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Surface application of a saline-sodic oil & gas drilling waste to winter wheat (*Triticum aestivum* L.)

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A B S T R A C T

Increased oil and gas drilling has resulted in large quantities of water-base "mud" (WBM) that requires disposal. Land application of WBM to agricultural land is a common disposal technique that presents agronomic and environmental challenges since the material is rich in total soluble salts (TSS). The objective of this study was to determine the impact of WBM application rate on salt accumulation and leaching in the soil, and the impact of application timing and rate on wheat (*Triticum aestivum* L.) production. A field study was conducted where WBM was applied once, at varying times (Oct., Dec., Jan., Feb., and March) at a 0.66× (4480 kg TSS ha^{-1}) rate and 1.0× (6720 kg TSS ha^{-1}). Soil samples were taken at 0, 30, and 90 days after application and on August 28th (post-harvest) for evaluating electrical conductivity (EC), pH, and sodium adsorption ratio (SAR). WBM rates had no effect on soil pH. In general, increasing WBM application rates increased soil EC beyond non-amended soils at 0, 30 and 90 days after application. However, this was highly dependent on the amount of precipitation received between WBM applications and sampling. By August, soil EC had decreased below 4 mS cm^{-1} at the 0–15 cm depth. However, soil SAR increased at every sampling date after application. WBM application date and rate had no significant effect on wheat (*T. aestivum* L.) yield. Yield loss and salt accumulation can be minimized if WBM is applied at less than 6720 kg ha^{-1} with proper timing relative to rainfall and crop growth patterns.

1. Introduction

The oil and natural gas drilling industry uses water-base drilling mud (WBM) to help lubricate and cool the drilling bit, seal off porous geologic formations, balance subsurface and formation pressures required for the prevention of well blowouts, and carry geologic drill cuttings from the bottom of the well up to the surface (Ukeles and Grinbaum, 2004). Water-base mud is generally used during shallow vertical drilling operations. Deville et al. (2011) found that WBM was more effective in drilling when they were customized for each individual shale play and developed based upon the distinct formation chemistry. However, WBM is characterized as typically containing a high amount of water (>70%), total soluble salts (TSS), and sodium (Na). Therefore it is the high salinity and sodicity of the WBM that presents the greatest risk and challenge of land application. Due to the high moisture content, WBM is usually sprayed onto soils. Typically, WBM consists of colloidal clays (bentonite), potassium chloride, sodium hydroxide, lignite, barium sulfate, mica, ground nut shells, polymers, and numerous other additives depending on the exact chemistry needed for the particular well (Moseley, 1983). Typical diameter of drilling pipe is 10 cm with the bottom of the well borehole diameter reaching up to 20 cm. Drilling operations can last anywhere from a few days to more than a year (Ukeles and Grinbaum, 2004). On average, the amount of WBM needed to drill a well is equal to three times the total volume of the well (U.S. Army Corps of Engineers, 2001). After the well has been completed, spent drilling fluids and geologic formation cuttings are allowed to settle in a holding pit before disposal.

Recently, there has been an explosion of oil and natural gas exploration across the United States. Newer technologies such as hydrofracking and horizontal drilling have allowed more access to harder to reach oil and natural gas reserves. A large portion of United States oil and natural gas exploration is occurring in the state of Oklahoma. In Oklahoma from the year 2000 to 2011 on average there were 2500 new wells drilled every year. These wells consisted of oil, natural gas, and dry holes. From 2009 to 2011, drilling permits and average monthly rigs in Oklahoma increased from 2500 to 3732 and 94 to 180, respectively (Oklahoma Corporation Commission, 2011).

This escalation in oil and natural gas drilling ultimately leads to an increase in WBM waste, and a need to properly dispose of WBM. Potential hazards to soil and plants can occur from disposal of WBM due to the high concentration of total soluble salts and sodium. There are several methods

Abbreviations: WBM, water-base mud; TSS, total soluble salts; SAR, sodium adsorption ratio; EC, electrical conductivity; Na, sodium.

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of WBM disposal which include onsite burial (aka "reserve pits"), storage in hazardous waste landfills, underground injection, and land application to agricultural and range land. Depending on circumstances, one or more of these disposal techniques may be used. In Oklahoma, disposal of WBM waste occurs primarily by land application. Land application of WBM in Oklahoma involves spraying the slurry at a predetermined rate based on soil conditions and composition of the WBM. Land application of WBM is regulated by the Oklahoma Corporation Commission (OCC). The rules are specifically stated in the Oklahoma administrative code and register in Title 165:10–7-19.

When applying high concentrations of saline and sodic water via WBM application there is an increased risk of causing soils to become saline, sodic, or saline-sodic. The effects of saline and sodic soils can lead to the potential loss of yield in crops, stunting of plant growth, complete crop failure, and loss of land due to salinization (Rhoades and Loveday, 1990). Not only does sodicity decrease crop yield, it can also have a negative impact on soil physical properties. Zvomuya et al. (2009) conducted a field plot study looking at the effects of WBM applications on hydraulic properties for a sandy loam soil in Medicine Hat, Alberta Canada. Specific densities of the WBM for the years 2003–2005 were 1170, 1065, and 1130 kg m^{-3}. Some of the plots received a single application of 80 m^3 ha^{-1} and 40 m^3 ha^{-1} over the three year period while other plots received one application per year. There was a 0 m^3 ha^{-1} (control) included each year for comparison. It was found that when applying WBM every year at the rate of 80 m^3 ha^{-1}, soil structure, hydraulic conductivity, and the hydraulically active macroporosity were negatively affected, whereas the 40 m^3 ha^{-1} annual application had no significant effect on the soil hydraulic properties when compared to the control that received no WBM. The results also showed that there was no significant effect on soil hydraulic properties after the single WBM application of 80 m^3 ha^{-1}. Bauder et al. (2005) conducted a two year study in which WBM was land applied to wheat in loamy to sandy loam soils. The specific gravity of the WBM samples used ranged from 1.03–1.29 g cm^{-3}, pH ranged from 8.40–9.60, EC ranged from 1.14–2.63 dS m^{-1}. The WBM was applied once a year during the fallow period at multiple rates that ranged from 2.2–94 Mg ha^{-1}. The authors showed that while a WBM application rate of about 100 Mg ha^{-1} was not beneficial to wheat production, it was not detrimental to yield on three of the four test sites. Bauder et al. (1999) established a greenhouse experiment to examine the effects of applying WBM to corn (*Zea mays* L.) and sorghum-sudangrass (*Sorghum bicolor* L. Moench DeKalb ST-6′-*S. sudanense*) crop growth, and iron and zinc uptake. They found that sorghum-sudangrass and corn both had an increase in dry matter yield due to the beneficial iron and zinc in the drilling fluid when applied at rates of 5 to 60 g kg^{-1} soil. Soil EC, pH, and SAR increased, but did not negatively impact the soil.

Numerous studies have been carried out looking at the effects of land applying saline and saline-sodic water for irrigation. However, there is a scarcity of research examining the effects of WBM application on wheat production and soil chemical properties. Thus, the objectives of this study were to (i) monitor the impact of WBM application rate on salt accumulation and leaching in the soil over time, and (ii) determine the impact of application timing and rate on winter wheat (*Triticum aestivum* L.) production in the Southern Plains of Oklahoma.

2. Materials and methods

The location of this field trial was in Lahoma, Oklahoma. The study was conducted using the Billings (Oklahoma Foundation Seed Stocks, 2010) wheat (*T. aestivum* L.) variety on a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustolls). The experimental design for soil analysis consisted of a split-split plot that had eleven treatments replicated three times. The main plot was WBM application date and rate; the two splits were sampling day and soil depth. The experimental design for wheat yield analysis consisted of a randomized complete block with three replications and eleven treatments. Each plot was 3.05 by 6.10 m. Composite soil samples were taken from all three reps before WBM was applied and analyzed as described below. Prior to planting, plots were fertilized with DAP $(NH_4)_2HPO_4$ at 112 kg ha^{-1} and disked 10.2 cm deep and then cultivated. Fertilizer rates were applied based on OSU recommendations provided by Zhang and Raun (2006). Billings' wheat was planted two inches deep on October 18th, 2012 at a planting rate of 78 kg ha^{-1}. The wheat plots received an additional 34 kg N ha^{-1} in February. The application of WBM to the wheat plots began on October 16th, 2012. The mud had a total soluble salts (TSS) concentration of 156,000 mg L^{-1} and was applied at two different rates using a 1/10th horsepower electric water pump. The WBM volume was measured with a Seametrics (MJ-Series) water meter. The 0.66× and 1.0× rates applied 4480 and 6720 kg TSS ha^{-1}, respectively. After the October 16th application, the plots were cultivated again to mix the WBM within the soil prior to planting. Application of the WBM was continued in December, January, February, and March on different plots that had not previously received WBM. Once a plot had received the WBM application, composite soil samples were taken at 0 (immediately after application), 30, and 90 days after application, at depths of 0–7.5, and 7.5–15 cm. In addition, soils were sampled several months after wheat harvest on August 27th, 2013 (post-harvest).

All soil samples were ground and passed through a 2 mm sieve. 125 g of each soil sample was used in a modified saturated paste extraction (USDA, 1954). Electrical conductivity (EC) and pH were determined on all extracts. Random soil samples were duplicated and check soils were used to assure accuracy and precision of the results. Extracts were analyzed for Na, Ca, Mg, K, SO_4, B, P, Fe, Zn, Cu, Mn, Al, Mo, As, Cr, Cd, and Pb by ICP-AES. The sodium adsorption ratio (SAR) was calculated using the equation below, where the concentrations of Na, Ca, and Mg are expressed as milliequivalents per liter:

$$SAR = \frac{Na^+}{\sqrt{[Ca^{2+} + Mg^{2+}]/2}}.$$

The Cl extract concentrations were measured via Lachat-FIA. The background soil samples were additionally tested for Mehlich-3 (M3) extractable P and K (Mehlich, 1984), and KCl extractable ammonium and nitrate (1:5 ratio soil:1 M KCl, followed by ammonium and nitrate analysis by Lachat-FIA). All wheat plots were harvested for grain yield by a combine on June 20th, 2013. Sub-samples were dried in an oven at 65 °C and weighed.

Analysis of variance methods were utilized in PROC GLM (SAS Institute, 2011) to analyze the effect of WBM application rates and timing on soil chemical properties and wheat production. When the main effects or interactions of WBM application rates and timing were significant, treatment means were separated using pairwise comparisons via Duncan's multiple range test. Statistical decisions were made at $\alpha = 0.05$, unless noted otherwise. The data analysis for this paper was computed using SAS software (Copyright, SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA).

3. Results and discussion

3.1. Background soil and water-base mud properties

The soil utilized for this experiment was relatively low in soil TSS concentration (Table 1) when compared to the OCC requirements (Oklahoma administrative code and register, Title 165:10–7-19) which allows the soil to receive a maximum amount of WBM that would result in a TSS concentration of 6700 kg ha^{-1}. The low initial soil TSS concentration allowed for higher loading rates of the WBM to be applied which simulated a worst case scenario where a soil TSS would change from relatively low concentrations to the maximum amount of soluble salts allowed. Based upon Oklahoma soil nutrient recommendations that were established by Zhang and Raun (2006),