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Soil microbial response to waste potassium silicate drilling fluid

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ABSTRACT

Potassium silicate drilling fluids (PSDF) are a waste product of the oil and gas industry with potential for use in land reclamation. Few studies have examined the influence of PSDF on abundance and composition of soil bacteria and fungi. Soils from three representative locations for PSDF application in Alberta, Canada, with clay loam, loam and sand textures were studied with applications of unused, used once and used twice PSDF. For all three soils, applying ≥40 m^3/ha of used PSDF significantly affected the existing soil microbial flora. No microbiota was detected in unused PSDF without soil. Adding used PSDF to soil significantly increased total fungal and aerobic bacterial colony forming units in dilution plate counts, and anaerobic denitrifying bacteria numbers in serial growth experiments. Used PSDF altered bacterial and fungal colony forming unit ratios of all three soils.

Introduction

Drilling fluid is a lubricant used in drilling oil and gas wells and in exploration drilling rigs. Used drilling fluid properties vary with additives to optimize and improve drilling (Zvomuya et al., 2009). With increased drilling and formation fracturing in the petroleum industry worldwide, unprecedented volumes of used drilling fluids are generated and must be disposed of in an environmentally responsible and cost effective manner. A few studies addressed impacts of used drilling fluids on soil physical and chemical properties and vegetation, but few addressed effects on soil microbial community dynamics. The main effects on soil–water–plant systems are related to high pH, salinity, heavy metals and petroleum hydrocarbons of drilling fluids (McFarland et al., 1992, 1994; Miller et al., 1980; Nelson et al., 1984; Wojtanowicz, 2008; Zvomuya et al., 2008). Soil anaerobic conditions increased as hydraulic conductivity decreased due to high salts and clay particles from drilling fluids (Yao, 2013; Yao et al., 2014; Zvomuya et al., 2009). Some drilling fluid utilizing microorganisms, such as *Alcaligenes* and *Micrococcus*, were isolated in a tropical mangrove swamp oil field (Benka-Coker and Olumagin, 1995). Struchtemeyer et al. (2011) found that adding drilling fluid components to drilling water increased bacterial numbers, culturable aerobic heterotrophs, acid producers and sulfate reducers.

Potassium silicate drilling fluid (PSDF), a water based mud system with organic polymers, high potassium and low sodium content, is becoming popular in major drilling areas (Ghiselin, 2004). Although its use as a soil amendment could negatively affect soil, similar to other drilling fluids, a few studies found no detrimental effects on soil quality and plant growth (Yao, 2013). Whether potentially negative effects are mitigated by natural attenuation is unknown. Adding PSDF to soil increased available potassium and sulfur concentrations that could stimulate indigenous microorganisms, by adding nutrients and oxygen to soil. Organic polymeric substrates and potential petroleum hydrocarbons and metals in PSDF may increase soil organic carbon and energy sources, which highly

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impact soil microbial decomposition processes (Atlas, 1981; Baldi et al., 1996; Lie et al., 1999; Röling et al., 2003). Increasing soil pH, electrical conductivity and sodium adsorption ratio following PSDF application could affect biodegradation efficiency, which can be affected by salinity (Okpokwasili and Odokuma, 1990), electron donors (Achtnich et al., 1995; Chukwuma et al., 2010), electron acceptors (Lovley et al., 1996) and fertilizer (Jobson et al., 1974). Yao et al. (2014) found that PSDF with highly exchangeable potassium and sodium and clay particles decreased soil hydraulic conductivity and increased anaerobic conditions, which in turn affect plant productivity and organic matter and nutrient dynamics (Tiedje et al., 1984). Some anaerobic bacteria have been identified in oil fields, such as sulfate reducing bacteria (Struchtemeyer et al., 2011), nitrate reducing bacteria (Myhr and Torsvik, 2000) and iron reducing bacteria (Greene et al., 1997), but it is not known if these groups were affected by PSDF.

Recycling drilling fluid to drill more than one hole is an important sustainability strategy to reduce waste volume and disposal costs. However, waste volumes increase with the load of rock cuttings and sub-surface water carried to the surface, with limited efficiency of cutting removal during rotary drilling (Wojtanowicz, 2008). These drilling cuttings have potential to change the properties and composition of used drilling fluid. Some research found that drilling fluid preparation and drilling processes introduced exogenous microorganisms into oil and natural gas reservoirs (Struchtemeyer et al., 2011). It is necessary to study soil microbial activity with unused and recycled PSDF to ascertain the influence of recycling PSDF on potential microbial loads.

Research has been conducted on distribution and diversity of microorganisms in remediation of oil based drilling fluid contaminated soil, but not on used PSDF as a soil amendment. We hypothesized that PSDF application could influence soil microbial community dynamics. The soil microbial community plays a major role in processing organic wastes and recycling nutrient constituents in PSDF. To test this hypothesis, we sought to determine whether soil biota (anaerobic and aerobic bacteria and fungi) were impacted by unused PSDF, recycled PSDF or rate of PSDF application; and determine the relationship between microorganism and soil response to PSDF application.

1. Material and methods

1.1. Experimental design

A replicated laboratory experiment was established using a complete randomized design with treatments representing reclamation scenarios. The same soil and drilling fluid were used in previous greenhouse and laboratory experiments (Yao, 2013; Yao et al., 2014). Soils were collected from three locations in Alberta, Canada, where drilling was active. Unused PSDF was provided by the supplier (Marquis Alliance Ltd., Canada) and the same used drilling fluids were collected from active well sites. All fluids were refrigerated until used. Soil and drilling fluid properties (chemical and physical) were determined by a commercial laboratory (Exova Laboratory Group, Canada).

Soil samples were air dried, sieved to remove large particles, then ground to <2 mm. Available nitrate (NO_3^-) and ammonium (NH_4^+) were determined by extraction with 2.0 mol/L KCl (Carter and Gregorich, 2008); available phosphorus and potassium by modified Kelowna extraction (Ashworth and Mrazek, 1995); and available sulfate by extraction with 0.1 mol/L $CaCl_2$ (McKeague, 1978). Cation exchange capacity was determined by exchange with ammonium acetate at pH 7 (McKeague, 1978). Total nitrogen was determined by Kjeldahl digestion distillation (Bremner, 1996). Total carbon was determined by dry combustion and total organic carbon by Walkley–Black wet dichromate oxidation (Nelson and Sommers, 1996). Water soluble cations (sodium, calcium, potassium, magnesium), pH, sodium adsorption ratio and electrical conductivity were determined from saturation paste extracts (Carter and Gregorich, 2008). Sulfate and chloride were determined by ion chromatography with chemical suppression (Clesceri et al., 1992). Hydrocarbon fractions (F1, F2, F3, F4) were from gas chromatographic results with flame ionization (CCME, 2001). Trace metals restricted in concentration by the Canadian Council of Ministers of the Environment (silver, arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, antimony, selenium, tin, thallium, uranium, vanadium, zinc) were determined by inductively coupled plasma (ICP) following strong acid digestion (USEPA, 2008) and hot water soluble boron was determined by azomethine-H method (McKeague, 1978). Sand, silt and clay were determined by hydrometer after treatment with calgon (Carter and Gregorich, 2008).

Three soil textures, sand, loam and clay loam, covered a range of soils with potential for reclamation using drilling fluids in Alberta. Three types of PSDF were unused, used once and used twice. Soil and PSDF were mixed at PSDF rates of 0, 40 and 120 m^3/ha (equivalent to 0, 15 and 45 mL PSDF per kg of dry soil, respectively), which were developed around the current regulated maximum disposal rate in summer (40 m^3/ha) for Alberta. Mixed PSDF with soil was stored in polypropylene bags at room temperature (25 to 27°C) for 2 weeks to allow time for soil microorganisms to respond to PSDF. The three types of PSDF without soil were also analyzed.

1.2. Enumeration of sulfate reducing, denitrifying and iron reducing bacteria

Numbers of culturable sulfate reducing, denitrifying and iron reducing bacteria in PSDF treatments were determined using most probable number (MPN) dilutions (Cochran, 1950). All MPN experiments were performed with quintuplicate serial dilutions from 10^{-1} to 10^{-5} by using 16 × 150 mm glass tubes and serially diluting 1.0 mL of sample into 9.0 mL of an appropriate sterile medium. Sulfate reducing bacteria were enumerated using a medium of 1 L distilled water with 0.5 g of K_2HPO_4, 1 g of NH_4Cl, 2.0 g of Na_2SO_4, 1.5 mL of 60% and 1.0 g of yeast extract (BD Difco™, Mississauga, Ontario, Canada) with pH 7.1 to 7.2 (Butlin et al., 1949). Denitrifying bacterial growth media was prepared by dissolving 5 g of KNO_3 and peptone in 1 L distilled water with pH adjusted to 7, excluding agar in the original formula (Aaronson, 1970). Iron reducing bacteria growth media was prepared by dissolving 0.5 g of NH_4SO_4, 0.5 g of Na_2SO_4, 0.1 g of K_2HPO_4, 1.0 g of $MgSO_4{\cdot}7H_2O$, 5 g of ferric ammonium phosphate and 5 g of nutrient broth into 1 L distilled water (Aaronson, 1970).

Replicated dilutions were incubated at 21°C for 7 days before initial assessment. Sulfate reducing bacteria, denitrifying bacteria