plots and selected plots were sampled to a depth of 300 cm by adding the 240 to 270 cm and 270 to 300 cm depth intervals. Sampling in 1995 (year 5) was similar to 1994 except fewer plots were sampled to the 300 cm depth. In 2003, surface soil samples representing the 0 to 15 cm depth interval were obtained from 25 of the plots. In addition deep hole sampling which involved collection of samples from the 0 to 15 cm and 15 to 30 cm depth intervals followed by intervals of 30 cm to a depth of 3 m was conducted at nine plots.

Tissue Sampling and Yield Assessment

Tissue sampling and plot harvesting were completed annually. Harvesting involved the removal of the forage cover from the entire plot by use of a lawn mower. Harvesting the entire plot removed any bias from randomly selecting smaller unit areas within each plot and the use of a mower equipped with a grass-catcher ensured, to the greatest extent possible, a uniform harvest height of 5 cm. The grass was weighed immediately at the site and subsamples were returned to the laboratory for moisture content determination. Tissue samples were obtained from six or more randomly selected locations in each plot, until approximately 500g of moist vegetation was collected. The samples were transported to the laboratory in paper bags, washed, dried at 70°C and ground prior to analysis.

Climate Monitoring Equipment

A weather station was installed at the experimental site in 1991. Two Model 824 Easylogger units (OmniData International Inc.), which are 12-channel portable data recorders, were installed to measure air and soil temperature, wind speed and direction, solar radiation and relative humidity. Rainfall intensity was measured by use of a tipping bucket rain gauge and total precipitation by use of a Taylor Clear-Vu rain gauge (Taylor Instrument, Sybron Corporation).

Soil temperature was measured at the 5 cm and 10 cm depths for the vegetated 0%, 1%, 2%, 3% and 4% oil application treatments.

Analytical Procedures

Water content of the solid waste samples was calculated after drying at 105°C for 24 hours. For all of the remaining analyses the samples were air-dried and ground to pass through a 2 mm stainless steel sieve. The pH was measured in a water paste (Doughty 1941) and in a 2:1 slurry of 0.01 M CaCl₂ (Peech 1965). Total carbon content was measured with a LECO CR12 carbon analyzer (Leco Corporation 1979), CaCO₃ equivalent by acid dissolution (Bascomb 1961) and acid neutralizing capacity by addition of 0.5 M HCl and back titration with 0.25 M NaOH (methods 1.004 and 1.005 (AOAC 1981)). Saturated pastes were prepared according to the USDA Soil Salinity Laboratory method (USDA 1954): were extracted and the extracts filtered through a 0.45 µm filter and analyzed for pH using a Radiometer combination electrode and Radiometer PHM 82 pH meter; electrical conductivity using a Yellow Springs Instruments conductivity cell and model 32 conductance meter; alkalinity (EPA method 310.2 (EPA, 1983)) and chloride (EPA method 325.2 (EPA, 1983)) with a Lachat flow injection analysis (FIA) instrument and the soluble ions (Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, Sr, Ti, V, Zn) using an ARL model 34000 simultaneous Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). Cation exchange capacity (CEC) and extractable cations of the sump solid samples were determined by extraction with a normal (1M at pH 7.0) ammonium chloride solution

(Holmgren et al. 1977), where NH_4 ion were determined by a Tecator Kjeltac Auto 1030 Analyzer distillation and titration unit and the exchangeable ions by the ICP-AES. The particle size analysis was done using a simplified hydrometer method (Gee and Bauder 1979).

DTPA- NH_4HCO_3 extractable elements (B, Ca, Cd, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Se, Zn) were determined by the method of Soltanpour and Workman (1981). Total elemental analysis of the solid sump samples was done by digestion in a CEM microwave digestion system. The procedure used included ashing the material overnight in a 425°C muffle furnace, digestion in a Teflon bomb in the microwave oven with 1.5 mL HNO_3 , 4.5 mL HCL and 10 mL HF for 10 minutes at 100 percent power, 20 minutes at 50 percent power and 10 minutes at 100 percent power. The digested solutions were transferred and made up with saturated H_3BO_3 to 50 mL, and the metal concentrations measured using ICP-AES.

Oil content in the samples was measured gravimetrically by soxhlet extraction with methylene chloride (McGill and Rowell 1977). The methylene chloride extract was separated into acid and base fractions by extracting with HCL and NaOH respectively, and with the remaining neutral fraction were submitted for analysis by gas chromatography mass spectroscopy (GC-MS) and high pressure liquid chromatography (HPLC).

Assessment of soil hydrophobicity was conducted by the Molarity of Ethanol Droplet (MED) test. Soil preparation prior to MED assessment involved air-drying, grinding to pass a 0.85 mm sieve, oven drying at 105°C for 24h, and allowing the soil to cool to room temperature in a desiccator. The test was performed by placing droplets (2-3 mm diameter) of increasing ethanol concentration on the leveled soil surface. MED indices were recorded as the molarity of the droplets of lowest ethanol solution concentration to penetrate completely into soil with 10 seconds or less.

The plant tissue was washed in a dilute (0.25%) metal free detergent (Versa-Clean) solution, rinsed three times in distilled water, dried at 70°C for 24 hours and then ground.

The plant tissue samples were digested with a concentrated HNO_3 – HClO_4 acid mixture in a closed teflon bomb heated in a CEM microwave digestion unit. The solution concentration of Al, Fe, Zn, Mn, Ca, Mg, Na, K, Sr, P, Ba, Mo, B, S, Si, and As was measured by ICP-AES, and Cd and Pb by graphite furnace atomic absorption. Chloride was extracted by the sodium nitrate extraction procedure of Gaines et al. (1984) and determined by EPA method 325.2 (EPA 1983) using a Lachat flow injection analysis (FIA) instrument.

RESULTS AND DISCUSSION

A total of 15 solid phase samples were obtained from the invert sump and three samples from the surface soil stockpile. These samples were analyzed for several chemical and physical properties, soluble ions in saturated paste extracts, plant available trace elements (DTPA extractable) and total elemental content.

Characterization Study Data

A complete set of characterization data are provided in Macyk et al. (1996). The pH in H₂O and CaCl₂ values ranged from 10.2 to 11.9 for samples from the invert sump. The mean values for pH of the soil in water and CaCl₂ were 5.5 and 4.8 respectively.

Acid neutralizing capacity (ANC) values ranged from 8 to 52% with a mean value of 30% for the invert materials. Oil content ranged from 6.4 to 11.9% with a mean value of 9.2% for the invert waste samples. The total organic carbon values (TOC) for the invert waste ranged from 10.8% to 22.5%. The TOC values were consistently higher than the oil contents indicating the presence of organic materials other than oil and grease which could be of humic or kerogen origin. The invert wastes had a texture ranging from loam to loamy sand.

The EC values for the invert wastes ranged from 26 dS/m to 39 dS/m which were similar to the mean values reported by Macyk et al. (1989) for invert wastes sampled in other locations in the province.

The SAR values ranged from 9 to 15 which were also similar to those reported by Macyk et al. (1989). The mean Cl value for the invert waste material was 16680 mg/L and the receiving soil had a mean Cl value of 26 mg/L. The plant available fractions of the soil elements were estimated by DTPA extraction. The chelate extractable elements have been shown to correlate well with plant elements (Soltanpour and Workman 1981). The receiving soil had higher levels of Mn, Ca, P, and Se than did the invert material and the reverse was true for the remaining elements.

The total elemental analysis of the wastes is used to assess the potential for heavy metal and other trace element contamination. Values for the total elemental content of the wastes were compared to the values for total elemental content of soil (Lindsay 1979) to assess any potential hazard to a receiving soil from the addition of the wastes. All the values for the various elements were within the range of values normally found in soils and were similar to the data reported by Macyk et al. (1989).

Field Study Data

A complete set of data from the field study component of the project is provided in Macyk et al. (1996).

Soil Parameters

The EC values for the surface soil (0 to 15 cm depth) were <0.25 dS/m prior to waste application in 1990. They increased substantially following waste application and by the fall of 1991 were back down to levels of 2 dS/m to 3 dS/m. In 2003 the values were in the 1 dS/m range and had not declined to the pre-application levels reported in 1990. Figures 2 and 3 provide EC values for treatments with 4% oil and with (Figure 2) and without (Figure 3) a vegetation cover for the period 1990 to 2003.

The chloride values for the surface soil (0 to 15 cm depth) were <50 mg/L prior to waste application in 1990. The values increased substantially to levels of 5000 to 12000 mg/L following waste application and by the fall of 1991 had decreased considerably. By the fall of 2003 the values were back down to baseline levels. Figure 4 illustrates the leaching of salts and chloride content with depth of soil sampled at plot 17 which did not have a vegetation cover. The initial chloride content was about 8500 mg/L or 9400 kg Cl/ha. In one year the chloride front was in the 60 to 105 cm depth zone with the highest value recorded in the 75 to 90 cm interval, suggesting a downward movement of about 80 cm in the first year. By the end of the first year (1991) after waste application, about 40% of the applied Cl was below 1 m depth. At the end of year 3 (1993) the chloride front had moved to the 90 to 135 cm depth interval and by the end of year 4 (1994) to the 135 to 180 cm interval. By the end of year 5 (1995) the chloride front was in the 135 to 210 cm interval. The highest chloride values recorded in 1993, 1994, and 1995 were in the 105 to 120 cm, 135 to 150 cm, and 150 to 180 cm depth intervals respectively. By 2003 the chloride applied initially had virtually all been leached beyond the 3 m depth as indicated by the values of 127 mg/L and 175 mg/L for the 270 to 300 cm and 300 to 325 cm intervals respectively.

The extent of movement was greatest in year 1 and declined thereafter. As the chloride front moved downward, particularly to depths greater than 1 m, subsequent movement decreased annually due to the fact that most rainfall events did not result in significant amounts of moisture percolating below 1 m. The data indicated that in thirteen years the chloride at plot 17 did move beyond the 3 m depth. A similar trend occurred at plot 29 (Figure 5) which was also a non-vegetated, 4% oil treatment. The initial oil contents following waste application were 0%, 1%, 2%, 3%, and 4%. Significant decreases occurred with time.

Loss of oil data are presented for the non-vegetated treatments (Figure 6) and the vegetated treatments (Figure 7). Non-vegetated treatments (roto-tilled periodically and not seeded) had more oil degraded than the vegetated treatments, particularly at higher rates of waste application. Non-vegetated plots experienced loss of oil for all treatments throughout the initial five year period while the oil loss in the vegetated treatments slowed down following the third year after application. The higher amount of oil loss from the rototilled and unseeded plots demonstrated the effect of mixing and aeration on the microbial degradation and photo decomposition of the oil component of the waste.

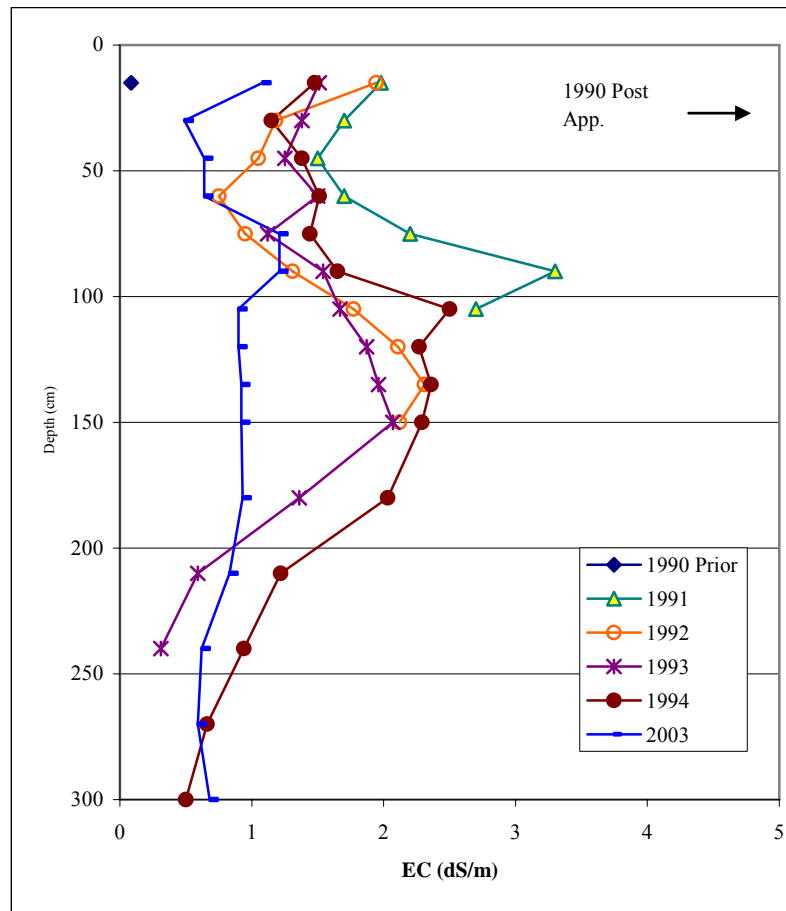


Figure 2. Electrical Conductivity Values at Plot 15
(4% Oil Treatment with Vegetation Cover).

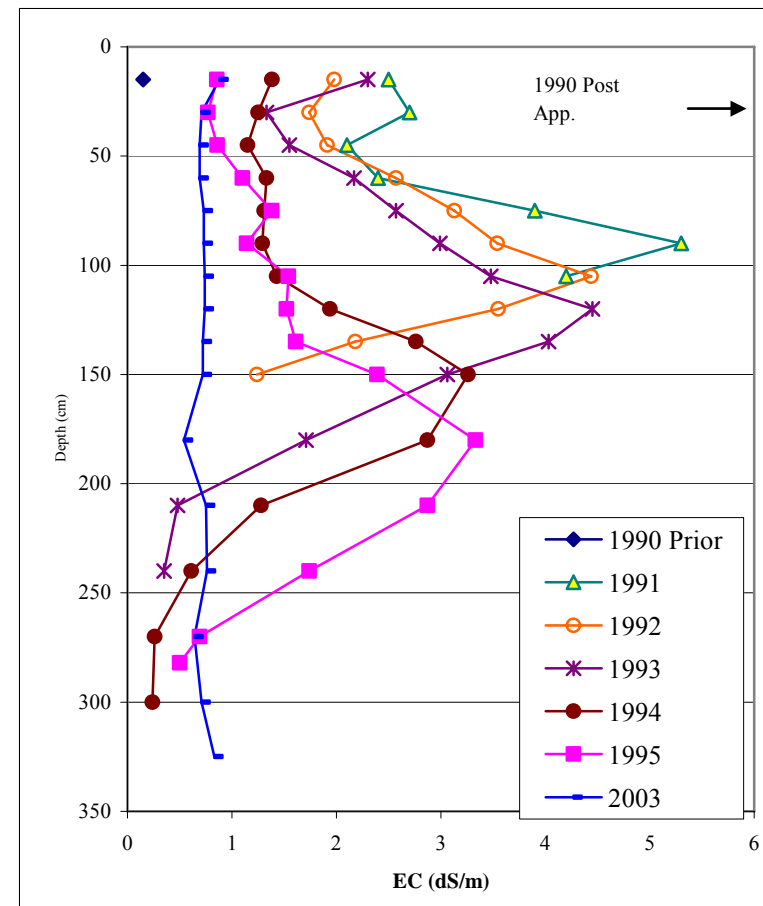


Figure 3. Electrical Conductivity Values at Plot 17
(4% Oil Treatment without Vegetation Cover).

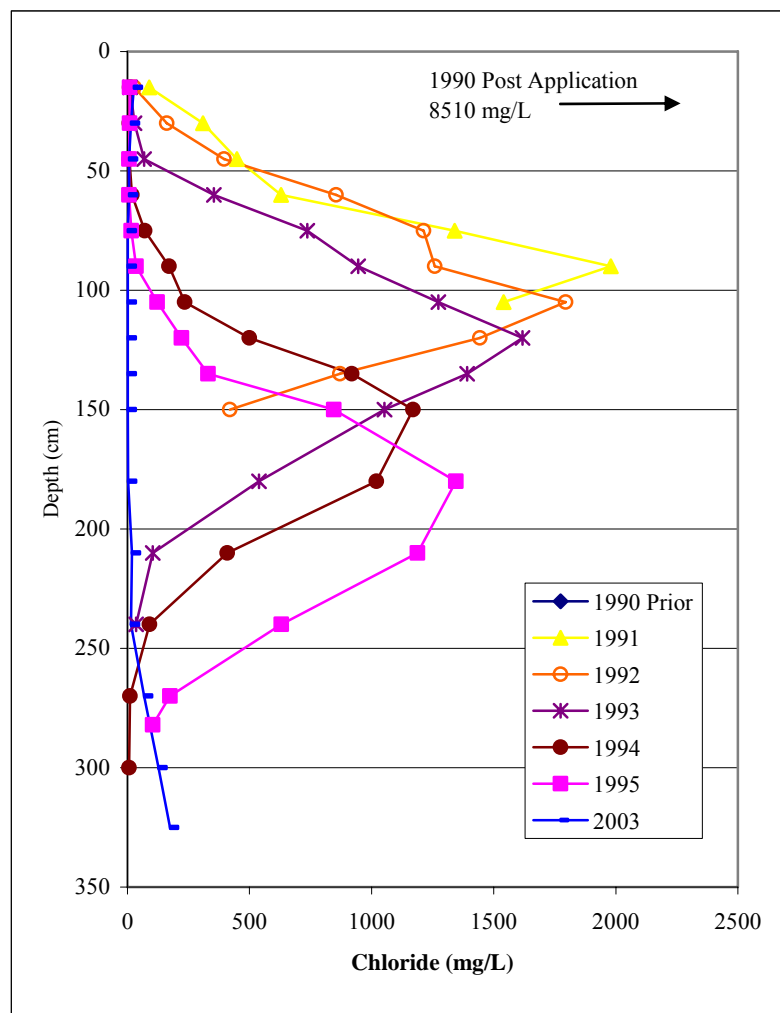


Figure 4. Chloride Values at Plot 17 (4% Oil Treatment without Vegetation Cover).

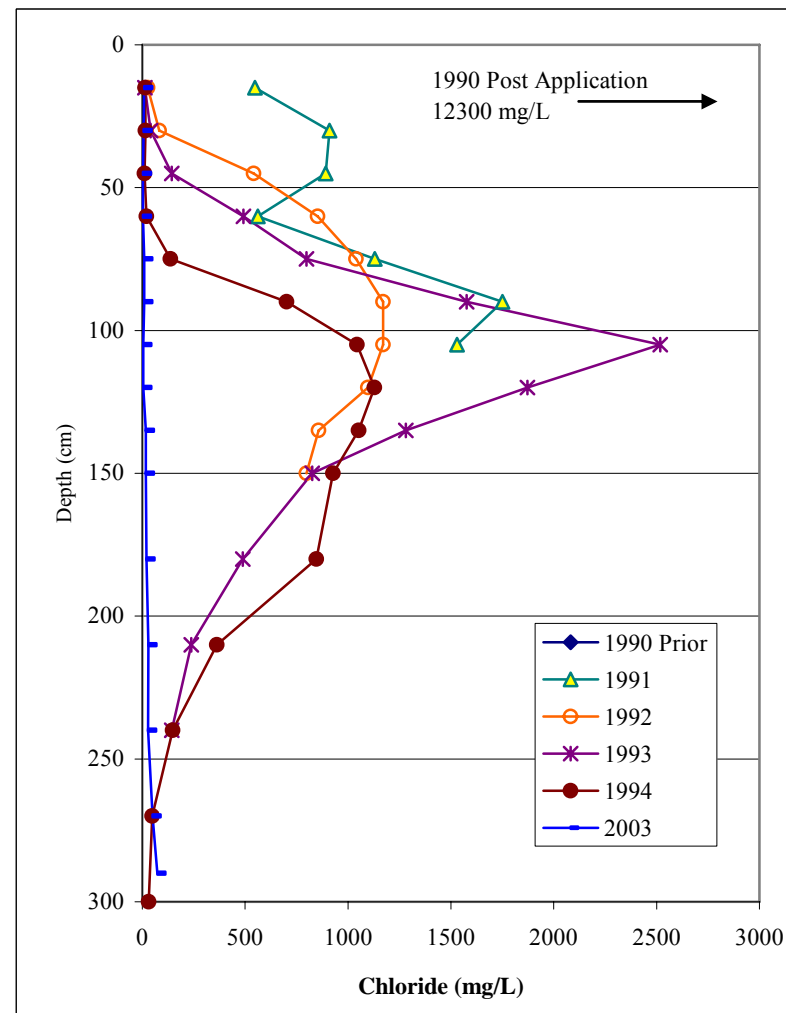


Figure 5. Chloride Values at Plot 29 (4% Oil Treatment without Vegetation Cover).

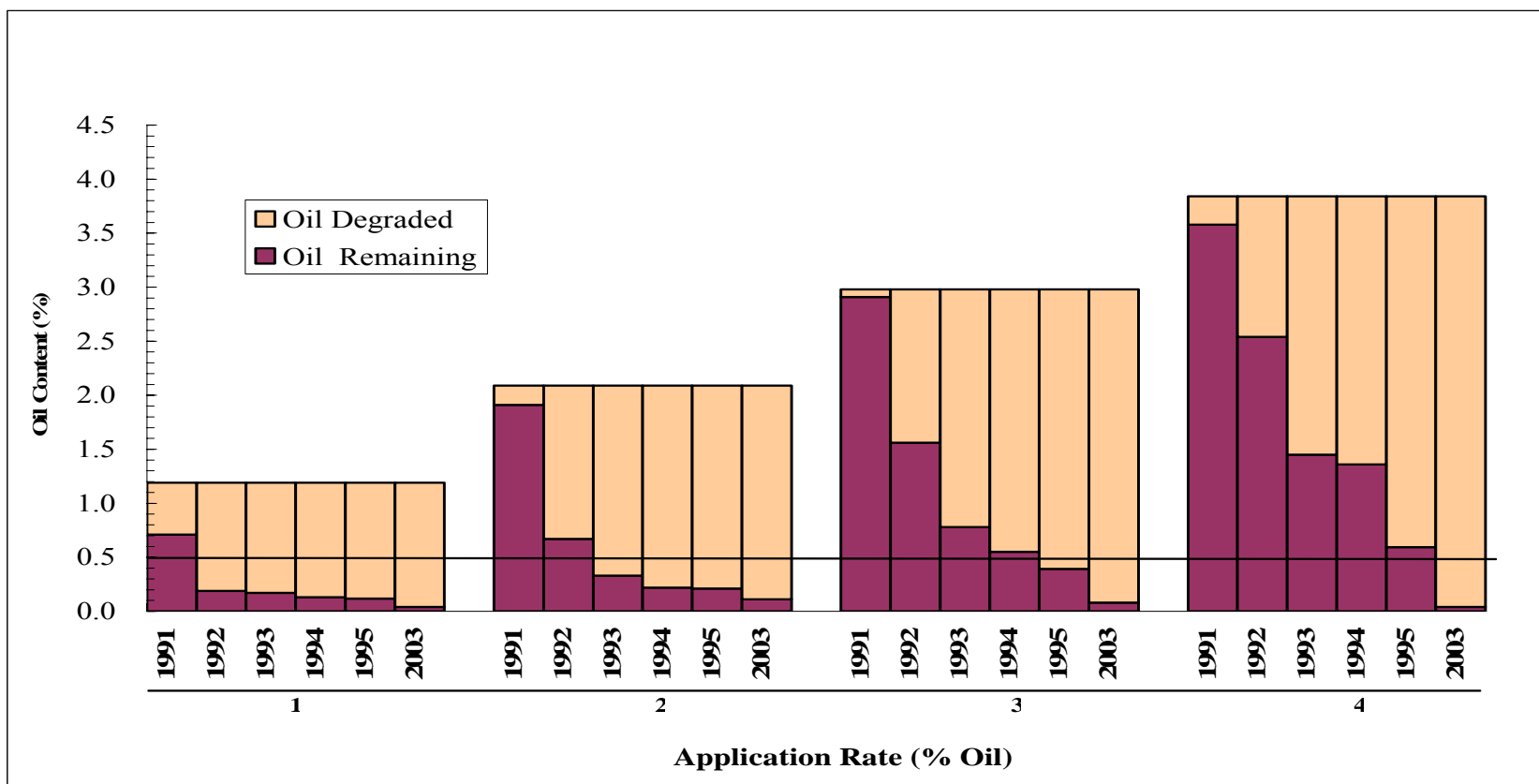


Figure 6. Mean Oil Contents of Non-Vegetated Treatments from 1991 to 2003.

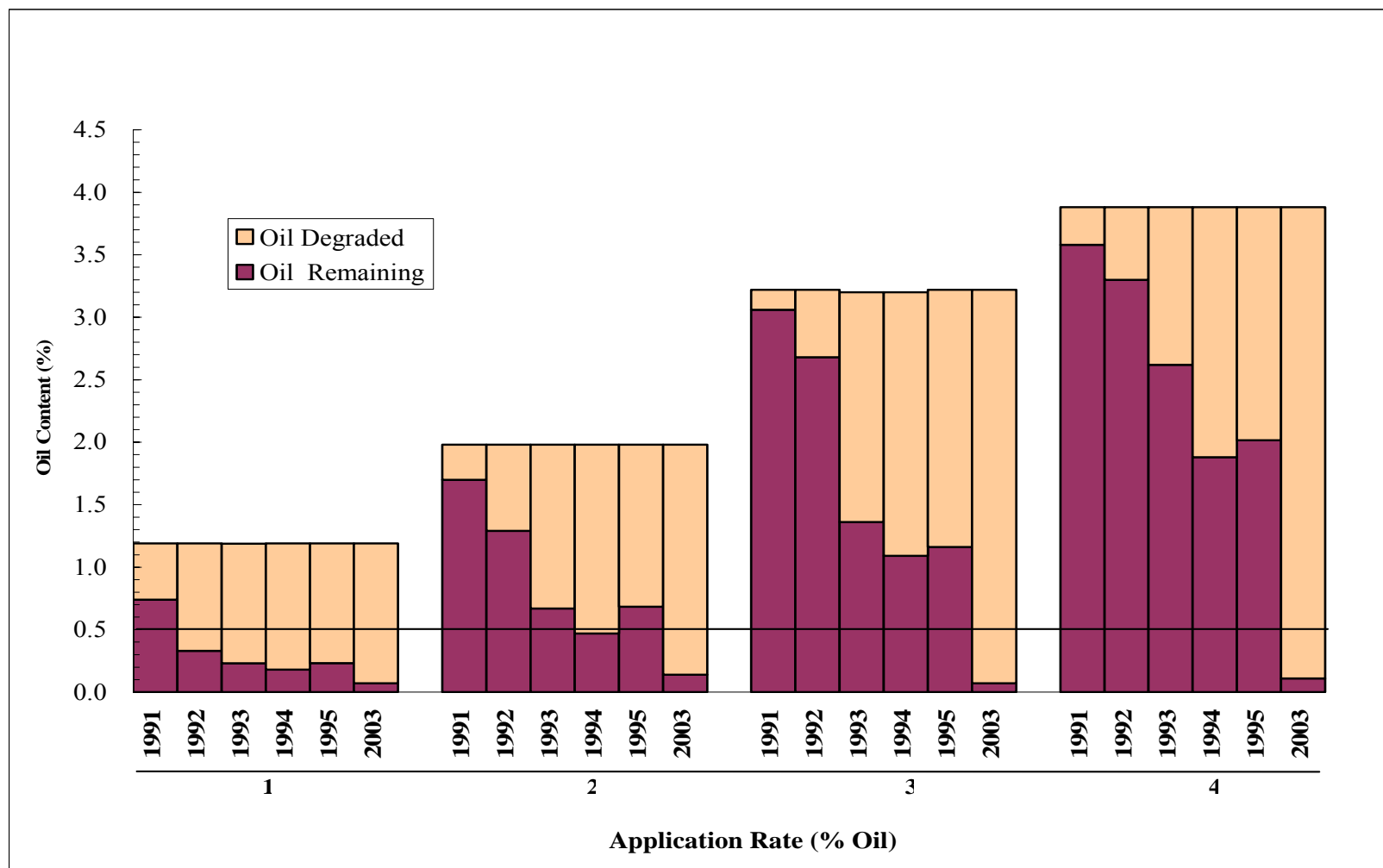


Figure 7. Mean Oil Contents of Vegetated Treatments from 1991 to 2003.

The Drilling Waste Management Guidelines (ERCB 1993) stated that when landspreading invert wastes the oil content in the waste/soil mix must be less than 0.5% in the upper 20 cm (topsoil). This target of 0.5% was readily achieved by the 1.0% non-vegetated treatment and barely achieved by the 1.0% vegetated treatment by the fall of 1992 (Figures 6 and 7). For the non-vegetated treatments the limit was achieved in 1993 (year 3) by the 2.0% treatment, in 1995 (year 5) by the 3.0% treatment and close to achievement in 1995 (year 5) for the 4.0% treatment. None of the 2.0%, 3.0%, or 4.0% vegetated or non-cultivated treatments achieved the 0.5% limit by the fall of 1995.

The results of the assessment of soil hydrophobicity for the various treatments at the study site were based on an arbitrary scale developed by King (1981) which ranks soil hydrophobicity as slight ($MED < 1.2M$), moderate ($1.2M \leq MED \leq 2.2M$), or severe ($MED > 2.2M$). Applying this scale to the values reported in Table 5 indicated that for those treatments that did exhibit some level of hydrophobicity, the levels were dominantly slight with a few in the moderate category.

Vegetation Establishment

The vegetation cover established at the wellsite area where operational reclamation and revegetation practices were employed is comprised mainly of grasses. Subsequent to incorporation of the invert mud and straw, woody debris was placed on the soil surface. Trees and shrubs are sparse within the wellsite area with some becoming established along the margins adjacent to the undisturbed forest. This lack of native cover establishment is likely due in part to the dense grass cover present in the area. This grass cover has resulted in a relatively thick organic layer in what can be considered a short period of time.

The vegetation cover established at the experimental area is currently more diverse than the cover at the adjacent wellsite area. Trees and shrubs are more common within the experimental area than in the wellsite area. Overall a wider range of species was identified in the experimental plot areas than at the wellsite. There did not appear to be a large difference in the total number of species per plot for the various treatments with the exception of the lower values reported for the grass mixture treatments. This mixture included creeping red fescue, timothy, crested wheatgrass, and white clover. The creeping red fescue and white clover are particularly competitive and would affect native encroachment.

SUMMARY AND CONCLUSIONS

The objective of this project was to assess the soil properties and vegetation characteristics at a field site where different rates of invert mud drilling wastes were applied in 1990.

The data indicated that chloride levels in the 0 to 15 cm depth interval which initially (1990) were in the range of 8500 mg/L had moved through the soil profile and beyond the 3 m depth by 2003.

The oil content data indicated that all treatments had met or exceeded the requirement of an oil content of <0.5% in the upper 20 cm of soil. An assessment of the hydrophobicity of these surface soils indicated that for those treatments that did exhibit some level of hydrophobicity, the levels were dominantly slight with a few in the moderate category.

The vegetation cover established at the wellsite or lease area where operational reclamation and revegetation practices were employed was comprised mainly of grasses. A wider range of species was identified in the experimental plot area than the wellsite area. Trees and shrubs were also much more common in the plot area.

The results obtained provide some perspective of what occurs in terms of salt movement and oil degradation associated with land application of invert mud drilling wastes. In this setting the salts moved relatively rapidly through the soil profile and beyond a depth of 3 m. The question still remains as to where these salts went – did they continue to move downward or did a significant portion move laterally? The latter is likely the case as soil sampling had to be discontinued at about the 3 m depth due to a relatively impenetrable layer.

It is encouraging to note that neither the salt content nor oil content have had any long-term effect on vegetation cover establishment and growth.

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