

Vegetation Response to a One-Time Spent Drilling Mud Application to Semiarid, Mixed-Grass Prairie

Francis Zvomuya,¹ Francis J. Larney,² Walter D. Willms,² Ryan K. Beck,³ and Andrew F. Olson³

Authors are ¹Associate Professor, Department of Soil Science, 362 Ellis Bldg, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2; and ²Research Scientists and ³Research Technicians, Agriculture and Agri-Food Canada, Lethbridge Research Centre, 5403 1st Ave S, Lethbridge, Alberta, Canada T1J 4B1.

Abstract

Landspraying while drilling (LWD) is an approved disposal method for water-based drilling mud (WBM) systems in western Canada. The mud is applied either on cultivated land, where it is incorporated by cultivation, or on vegetated land where it is not incorporated. This study examined the effects of summer WBM application (0, 15, 20, 40, and 80 m³ · ha⁻¹) on native vegetation properties. Our results indicated that LWD increased bare ground but decreased lichen cover at the 80 m³ · ha⁻¹ rate relative to the untreated control. Nitrogen (N), sulfur (S), and magnesium (Mg) concentrations in aboveground plant tissue increased with increasing LWD rate in samples taken 45 d after WBM application, but these differences disappeared 1 yr after treatment. Increase in tissue concentration of phosphorus (P) with LWD rate, however, was only detected 3 yr after LWD. Nonetheless, these changes in tissue chemistry were not associated with significant changes in biomass yield or species composition. Overall, our results suggest that single WBM applications at rates (≤ 20 m³ · ha⁻¹) commonly used in western Canada, if properly managed, are unlikely to adversely affect native prairie vegetation.

Resumen

El rociado del terreno durante la perforación (LWD) es un sistema aprobado de eliminación de lodo en sistemas de perforación basados en el uso de agua (WBM) en el oeste de Canadá. El lodo puede aplicarse a tierras arables, donde es incorporado al suelo mediante la labranza, o a tierras con cobertura de vegetación donde no es incorporada al suelo. Este estudio examinó el efecto de la aplicación de WBM durante el verano (0, 15, 20, 40, y 80 m³ · ha⁻¹) sobre las propiedades de la vegetación nativa de la pradera. Nuestros resultados indicaron que el LWD incrementó el suelo desnudo pero provocó una disminución en la cobertura de líquenes comparado con el testigo cuando la aplicación fue de 80 m³ · ha⁻¹. La concentración de nitrógeno (N), azufre (S), y magnesio (Mg) en los tejidos vegetales aéreos aumentó con incrementos en la dosis de LWD en muestras tomadas 45 días luego de la aplicación del WBM, pero estas diferencias desaparecieron un año después del tratamiento. El aumento en la concentración de fósforo (P), sin embargo, sólo se detectó tres años después del LWD. No obstante, estos cambios en la composición química de los tejidos no estuvieron asociados a cambios significativos en la producción de biomasa o en la composición de especies. Nuestros resultados sugieren que en general, una única aplicación de WBM en dosis (≤ 20 m³ · ha⁻¹) comúnmente usadas en el oeste de Canadá, no tendría un efecto negativo sobre la vegetación de la pradera si la misma es manejada correctamente.

Key Words: biodiversity, energy exploration, hydrocarbon extraction, native rangeland, oil and natural gas

INTRODUCTION

Drilling muds (or fluids) are used during exploratory and development drilling for oil and natural gas to lubricate and cool the drill bit and control subsurface wellbore pressure (Neff et al. 1987; Ukeles and Grinbaum 2004). They also function to remove drilled-out rock cuttings from the well, clean the bit and the bottom of the hole, and stabilize the wellbore. Water-based drilling muds (WBMs) are the most commonly used mud system for shallow gas wells (250–650 m deep) in western Canada. The WBMs consist of fresh water as the base and bentonite to provide viscosity and create a filter cake on the borehole wall to control fluid loss (Bloys et al. 1994). Polymers, such as partially hydrolyzed polyacrylamide, are sometimes added to increase

fluid viscosity, inhibit clay and shale swelling and sticking, and flocculate drilled solids. Inorganic chemical additives include sodium hydroxide (caustic soda) and potassium hydroxide (caustic potash) to control (increase) mud pH and minimize corrosion of the drill pipe, casing, and rig equipment, and sodium carbonate (soda ash) to reduce water hardness.

As drilling muds circulate down the hole and back up to the surface, some of the liquid and solid materials end up as drilling waste. Drilling waste consists of the drilling fluid that was originally used and the formation cuttings (e.g., clay and rock pieces) that were transported back to the surface. A typical shallow gas well in southern Alberta commonly generates approximately 68 m³ of spent drilling mud (EnCana Corp, unpublished data, 2006). Various methods can be used to dispose of drilling waste, including underground injection, on-site burial (pits and landfills), land treatment (land spreading, land farming, and road spreading), evaporation from sump storage, surface discharge, recycling, and off-site disposal at commercial disposal facilities (Veil 1997). Choice of disposal

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Correspondence: Francis Zvomuya, Dept of Soil Science, 362 Ellis Bldg, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2. Email: zvomuyaf@cc.umanitoba.ca

method is determined by waste characteristics, government regulations, and the availability and cost of commercial off-site disposal facilities.

In western Canada, landspraying while drilling (LWD) is a commonly used disposal approach for WBMs (Alberta Energy and Utilities Board 1996). LWD involves collection of drilling wastes from approved mud systems (fresh water gel, gypsum water, or nitrate gypsum water) during the drilling operation and their prompt spraying on the soil surface of nearby lands at low application rates. The WBMs are landsprayed at maximum rates of $40 \text{ m}^3 \cdot \text{ha}^{-1}$ in summer or $20 \text{ m}^3 \cdot \text{ha}^{-1}$ in winter or on frozen ground (Alberta Energy and Utilities Board 1996). Additionally, total loadings of solids from LWD must not exceed $6 \text{ Mg} \cdot \text{ha}^{-1}$. Spraying techniques may include the use of vacuum trucks with spread plates or similar equipment. On cultivated land, LWD is normally followed by soil incorporation. However, on native rangeland, incorporation is obviously not an option and the drilling mud remains on the soil surface or vegetation canopy.

Native grasslands are among ecosystems on the Canadian prairies that are most pressured by various land uses. It is estimated that only 24% of the Mixedgrass and Dry Mixedgrass Natural Subregions of western Canada remains, as a result of fragmentation by urbanization, industrial development, live-stock grazing, or conversion of rangeland to annual cropping or seeded pastures (Environment Canada 2007). Native plant species could conceivably show different patterns of response to drilling mud application, resulting in changes in plant community composition and structure. As a result, there is a need for more information on the potential impacts of LWD on these ecosystems in order to prevent further degradation.

Potential benefits of LWD include elimination of the need for local or remote sumps to store drilling waste, which in turn, reduces truck traffic and disturbance on native prairie associated with drilling mud haulage from wellsites to sumps. On the other hand, LWD may adversely affect vegetation through plant uptake of toxic components or excess coating or burial of the vegetation (which could inhibit photosynthesis or delay flowering or seed set). Detrimental effects on native prairie soil properties have recently been reported. For example, studies in western Canada indicate that moderate to high rates (40 and $80 \text{ m}^3 \cdot \text{ha}^{-1}$) of LWD can reduce the near-saturated hydraulic conductivity of sandy loam soils under native prairie (Zvomuya et al. 2009). Results from a related study showed that LWD rates of $40 \text{ m}^3 \cdot \text{ha}^{-1}$ or higher resulted in lower ground surface albedo leading to elevated surface heat flux and root zone temperature in native prairie soils during summer (Zvomuya et al. 2008).

The objective of this study was to assess the impacts of drilling mud application on native prairie vegetation. Specifically, the study examined 1) changes in plant canopy cover, 2) biomass production, and 3) total nutrient and elemental concentration of native plant species following one-time, summer applications of WBM.

METHODS

Site Description

The study was located within the Canadian Forces Base (CFB) Suffield Range (lat $50^{\circ}15'N$, long $111^{\circ}12'W$) near Medicine

Hat, Alberta. The Range is comprised of 2690 km^2 of biologically diverse native prairie landscape and lies within the Dry Mixedgrass natural subregion of Alberta. The area has a typical continental climate with cold winters, warm summers, and low precipitation. Monthly mean temperatures (1971–2000) vary from -13°C in January to 20°C in July and annual precipitation averages 318 mm , $\sim 70\%$ of which is rainfall. Due to the warm temperatures and high wind speed throughout the summer, evaporation is high ($\sim 365 \text{ mm}$ annually; EnCana Corp, unpublished data), resulting in an annual moisture deficit of nearly 50 mm .

The soil at the site is a Typic Haploboroll of sandy loam texture. Plant canopy cover is dominated by the grasses *Bouteloua gracilis* (Kunth) Lag. ex Griffiths and *Hesperostipa comata* Trin. & Rupr. while *Sphaeralcea coccinea* (Nutt.) Rydb. was the dominant forb. The site had not been grazed by cattle since fall 2003. Oil and gas development at CFB Suffield commenced in 1975 and to date, more than 9000 natural gas and at least 500 oil wells have been drilled (EnCana Corp, unpublished data).

Experimental Design

The experiment consisted of 45, 100-m long \times 12-m wide contiguous plots, which occupied an area of $100 \times 540 \text{ m}$. Conventional landspraying equipment (18 m^3 vacuum truck) was used to apply the drilling mud in late June 2004, 2005, and 2006. The plot length included a 25-m headland at each end to allow start-up of the vacuum trucks to attain correct forward speed and shut-down at the end of the plot.

We used a staggered-start design (Loughin et al. 2007), which included three replications in time (2004, 2005, and 2006) and triplicate LWD rate treatments (0, 15, 20, 40 and $80 \text{ m}^3 \cdot \text{ha}^{-1}$) in each year arranged in a randomized complete block design. Fifteen plots were treated in each of the 3 yr for a total of 45 plots.

Drilling Mud Application

The spent drilling mud used in the experiment came from different wells and was derived from a WBM system, which was an aqueous suspension of bentonite (primarily sodium montmorillonite) in freshwater. Prior to mud application on the plots, application rates were verified using Harmonie disposable underpads (padded area $48.5 \times 35 \text{ cm}$; weight 24.2 g ; SCA Hygiene Products, Drummondville, Québec). The spreading width of the vacuum truck was adjusted to 12 m, which was the width of each individual plot. Calibration entailed laying eight underpads on the ground in each of two parallel 12-m wide rows that were 10 m apart. The vacuum truck was then driven across the middle of and perpendicular to the rows, starting 25 m from the first row, adjusting the truck speed and pump pressure until the target mud rate was achieved. The rate after each pass was determined from the net weight gain of the mud-soaked underpads and the specific density of the mud. The speed and pressure corresponding to each rate was noted for use in the appropriate plots. During application to plots, actual mud rates applied were verified by placing underpads on the ground surface in the spread path of the drilling mud application. Two 12-m rows of eight underpads each were placed at the 25-m mark from each end of the plot. One or

more passes were made down the centre of the plot while making sure the mud spray did not extend to adjacent plots. Actual rates applied were then calculated as described for the calibration above.

Drilling Mud Characterization

Chemical Analysis. Drilling mud samples were taken in duplicate from each of the 21 truckloads for chemical and physical analysis. Multi-element concentrations were determined by inductively coupled plasma optical emission spectrometry (ICP-OES; Spectro Analytical Instruments, Kleve, Germany) following digestion of freeze-dried mud subsamples according to US Environmental Protection Agency (USEPA) Method 3050B (USEPA 1996). The actual oven-dry weight of the subsamples ranged from 0.13 g to 2.4 g (mean 0.4 g) per 50 mL digest, reflecting differences in mud density among truckloads. Elemental concentrations are reported on a dry weight basis.

For determination of major analyte and trace element concentrations in solution, the drilling mud was centrifuged and the supernatant filtered through a Whatman #1 (11 μm) filter paper. Electrical conductivity (EC) and pH of the extract were measured with a pH/conductivity meter (Accumet pH meter 50; Fisher Scientific, Hampton, NH). Dissolved N ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) concentration was determined in the supernatant by micro-segmented flow analysis using an Astoria 2 Analyzer (Astoria-Pacific International, Clackamas, OR). Multi-elemental concentrations in the extract were determined by ICP-OES as described above. Sodium adsorption ratio (SAR) was calculated from Na, Ca, and Mg concentrations from the ICP analysis.

Mud Density. The density of drilling mud from each truckload was measured using a mud balance (Wyo-Ben, Inc, Billings, MT). Dry bulk density (DBD; i.e., the weight of dry solids per unit volume of wet mud) was calculated by substituting the measured mud density into the following equation:

$$\text{DBD}(\text{kg} \cdot \text{m}^{-3}) = \left\{ \left[\text{measured mud density}(\text{kg} \cdot \text{m}^{-3}) - 1000(\text{kg} \cdot \text{m}^{-3}) \right] \times 2.65(\text{g} \cdot \text{cm}^{-3}) \right\} / \left[2.65(\text{g} \cdot \text{cm}^{-3}) - 1(\text{g} \cdot \text{cm}^{-3}) \right]$$

where measured mud density is equal to specific gravity ($\text{g} \cdot \text{cm}^{-3}$) \times 1000, 2.65 is the particle density of solids, and 1 000 $\text{kg} \cdot \text{m}^{-3}$ ($=$ 1 $\text{g} \cdot \text{cm}^{-3}$) is the density of water.

Vegetation Measurements

Canopy cover for each species was visually estimated in July each year using the percentage cover method of Daubenmire (1968) in two transverse transects situated 40 m from either end of each plot. Canopy cover (%) was assessed in six quadrats per transect, avoiding vacuum truck wheel tracks. The data were used to compute species richness (S), species evenness (E), and species diversity (Shannon–Wiener Index, H'). Plant species in the plots were classified into two growth forms: grasses/grass-like and forbs. Seed-head density of dominant grasses was determined by counting the number of inflorescences within each 0.25 m^2 quadrat.

Visual estimates of ground cover were conducted as well, and included the basal cover of live vegetation, little club moss, lichen, litter, or bare ground. Percent bare ground was calculated as the difference between 100% and the sum percent of areas covered by moss, lichen, and litter plus the basal area of live vegetation (Willms et al. 2002).

Standing vegetation was clipped at ground level each year from six 0.5 \times 0.5 m areas within each plot (outside the quadrats used for plant cover assessment), avoiding areas that had been clipped the previous year. Surface litter was hand-raked from a 0.5 \times 0.2 m area inside two of the six clipped quadrats. Standing biomass and litter samples were stored separately and oven-dried to a constant weight at 70°C. A subsample consisting of 10% of the total standing biomass from each plot was hand-sorted into annual production from the current year (live standing biomass or annual net primary production [ANPP]) and biomass from previous years (dead standing biomass; Willms et al., 2002). These were separately weighed and ground in a Wiley mill using a 20-mesh screen prior to chemical analysis. The proportions of live biomass and standing dead biomass were applied to the total biomass yield from each plot to estimate ANPP and standing litter as described by Willms et al. (2002).

Determination of Ash-free Dry Weight. Ash concentration of all plant material was determined to eliminate the variation in dry weight that might arise from drilling mud application. Oven-dry subsamples from each plot were composited, thoroughly mixed, and weighed to determine “dry weight.” Coarse plant material was separated from any fines settled at the bottom of the bowl. The weight of the fine material was recorded (it was assumed dead:green ratio was similar to that in coarse material). A subsample (\sim 10 g) from the coarse material was separated into live and dead (standing) biomass, which were then weighed separately. The green and dead biomass subsamples were ashed in a muffle furnace at 650°C for 24 h. The ash residue (inorganic remains) was weighed, and ash-free dry weight (AFDW) was obtained by subtracting the ash weight from the corresponding oven-dry weight. All dry matter yields and chemical analyses on the rest of the biomass sample were expressed on an AFDW basis.

Plant Tissue Analysis. Plant samples were oven-dried at 70°C before chemical analysis. Fine-ground samples ($<$ 0.15 mm) were analyzed for total C and N by dry combustion using an automated CNS analyzer (Carlo Erba, Milan, Italy). Total P, S, and trace element ion concentrations were determined following digestion of 0.25-g subsamples with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). Simultaneous analysis of the elements was performed by ICP-OES (Spectro Analytical Instruments).

Data Analysis

Canopy and basal cover data were $\log_e(x + 10)$ -transformed to meet assumptions of normality (Shapiro Wilks test) and equality of variances (Levene’s test). These and the nontransformed diversity index (S , E , and H') data were analyzed using PROC MIXED for repeated measures in SAS (Littell et al. 1996; SAS Institute 2005), with time elapsed (days after

Table 1. Measured pH, electrical conductivity (EC), sodium adsorption ratio (SAR), water, and solids content of drilling muds applied during the 3 yr.

Parameter	pH	EC	SAR	H ₂ O	Solids
		dS · m ⁻¹		----- g · kg ⁻¹ -----	
Minimum	7.17	2.50	7.98	620	105
Maximum	10.8	9.97	57.2	895	380
Mean	8.12	4.95	19.1	764	236
Median	7.50	4.13	18.1	767	233

treatment [DAT]) as a repeated measures effect with the first order autoregressive covariance structure. Year was also included as a repeated measures effect in the model that allowed for random variations over time (Loughin et al. 2007). The Tukey multiple comparison procedure was used for all pairwise comparisons. Effects were considered significant if $P \leq 0.05$.

RESULTS

Precipitation

Weather data were obtained from the CFB Suffield weather station. Annual rainfall totals were 179, 332, 221, and 200 mm for 2004, 2005, 2006, and 2007, respectively. Corresponding annual snow totals were 86, 52, 92, and 62 mm. In 2005, which was the wettest of the 4 yr, 156 mm of rainfall were received in June alone, compared with 34–89 mm for the other 3 yr. The long-term mean rainfall total for June at Suffield is 58 mm. Of the total rainfall received in June 2005, 27 mm were recorded within a day following mud application. In contrast, rainfall amounts within 4 wk of mud application were minimal in 2004 and 2006.

Drilling Mud Rates

The measured mud rates applied using vacuum trucks during the 3 yr averaged 14, 18, 42, and 90 m³ · ha⁻¹ for target rates of 15, 20, 40, and 80 m³ · ha⁻¹, respectively, indicating reasonable accuracy (93%, 90%, 105%, and 113% of target rates, respectively), with an overall coefficient of variation of 12.3%. Our calibrations indicated that at a pumping pressure of 69 kPa at 1200 rpm, truck speed ratios corresponding to 4H, 3H, and 1L were associated with mean mud application rates of 14.5 ± 0.5, 19.2 ± 2.0, and 29.4 ± 2.2 m³ · ha⁻¹. We were unable to attain rates > 30 m³ · ha⁻¹ in one pass with a spread width of 12 m in this study, thus necessitating multiple passes (in immediate succession) for the 40 (two passes at 3H) and 80 (two passes at 1L and one pass at 3H) m³ · ha⁻¹ rates. This partly explains the lower accuracy associated with the 40 and 80 m³ · ha⁻¹ rates.

Drilling Mud Properties

Specific density of the drilling mud ranged from 1.08 to 1.26 g · cm⁻³ in 2004, 1.07 to 1.20 g · cm⁻³ in 2005, and 1.13 to 1.22 g · cm⁻³ in 2006. This variability was expected because the mud came from multiple wells since a single well could not

supply enough mud for all plots. Filtrate pH, EC, SAR, water content, and solids content of drilling muds are presented in Table 1, while total and available N concentrations are presented in Table 2. Based on the available N concentrations, a target LWD rate of 20 m³ · ha⁻¹ would add available N of up to 20 kg · ha⁻¹. Concentrations of other major nutrients, minor nutrient elements, and Na are presented in Table 2, while the rest of the trace elements are presented in Table S1.¹ These data indicate a wide variability in elemental concentrations, likely reflecting the vertical and spatial variation in the distribution of these elements in the different formations drilled, as well as, in some cases, varying amounts of additives applied to the muds.

Vegetation Properties

Drilling mud rate had a significant effect on only two of the six basal cover classes: lichen and bare soil (Table 3). Lichen basal cover was significantly lower at 80 m³ · ha⁻¹ (0.35%) compared to the control (1.76%) but differed little among the rest of the rates. The opposite effect was observed for bare soil exposure, which was highest at the 80 m³ · ha⁻¹ rate (6.12%) vs. the control (4.1%). All other basal cover classes were unaffected by LWD rate and none of the six were affected by time of sampling.

Canopy coverages for the major grass and grass-like species were dominated by *B. gracilis* (mean 41%) and *H. comata* (31%) followed by *Carex* spp. (15%; Table 4). Other major species were *Koeleria macrantha* (Ledeb.) Schult., *Pascopyrum smithii* Rybd., and *Calamagrostis montanensis* Scribn. ex Vasey, which accounted for 3%, 2%, and 1% of the canopy cover, respectively. Drilling mud application had no significant effect on any of the species, but temporal variation was evident for *H. comata* and *C. montanensis*. *H. comata* canopy cover was highest 45 and 410 DAT while that for *C. montanensis* was highest 45 DAT. Drilling mud rate and application time effects were significant only for *K. macrantha* inflorescence density for which the inflorescence density was higher at the 40 m³ · ha⁻¹ (1.12 [0.25 m²]⁻¹) compared with the control (0.64 [0.25 m²]⁻¹) and significantly higher at the 775 (3.01 [0.25 m²]⁻¹) DAT than at any other sampling time (0.38–0.85 [0.25 m²]⁻¹).

Dominant forb species were *S. coccinea* (3.6% of total canopy cover, averaged across drilling mud rates), *Artemisia frigida* Willd. (2.1%), *Phlox hoodii* Richardson (0.74%), *Plantago patagonica* Jacq. (0.4%), and *Erigeron caespitosus* Nutt. (0.2%; Table 5). *E. caespitosus* cover at 1140 d after treatment was significantly higher at 15 m³ · ha⁻¹ (1.02%) than at all other rates (< 0.01%). Rate effects at dates before 1140 DAT were not significant (geometric means 0.07%, 0.35%, and < 0.01% at 45, 410, and 775 d after treatment, respectively). *A. frigida* cover was significantly higher at 775 DAT (3.05%) compared with 0 DAT (1.40%), while *P. patagonica* was significantly higher at 1140 DAT (0.98%) compared to 0, 45, and 410 DAT (0.09–0.15%).

Total biomass yields assessed each year averaged 1.6 Mg · ha⁻¹ over the 3 yr (Table S2). The total biomass was not significantly affected by LWD rate but decreased with time from a mean of 1.74 Mg · ha⁻¹ in the baseline and at 45 DAT to 1.32 Mg · ha⁻¹ at 1140 DAT. ANPP was not affected

¹Available at <http://dx.doi.org/10.2111/REM-D-10-00028.s1>.

Table 2. Concentrations of major and minor nutrient elements in the drilling mud applied in the study plots during the 3 yr.

Parameter	N			P	K	S	Ca	Mg	Na	Fe	Cu	Zn	Mn	B	Mo
	Total	NO ₃	NH ₄												
	g · kg ⁻¹			mg · kg ⁻¹ mud											
Minimum	1.12	0.05	< 0.01	598	2590	5886	12302	5594	2195	23965	23.9	104	113	8.8	0.88
Maximum	5.65	808	38.45	1656	4000	19883	40196	10664	6727	31374	113.0	182	390	40.9	6.96
Mean	2.22	246	9.35	889	3126	13308	18614	7219	4076	27252	36.8	120	192	26.4	3.40
Median	1.58	222	3.79	773	3136	13307	15518	7117	3654	27186	32.2	117	189	27.5	3.30

by LWD rate or time elapsed since mud application and averaged 1.1 Mg · ha⁻¹. Standing dead biomass (mean 0.5 Mg · ha⁻¹) and ground litter (0.4 Mg · ha⁻¹) were also not significantly affected by LWD rate. Similarly, there were no significant effects (data not shown) of LWD rate or time of sampling on plant *S*, *H'*, and *E*. These indices averaged 11 (0.25 m²)⁻¹, 1.9, and 0.8, respectively.

Nutrient Concentration in Plant Tissue

Aboveground Standing Live Biomass. Total N concentration in plant tissue of ANPP (16.3 to 17.7 g · kg⁻¹) was significantly affected by LWD rate; however, the rate effect varied with time elapsed since mud application, as indicated by the significant rate by time interaction (Table S3). The N concentration increased by 0.4% for each 1 m³ · ha⁻¹ LWD rate increment ($r^2 = 0.92$) in live biomass samples collected 45 d after mud application, but there were no significant changes in the concentration measured at later sampling dates (Fig. 1a). At all rates investigated, N concentrations were lowest (mean 15.1 g · kg⁻¹) in samples taken 775 and 1140 d after mud application.

There was a significant rate by time interaction for P concentration in the live biomass (Table S3), which indicated

that LWD effects differed with sampling time. The P concentrations at LWD rates of 40 and 80 m³ · ha⁻¹ were significantly higher than those in the control in samples collected 1140 DAT, but no significant rate effects were detected at earlier sampling times (Fig. 1b). The P concentrations at the 40 and 80 m³ · ha⁻¹ rates were also significantly higher at 1140 DAT compared with concentrations measured in samples taken just before (baseline) or 1 yr after mud application.

Tissue concentrations of S, Mg, and Na increased significantly with LWD rate at 45 DAT, but no significant effects were observed at later sampling dates (Table S3; Fig. 1). At all sampling dates, drilling mud rate had no significant effect on Ca and K concentrations in the live biomass.

Aboveground Standing Dead Biomass. Elemental concentrations in the standing litter were lower than those in the live biomass, with the exception of Ca and Na concentrations, which were 2% and 44% higher, respectively, in the standing litter (Table S4). Nitrogen (mean 10 g · kg⁻¹), P (808 mg · kg⁻¹) and K (2012 mg · kg⁻¹) concentrations were not significantly affected by LWD rate, while N concentration was significantly lower 3 yr after mud application (9.1 mg · kg⁻¹) compared to samples collected 1 yr post-treatment or earlier (10.4–10.9 mg · kg⁻¹). Drilling mud rate effects on tissue concentra-

Table 3. Changes in basal cover with drilling mud rate and sampling time. Probability values in bold indicate significance at $P \leq 0.05$.

Treatment	Lichens	Ground litter	Total vegetation	Bare soil	Live club moss	Dead club moss
-----%-----						
Rate (m ³ · ha ⁻¹)						
0	1.76 a ¹	24.62	46.59	4.10 b	10.49	12.42
15	1.07 ab	25.69	46.73	4.26 ab	10.24	12.01
20	0.57 ab	24.67	46.63	3.99 b	10.77	13.37
40	1.25 ab	24.58	46.03	4.85 ab	10.29	13.00
80	0.35 b	25.54	46.62	6.12 a	8.59	12.79
Time (DAT) ²						
0	1.09	25.74	43.97	4.86	11.99	12.35
45	0.90	24.93	43.43	5.07	10.88	14.79
410	1.01	23.91	43.52	6.88	10.16	14.53
775	0.88	23.96	50.69	4.16	8.51	11.80
1140	1.00	26.55	52.11	2.52	8.33	9.49
-----P value-----						
Rate	0.03	0.57	0.43	0.01	0.67	0.71
Time	0.81	0.75	0.85	0.45	0.21	0.21
Rate · Time	0.99	0.84	0.99	0.49	0.67	0.73

¹Means within a column followed by the same letter are not significantly different according to Tukey's multiple comparison test ($P \leq 0.05$).

²DAT, days after treatment.

Table 4. Changes in major grass species canopy cover with drilling mud rate. Probability values in bold indicate significance at $P \leq 0.05$.

Treatment	<i>B. gracilis</i>	<i>K. macrantha</i>	<i>H. comata</i>	<i>C. montanensis</i>	<i>Carex</i> spp.	<i>P. smithii</i>
-----%-----						
Rate ($m^3 \cdot ha^{-1}$)						
0	36.6	2.17	34.0	0.74	18.6	0.78
15	42.3	2.04	28.4	0.95	16.9	2.61
20	44.5	2.58	29.8	0.78	11.9	3.20
40	41.0	4.57	31.2	0.78	13.9	1.66
80	42.2	2.65	30.7	1.00	15.7	0.66
Time (DAT) ²						
0	41.5	2.27	30.8 ab ¹	0.71 b	16.4	1.75
45	43.2	3.06	31.1 a	1.23 a	13.0	2.01
410	41.7	2.51	31.4 a	0.73 b	14.5	1.65
775	39.5	3.74	30.5 b	0.71 b	16.1	1.77
1 140	41.4	2.28	30.2 b	0.92 ab	16.8	1.50
----- P value -----						
Rate	0.31	0.27	0.43	0.17	0.27	0.17
Time	0.78	0.27	0.05	0.05	0.30	0.96
Rate · Time	0.99	0.96	0.99	0.75	0.99	0.99

¹Means within a column followed by the same letter are not significantly different according to Tukey's multiple comparison test ($P \leq 0.05$).

²DAT, days after treatment.

tions of S, Mg, Ca, and Na were significant only in samples taken at 45 DAT, in which the concentrations increased with LWD rate (Fig. 2).

DISCUSSION

Overall, this study showed no evidence of detrimental effects on important vegetation properties at rates $\leq 20 m^3 \cdot ha^{-1}$ or

$\leq 6 Mg \cdot ha^{-1}$ total solids loadings, which are commonly applied in western Canada. Even at the $40 m^3 \cdot ha^{-1}$ rate, there were no significant negative effects on vegetation attributes. Results from an earlier study (Zvomuya et al. 2008) showed that at LWD rates of 40 and $80 m^3 \cdot ha^{-1}$, drilling mud application could alter soil micrometeorological properties that may impact on plant growth. Any such impacts, however, were not evident in vegetation measurements from the present study. It is noteworthy that micrometeorological effects in the

Table 5. Changes in canopy cover of major forb species with drilling mud rate and sampling time. Probability values in bold indicate significance at $P \leq 0.05$.

Treatment	<i>E. caespitosus</i>	<i>P. hoodii</i>	<i>A. frigida</i>	<i>S. coccinea</i>	<i>P. patagonica</i>
-----%-----					
Rate ($m^3 \cdot ha^{-1}$)					
0	0.12	0.87	2.81	3.22	0.09
15	0.70	0.35	2.50	2.95	0.33
20	0.08	0.92	1.77	3.92	0.54
40	0.11	0.73	1.70	3.87	0.54
80	0.11	0.84	1.58	4.02	0.54
Time (DAT) ²					
0	0.56	0.70	1.40 b ¹	3.77	0.15 c
45	0.07	0.73	1.95 ab	3.56	0.09 bc
410	0.35	0.67	1.89 ab	4.49	0.11 bc
775	< 0.01	0.73	3.05 a	3.29	0.66 ab
1 140	0.16	0.87	1.95 ab	2.96	0.98 a
----- P -----					
Rate	0.01	0.74	0.51	0.34	0.77
Time	0.02	0.84	0.01	0.53	< 0.0001
Rate · Time	0.02	0.97	0.99	0.76	0.87

¹Means within a column followed by the same letter are not significantly different according to Tukey's multiple comparison test ($P \leq 0.05$).

²DAT, days after treatment.

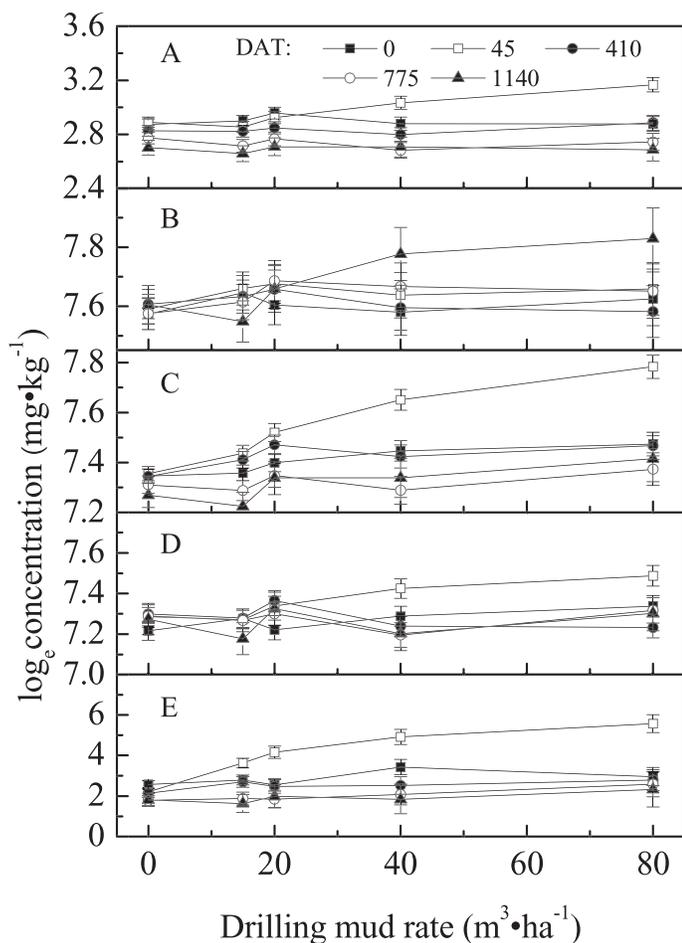


Figure 1. Effects of drilling mud rate and sampling time (days after treatment [DAT]) on tissue elemental concentration in the live biomass (A: nitrogen; B: phosphorus; C: sulfur; D: magnesium; and E: sodium).

aforementioned study were monitored for less than 2 mo, thereby precluding assessment of persistent effects over an extended period. Other evidence (Zvomuya et al. 2009) indicates that drilling mud application at the $80 \text{ m}^3 \cdot \text{ha}^{-1}$ rate can impede near-saturated hydraulic conductivity, ostensibly due to clogging of conductive macropores in the receiving soil. Water that fails to infiltrate and instead remains on the soil surface is subject to runoff or evaporation losses, and is therefore not available for plant uptake or soil storage. Under the semi-arid conditions of the current study site, this would be expected to adversely affect nutrient uptake, plant growth, and ANPP. However, such effects were not evident, perhaps because the hydrological effects did not persist beyond 1 yr following drilling mud application. High rainfall (332 mm) in 2005, particularly the 27 mm recorded within a day of mud application, meant that much of the mud was washed off the vegetation before it had enough time to impart any adverse effect on the vegetation.

The decrease in lichen cover at the $80 \text{ m}^3 \cdot \text{ha}^{-1}$ LWD rate compared with the control was probably due to smothering of lichens by the mud. With the disappearance of the lichen cover, more soil was exposed, explaining the significant increase in bare ground at the highest LWD rate. A high lichen cover is considered beneficial to the semi-arid grasslands as it contributes

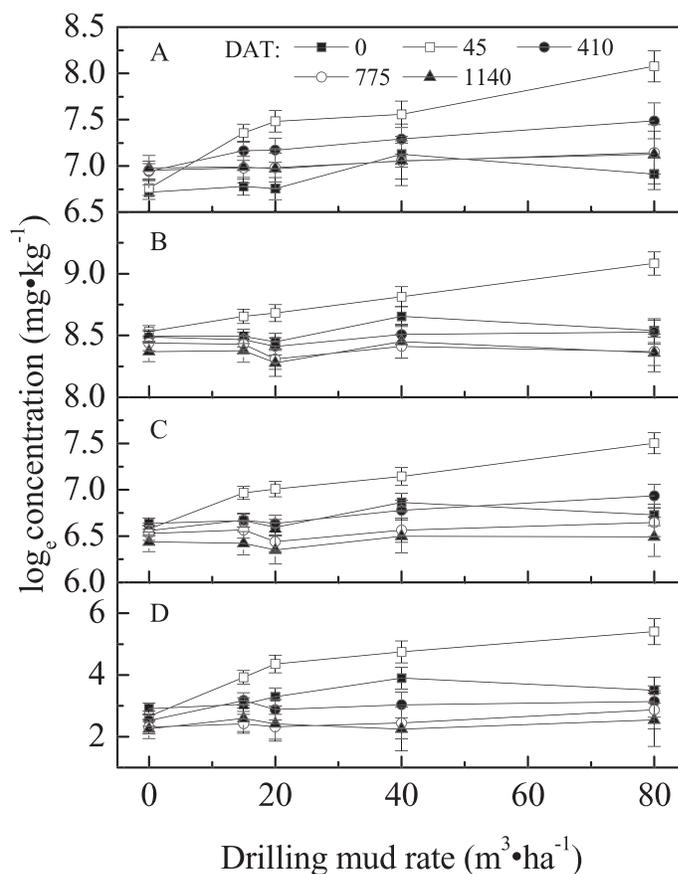


Figure 2. Effects of drilling mud rate and sampling time (days after treatment [DAT]) on tissue elemental concentration in the standing dead biomass (A: sulfur; B: calcium; C: magnesium; and D: sodium).

to stabilization of the soil, improvement of water infiltration, and nitrogen fixation by blue-green algae (Willms et al. 2002).

The observed LWD rate effects on tissue N, S, and Mg concentrations 45 d after mud application is consistent with the plant availability of these elements once applied to the soil. Unlike P addition in the LWD, which had no immediate effect (i.e., within the first year), these elements do not form products, in the mud or in the soil, that are only slowly available. Thus, they become immediately available for uptake by plants as soon as they are applied to the soil. Secondly, since LWD leaves the mud and its constituent elements on the surface, the elements have to be translocated into the root zone before they can be taken up by plants. Elements such as N, S, and Mg, a large proportion of which remains in a soluble form, are therefore more easily transported with percolating water to the root zone. Because there is no slowly-available form of these elements added with the mud, their effects on tissue concentrations do not persist beyond 1 yr. By contrast, P forms various insoluble or slowly-available compounds or complexes in the soil, and therefore moves more slowly down the profile to the root zone. This explains why significant P effects in plant tissue are only observed 3 yr after LWD. Phosphorus is also strongly adsorbed by soil constituents, which makes it more slowly-available for plant uptake.

Although median total N loadings ranged from $28.9 \text{ kg} \cdot \text{ha}^{-1}$ at the $15 \text{ m}^3 \cdot \text{ha}^{-1}$ LWD rate to as much as $154 \text{ kg} \cdot \text{ha}^{-1}$ at the

80 m³ · ha⁻¹ rate, treatment differences in biomass yield and species diversity were not observed. This was not surprising, considering that only ~15% of applied N was readily available (predominantly NO₃-N). Similar N fertilization effects on mixed-grass prairie have been reported elsewhere. For example, Samuel and Hart (1998) found no increase in biomass production following application of up to 34 kg · N · ha⁻¹ to mixed-grass rangeland in southeast Wyoming. By contrast, many other studies on native range in the central and northern Great Plains have reported increases in biomass production in response to very low to very high N rates (e.g., Black and Wight 1979; Power 1985; Jacobsen et al. 1996). A few others have reported changes in species diversity in response to N application (Goetz 1969; Rauzi and Fairbourn 1983; Samuel and Hart 1998). For example, in a study on rangeland in southwestern North Dakota, three annual applications of up to 112 kg · N · ha⁻¹ reduced cover of *B. gracilis* (H.B.K.) Griffith's and increased cover and density of *P. smithii* (Rydb.) A. Love and *Artemisia* spp. (Goetz 1969).

Another study examining the response of more than 900 plant species to N fertilization in North American terrestrial ecosystems demonstrated a significant loss in species diversity, including that of native grasses, regardless of their initial abundance, as production increased with N application (Suding et al. 2005). The difference in response between these and our study is not surprising: in these past studies, fertilizer was applied as a nutrient source containing no other potentially detrimental additives. By comparison, the nutrients in our study were contained in a matrix (drilling mud) that could adversely affect plant growth through, for example, coatings on the vegetation canopy that interfere with light interception and absorption and CO₂ uptake. Reduced photosynthesis and productivity due to particulate coverings on plant canopies are well documented and have been attributed to leaf shading and interference with stomatal activity (Farmer 1993; Hirano et al. 1995; Sharifi et al. 1997; Glenn et al. 2001). Hirano et al. (1995) further noted that additional absorption of incident radiation by the chemically inert dust tested in their study increased leaf temperature and consequently, altered photosynthetic rate and increased transpiration. Such effects have been found to be significant in situations, such as in the present study, where the fine particles are deposited during the day when stomata are open, thus plugging the stomata (Thompson et al. 1984) and preventing them from closing during dark hours (Flückiger et al. 1979). The effects are likely to be greater in the case of drilling mud, which, unlike dusts, covers the leaf surfaces with a crust. It is possible that such adverse, confounding effects may have counteracted any yield benefits from the nutrient additions.

Additionally, application of N and other elements/additives within the same treatment varied by year and sometimes within a given year, possibly resulting in high variability in vegetation response, and therefore possibly a reduced power to detect significant differences. Perhaps more important is the possibility that much of the inorganic N added with the mud was immobilized by microorganisms in the organic matter-rich surface soil, which has low native N reserves. Rapid immobilization of applied N in mixed prairie soil is well-documented (Risser and Parton 1982; Willms and Jefferson 1993). Power (1972) reported that N immobilization by plant

roots, soil organic matter, and microbial cells plus gaseous losses accounted for as high as 37% (200 kg · N · ha⁻¹) of N applied (540 kg · N · ha⁻¹) in an *Agropyron-Stipa-Bouteloua* community. Furthermore, while it is well established that soil moisture and temperature regimes play a critical role in regulating N transformations (Power 1967) and productivity (Willms and Jefferson 1993) in grassland soils, it has been shown in other studies that N application alone is unlikely to greatly increase biomass yield if moisture is limiting (Smika et al. 1965). In our study, drilling mud (hence N) applications were typically followed by long, dry periods, which are typical of the Dry Mixedgrass natural subregion of Alberta, and this might have contributed to low availability of N for plants, thus resulting in no biomass yield increase.

The lower concentrations of nutrient elements measured in the standing dead biomass vs. that in live biomass were expected and have been reported in other studies (e.g., Sundriyal and Joshi 1992). Towards the end of the growing season, nutrients are translocated from aboveground biomass to roots and rhizomes (Sundriyal and Joshi 1992), resulting in lower concentrations in the standing dead biomass compared with live, current season biomass. Additionally, nutrients within dead biomass from the previous season may be leached out by precipitation and translocated to new tissue (Dowding et al. 1981).

The drilling mud used in this study presents no toxicity concern to grazing animals. Trace element concentrations in the mud (Table S1) were low and did not significantly raise concentrations in the soil or plant tissue relative to the control (data not presented). Total lifetime loadings (per ha), from all disposal methods, allowed by Alberta regulations in order to protect animals and flora are 10 kg boron (B), 3 kg cadmium (Cd), 200 kg chromium (Cr), 400 kg copper (Cu), 200 kg lead (Pb), 50 kg nickel (Ni), and 600 kg zinc (Zn; Alberta Energy and Utilities Board 1996). In this study, loadings of these trace elements were small even at the highest LWD rate (80 m³ · ha⁻¹) at which only 2.7 kg B, 0.2 kg Cd, 2.3 kg Cr, 3.8 kg Cu, 2.5 kg Pb, 4.0 kg Ni, and 11.1 kg Zn were added per ha.

IMPLICATIONS

Drilling mud application at rates commonly applied in western Canada had no significant effect on most native vegetation properties measured in this study. Exceptions were bare ground, which increased, and lichen cover, which decreased at the 80 m³ · ha⁻¹ rate relative to the control. Our results also indicated significant LWD effects on plant tissue chemistry, specifically N, P, Mg, and S concentrations. The more soluble nutrient elements, N, Mg, and S, increased significantly with increasing LWD rate in samples taken 45 d after drilling mud application; however, no significant LWD effects were detected after 1 yr. Tissue P concentration, on the other hand, showed significant LWD rate effects only after 3 yr since LWD. Nonetheless, these changes in tissue chemistry were not associated with significant changes in the biomass yield or species composition.

Overall, our results indicate that proper, one-time applications of water based drilling mud at rates (≤ 20 m³ · ha⁻¹) commonly applied in western Canada are unlikely to cause significant adverse effects on native prairie vegetation. This has

important implications on the management of drilling waste on native prairie in this and other regions. When current Alberta regulations, as embodied in Directive 50, were promulgated in 1993 and revised in 1996 (Alberta Energy and Utilities Board 1996), they represented the best current knowledge and practices undertaken in the Province at the time, with the understanding that the regulations would be subject to review and modification as newer knowledge became available. Our results provide regulators and the petroleum industry with the first science-based information that can be used in the review of current regulations. In the event that such a review leads to relaxation of some of the restrictions on LWD, this could significantly reduce the ecological footprint associated with the mix-bury-cover disposal option (which involves mixing the drilling solids with clean soil and burying the mixed material in an unlined pit). While the practice of LWD has not been entirely satisfactory, in other regards, largely due to improper application methods leading to overapplication, our data confirm that with proper application, LWD can have minimal adverse effects on native prairie vegetation.

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