TRACKING SALT AND SODIUM BUILD UP DUE TO IRRIGATION WITH COALBED NATURAL GAS PRODUCT WATER: SOIL SOLUTION LYSIMETER AND SOIL SATURATED PASTE EXTRACT STUDIES[1]

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Abstract: Irrigation with coalbed natural gas (CBNG) co-produced water is a popular management option used by many gas companies operating in northwestern Powder River Basin (PRB), Wyoming. Depending upon local conditions and production rates, a CBNG well may be productive for 2 to 20 years, with an average lifespan of 7 years. At present there are over 20,000 CBNG wells permitted or drilled in the PRB region and it is estimated that another 50,000 to 100,000 new wells will be drilled in the future. The total CBNG water production in the PRB is expected to peak at about 47,000 ha-m in 2006 and the cumulative CBNG-water production during the period 2002-2017 is estimated to be 366,000 ha-m. CBNG water is dominated by sodium (Na^+) and bicarbonate (HCO_3^-) ions and the average discharge of a single CBNG well ranges from <1 to 100 liter per minute, with pH ranging from 6.8 to 9.0, electrical conductivities (EC) from 0.4 to 4 dS/m, Na adsorption ratio (SAR) from a low of 5 to an extreme high of 70 and total dissolved solids (TDS) concentrations from 270 to 2720 mg/L. Application of poorer quality CBNG water can have significant impacts on soil physical and chemical properties. Changes in soil chemistry due to land application of CBNG waters were investigated using lysimeters installed at depths of 15, 30, and 60 cm. Soil solutions collected during June to August 2004 from soil solution lysimeters were analyzed for EC and SAR. Soil solution chemistry data were compared with EC and SAR data from saturated paste extracts of CBNG irrigated soil samples collected at the same depth. Preliminary data indicate the build up of salts and Na in the upper horizons of irrigated fields. The EC values of lysimeter soil solution samples were greater than those of saturated paste. However, SAR of lysimeter soil solution and saturated paste extracts were comparable. The results of this study will be useful to understand potential changes in soil properties due to land application of CBNG waters and to develop possible mitigating criteria for reclaiming impacted PRB ecosystems.

Additional Key Words**:** Lysimeters, soil saturated paste, CBNG water, irrigation, electrical conductivity, sodium adsorption ratio, Powder River Basin (PRB), Wyoming

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Introduction

Powder River Basin (PRB), which covers parts of Wyoming and Montana, is one of the most active coalbed natural gas (CBNG) producing area in the U.S. Natural gas (i.e., Methane) is an important source of energy for the nation's residential and industrial sectors, and coal seams are one of our important sources of natural gas (Pinkser, 2002). Coalbed natural gas production involves pumping water (hereafter referred to as CBNG water) from coal seams to reduce hydrostatic pressure. At present there are over 20,000 CBNG wells permitted or drilled in the PRB region, and it is estimated that up to 100,000 new wells will be drilled in the near future (Vance et al., 2004; Wyoming Oil and Gas Conservation Commission, 2005). The total CBNG water production in the PRB is expected to peak at about 47,000 ha-m in 2006 and the cumulative CBNG-water production during the period 2002-2017 is estimated to be 366,000 ha-m (BLM, 2003). The quality of CBNG water is variable within the region and is often not suitable for direct irrigation. The CBNG water is dominated by sodium (Na^+) and bicarbonate (HCO_3^-) ions, with pH ranging from 6.8 to 9.0, electrical conductivity (EC) from 0.4 to 4 dS/m, sodium adsorption ratio (SAR) from a low of 5 to a high of 70 and total dissolved solids (TDS) concentrations from 270 to 2720 mg/L (Rice et al., 2002; King et al., 2004).

Land application of CBNG water is fast becoming a preferred water management option in Wyoming. However, CBNG water brings with it a number of problems associated with poor quality irrigation water. Application of CBNG waters with high salinity (e.g., EC) can result in reduced water uptake and water stress to vegetation due to increased energy requirements of plants in obtaining soil water (Burrow et al., 2002). While tolerance to salinity varies among crop types, it is generally accepted that saline conditions have negative impacts on most crops. High saline levels can result in toxicity of certain ions such as chloride (Cl^-), Na^+, and boron (B) to plants. At higher pH, availability of micronutrients such as iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn) will be reduced. Buildup of Na causes dispersion of soil clay particles and organic matter, resulting in surface crusting, reduced infiltration and reduced hydraulic conductivity (Park and O'Connor, 1980; Ganjegunte et al., 2004; King et al., 2004). Soils in the PRB region are dominated by smectitic clays, and nearly 41% of the PRB area is covered with soils characterized by poor drainage (BLM, 2003). Therefore, application of saline-sodic CBNG water on these lands can have negative impacts on soil physical and chemical properties, in addition to concerns related to vegetation growth as discussed above.

In order to avoid permanent damage to the fragile rangeland ecosystem, it is important to monitor the movement of salts and Na through the soil profile in fields irrigated with CBNG water. This information will be useful to understand the potential impacts of saline-sodic CBNG water application on soil chemistry and to devise suitable amelioration plans. The major objective of this study was to monitor the build up of salts and Na in soil profiles that have been irrigated with CBNG water for up to 4 years.

Methods and Materials

Study Area

The PRB, located in northeast Wyoming and southeast Montana (Fig. 1), is situated between the Black Hills to the east, the Big Horn Mountains to the west and the Miles City Arch to the north. Land surface generally slopes northward from higher elevations in Wyoming and drains to the Yellowstone River in Montana. Groundwater flow in the PRB is generally from the south to the north. In some parts of the PRB, coal seams are an important groundwater resource for livestock. Shallow coal seams are readily tapped as water resources. Soils of the PRB have developed under a climatic regime characterized by cold winters, warm summers and precipitation of 30 to 38 cm (includes 91-152 cm of snowfall). Soil textures vary and are influenced by dominant geologic conditions. Soils are generally alkaline and low in organic matter. Farming is conducted along valleys with perennial streams that support irrigation.

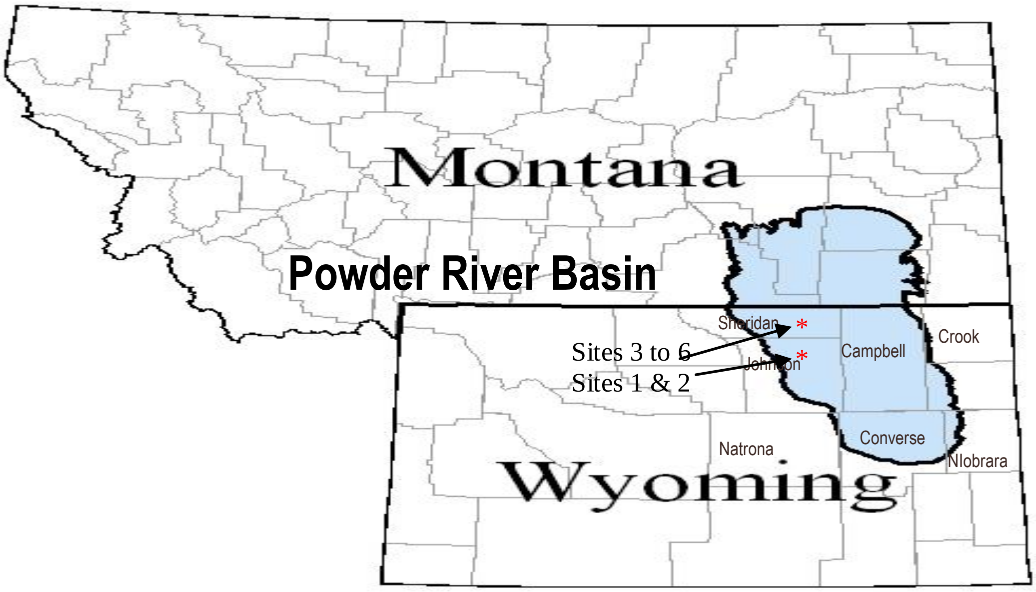

Figure 1. Powder River Basin (PRB), covering parts of Wyoming and Montana, contains extensive coal reserves. The CBNG activities in the PRB in Wyoming are currently one of the most active in the U.S.

Study Sites, Water and Soil Sampling

Six sites that have received CBNG water for up to 4 years (irrigation seasons) were selected to monitor salt and Na buildup in soil profiles. These sites are located in Johnson and Sheridan counties in Wyoming (Fig. 1). The dominant vegetation types on the irrigated sites are listed in Table 1.

Table 1. Details of dominant vegetation in study sites.

	Irrigated
Site 1	Western wheatgrass (*Pascopyrum smithii*)
Site 2	Oats (*Avena sativa*) and western wheatgrass
Site 3	Needleandthread (*Stipa comata*) and western wheatgrass
Site 4	Alfalfa (*Medicago sativa*)
Site 5	Smooth Brome (*Bromus inermis*)
Site 6	Needleandthread and western wheatgrass

Study sites were irrigated with CBNG water between April and December and managed by different CBNG companies. Details of the study sites are summarized in Table 2.

In an effort to minimize the adverse impacts of direct application of CBNG water to soil, some of the CBNG producers have adopted water treatments such as sulfur burners and passing CBNG waters through zeolite beds before land application. A sulfur burner is a device that acidifies CBNG water to reduce HCO_3^- concentrations. Under acidic conditions HCO_3^- ions are converted into gaseous CO_2 that escapes into the atmosphere. Acidic water may also help in

Table 2. Details of water application methods, water treatments, soil treatments and years of water application in the study sites.

Site No	County	Water Application Method	Water Treatment Before Irrigation	Soil Treatment and/or Amendments	Years of irrigation
1	Johnson	Center Pivot	None	Surface application of Gypsum and Sulfur	4
2	Johnson	Center Pivot	Zeolite	None	< 1 round of irrigation
3	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	4
4	Sheridan	Center Pivot	Sulfur Burner	Surface application of Gypsum and Sulfur	3
5	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	3
6	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	4

improving the solubilization of calcite ($CaCO_3$) and gypsum ($CaSO_4$) in soil (Yu et al., 2003). Zeolite, a geologic material with high cation exchange capacity (CEC), may enhance the ability of these materials to reduce the amount of Na^+ in CBNG waters (Boettinger and Ming, 2002). Soil treatments such as gypsum ($CaSO_4$) and reduced sulfur (S) are being used to enhance Ca^{++} availability that results in displacement of Na^+ from clays and to increase the acidity, respectively (Shainberg et al., 1989).

CBNG producers use a variety of methods to irrigate fields, including center-pivot, side-roll irrigation systems, portable water canons, and misters (Vance et al., 2004). Complex site-specific environmental factors such as topography, land use, soil types and quality, soil hydrologic characteristics, water quality and application rates, and vegetation types and tolerances are considered when determining site-specific application methods. Non-environmental factors such as equipment installation and operating costs, landowner agreements, and regulatory environment are also important (Vance et al., 2004).

Samples of CBNG water used at these sites were collected in plastic bottles during early, mid and late irrigation seasons of 2004 and stored in a refrigerator until analyzed (2-3 days). To monitor salt and Na buildup, 2 to 4 nests of soil solution lysimeters (site 5 - 2 lysimeters, sites 3, 4 & 6 - 3 lysimeters, and sites 1 & 2 - 4 lysimeters) were randomly installed in irrigated fields at 15, 30 and 60 cm depths in Aug 2003. A suction lysimeter consists of a porous ceramic cup fixed on the bottom of a PVC tube that is used to collect the soil solution. After creating suction inside the tube (using a vacuum pump), soil solution is drawn from the soil through the porous ceramic cup into the tube. After a few hours, soil solutions are removed from the lysimeter using the vacuum pump. Lysimeters were allowed to equilibrate for several months with soil solutions collected in lysimeters during the late 2003 irrigation season discarded. Lysimeter soil solution samples collected during the 2004 irrigation season were stored in plastic bottles and transportation to the laboratory for further analysis. In addition to lysimeter samples, 3 replicate soil samples were collected from 6 depths (0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm) from each of the irrigated fields.

Laboratory Analyses

Soil samples were air dried, ground, and passed through a 2-mm sieve. Soil saturated paste extracts were prepared by using the method described by Rhoades (1999). The pH and EC values for saturated paste extracts, CBNG water samples, and lysimeter soil solution samples were determined using pH and EC electrodes, respectively (Rhoades, 1999; Thomas, 1999). Soluble Ca, Mg and Na concentrations in saturated paste extracts, CBNG water samples, and lysimeter soil solution samples were determined using inductively coupled plasma spectrophotometry (Suarez, 1999).

Sodium adsorption ratios (SAR) for saturated paste extracts, CBNG waters, and lysimeter soil solutions were calculated by using the formula given below:

$$SAR = Na^+ / [Ca^{2+} + Mg^{2+}]^{0.5} \qquad \textbf{(1)}$$

where Na, Ca and Mg represent concentrations in mmols L^{-1} of the respective ions.

Statistical Analysis

The results of soil solution chemistry were compared with those obtained from saturated paste extract analyses for corresponding depths (15, 30 and 60 cm) using two sample t-test. All the tests for significance were carried out at $P = 0.05$ unless otherwise mentioned in the text.

Results and Discussion

CBNG Water Chemistry

Results of CBNG water analyses are presented in Table 3. The data show that EC and SAR values for water samples were well above desired levels of 0.75 dS m^{-1} and SAR of 10, recommended for irrigation water (U.S. Salinity Laboratory Staff, 1954). These results are in agreement with previous literature on CBNG water chemistry (Rice et al., 2002; McBeth et al., 2003).

Table 3. Selected chemical properties of CBNG water samples collected during early irrigation season of 2004.

Parameter	Average	Range
pH	8.1	7.4 – 8.9
EC (dS m^{-1})	3.17	1.91 – 3.93
Ca (mg L^{-1})	16	5 – 29
Mg (mg L^{-1})	14	4 – 40
Na (mg L^{-1})	751	487– 1832
SAR	31	18 – 57

Soil Solution Chemistry

Textures of irrigated soils ranged from sandy loam to clay, with CEC ranged from 5.2 $cmol_{(+)}kg^{-1}$ in 90-120 cm horizon of site 4 to 27 $cmol_{(+)}kg^{-1}$ in the 0-5 cm horizon of site 2 (Ganjegunte et al., 2004). The results of soil saturated paste and soil solution lysimeter chemistry are provided in Table 4. The data for site 2 is not included because it did not receive one complete round of CBNG water irrigation. The pH values of soil samples from the 3 depths ranged from 7.5 to 8.2. Soil EC is the most widely used measure of salinity and EC values >4 dS m^{-1} are considered saline (U.S. Salinity Laboratory Staff, 1954). Lysimeter soil solution EC values indicated that sites 1, 3, and 4 contained high salt concentrations in the upper 60 cm, while site 6 contained high salt concentrations only at 60 cm depth. The saturated paste extracts also indicated presence of high salt concentration in the upper 60 cm in site 1, and the upper 30 cm in site 4, but sites 3 and 6 were not saline.

Table 4. Chemistry of lysimeter soil solution and saturated paste extracts of soil samples collected during early irrigation season of 2004.

Properties	Sample	Depth	Site 1	Site 3	Site 4	Site 5	Site 6
pH	Saturated Paste Extract						
		15 cm	7.5	7.7	7.9	7.9	8.0
		30 cm	7.2	7.7	7.9	7.9	7.9
		60 cm	6.9	7.7	7.9	7.8	8.2
EC (dS m^{-1})							
	Lysimeter soil solution						
		15 cm	8.9	4.1	5.5	3.5	2.5
		30 cm	7.5	5.7	6.7	3.7	5.9
		60 cm	7.5	4.4	4.7	3.2	4.4
	Saturated Paste Extract						
		15 cm	10.1	2.6	4.1	3.8	1.8
		30 cm	8.0	2.6	4.3	2.4	2.0
		60 cm	4.3	2.3	2.7	2.4	1.6
SAR							
	Lysimeter soil solution						
		15 cm	14.5	4.0	7.6	3.3	N.D.
		30 cm	5.8	3.7	5.5	2.5	7.2
		60 cm	7.2	6.3	4.8	3.7	N.D.
	Saturated paste extract						
		15 cm	14.6	5.0	6.5	5.4	5.1
		30 cm	9.3	5.3	4.4	4.3	2.9
		60 cm	3.4	3.7	2.2	2.8	3.6

The concentration of salts in solution is a function of soil to moisture ratio (U.S. Salinity Laboratory Staff, 1954). Soil moisture content has a significant impact on soluble salt concentrations for soils containing less soluble salts such as carbonates and bicarbonates (U.S. Salinity Laboratory Staff, 1954). Reduction in soil moisture content increases the soil solution salt concentrations. Lysimeter soil solutions were obtained under variably saturated field conditions relative to soil saturated paste extracts that were obtained in the laboratory with all soil pore space filled with water. Therefore, the concentration effect due to lower moisture content under field conditions could be the reason higher EC values were observed in lysimeter solutions. However, differences between lysimeter solution and saturated paste extract EC values were not statistically significant in any of the sites or depths. The decrease in salt concentration with depth indicates build up of salts in near surface horizons. This may be due to reduction in soil moisture content due to high evapotranspiration rates observed in arid PRB environments.

Soil SAR values greater than 13 indicate there may be a potential Na hazard (U.S. Salinity Laboratory Staff, 1954). In the present study, SAR values of lysimeter solution samples and soil saturated paste extracts indicated that the upper 15 cm soil horizon of site 1 is sodic. In the remaining sites, SAR values are less than 13. Differences between SAR values of lysimeter soil solution samples and saturated paste extracts were not significant; however, it is evident from table 4 that SAR values are generally greater in near surface horizons indicating Na build up. Irrigation with saline-sodic CBNG water contributes to increased Na concentrations through evapotranspiration and Na adsorption by soil (Burrow et al., 2002). Increased Na contents lower in the profile, may be due to downward movement (leaching) of CBNG irrigation water.

From Table 2 it is evident that various CBNG companies have been applying variable quantities of gypsum over time. Results from studies (Ganjegunte et al. 2004; King et al. 2004) carried out on these sites, and as well as the present study, indicate that SAR levels in CBNG water irrigated soils have increased over time. This may be due to CBNG water containing high amounts of alkalinity, which results in precipitation of Ca as calcium carbonate ($CaCO_3$), which renders Ca unavailable for exchange reactions, or $CaCO_3$ might have caused surface sealing due to clogging of pores. The amount of gypsum added may not be adequate to counter Na^+ derived from CBNG water, and the particle size of gypsum may not be optimal for enhanced dissolution. Studies on soil physical properties indicate irrigated soils have lower infiltration rates and reduced hydraulic conductivity compared to adjacent non-irrigated sites (King et al., 2004). Thus, a combination of the amount of gypsum applied, gypsum particle size, precipitation of Ca as $CaCO_3$, clogging of soil pores by $CaCO_3$, and the lower soil water flux in CBNG irrigated soils might have affected the efficiency of gypsum amendments used at our study sites.

Addition of reduced S also improves soil Ca supply as it produces sulfuric acid (H_2SO_4) upon oxidation that results in the dissolution of $CaCO_3$, which is commonly found in arid and semi-arid soils. Although CBNG companies have been applying reduced S to soils irrigated with CBNG water, the conversion of S to H_2SO_4 is a slow biological process. In addition, S burners have not typically been in operation throughout the irrigation season, which may have influenced the SAR increase in CBNG water irrigated sites.

Conclusions

Preliminary results of this study have indicated that CBNG water being used for irrigation is not recommended for long-term direct irrigation. Trends of salt and Na accumulations in upper soil horizons in fields irrigated with CBNG water were evident. Our results indicate that irrigation or land disposal of poor quality (saline-sodic) CBNG water on soil with high clay contents can potentially have serious negative impacts on fragile cropland and rangeland ecosystems in the PRB. It is expected that CBNG production will continue to develop at a rapid rate, creating economic benefits and potential impacts to PRB environments. Addressing these impacts in a meaningful way will require continued data collection through monitoring of CBNG production and recovery responses as determined by on-going research projects.

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