LAND APPLICATION OF SALINE-SODIC COALBED NATURAL GAS (CBNG) CO-PRODUCED WATERS: SOIL AND VEGETATION IMPACTS[1]

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Abstract. Aggressive coalbed natural gas (CBNG) development in the Powder River Basin (PRB) of Montana and Wyoming is driven by the Nation's growing demand for energy. Wyoming's PRB had over 13,000 CBNG producing wells in 2004 with more than 50,000 future wells projected. Extraction of CBNG is associated with production of significant volumes of saline-sodic co-produced water in the PRB, estimated to exceed 162,000 ha-m by 2020. Suitable water-management strategies will need to be developed and implemented to address long-term soils impacts from these large water volumes. Land application with sprinkler irrigation systems is a common method for managing these waters. This study examined various soil and native vegetation impacts resulting from up to 5 seasons of land application with saline (EC = 1.6 to 4.8 dS m^{-1}) and sodic (SAR =17 to 56) CBNG water. Treated (irrigated) and representative control (non-irrigated) areas were established at several study sites and examined through the 2003-2005 field seasons. Soil and vegetation types, water application rates, and water and soil treatment strategies were variable across study sites so parameters from each treated area were compared directly to those from representative control areas. Soil texture, pH, EC, SAR, bulk density, surface infiltration rate and Darcy flux rates were measured at various depth intervals to 120 cm. Multiple year applications of CBNG water produced consistent trends of increased soil EC and SAR values at depths to 60 cm, reduced surface infiltration rates and reduced Darcy flux rates to 120 cm. These differences were significant ($P<0.05$ or $P<0.10$) at most depths on most sites. CBNG water applications also resulted in significant ($P<0.05$) increases in native perennial grass biomass production and cover (treated vs. control areas). However, species diversity as measured by evenness was reduced. Biological effects were variable and complex, reflecting site specific conditions and management strategies. These findings indicate concern for effective Na^+ and soluble salt leaching success with current management and treatment strategies on these study sites. Degraded soil physical and chemical properties will require mitigation during reclamation efforts following cessation of CBNG water applications.

Additional Key Words: coalbed methane, Powder River Basin, electrical conductivity, sodium adsorption ratio, infiltration rate, vegetation cover, diversity.

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Introduction

Driven by growing national demand for energy, substantial coalbed natural gas (CBNG) reserves (also known as coalbed methane) in the Powder River Basin (PRB) of Wyoming (WY) and Montana (MT) are being actively developed. As reported by Ruckelshaus IENR (2005), WY's portion of the PRB had over 13,000 producing wells in 2004 and more than 50,000 future wells are projected (USDOI-BLM, 2003). Indeed, annual CBNG production from Wyoming's PRB in 2003 represented 1.5% of total United States' natural gas consumption (Ruckelshaus, IENR, 2005; US-EIA, 2006).

Production of CBNG requires removal of co-produced water (hereafter referred to as CBNG water) to reduce the hydrostatic head within coal seams. CBNG water extraction within the PRB is extensive, reaching an annual rate of nearly 9,000 ha-m in 2003 (Ruckelshaus IENR, 2005). It is estimated that over 162,000 ha-m of CBNG water could be extracted within the PRB by 2020 (USDOI-BLM, 2003; Ruckelshaus IENR, 2005). Normal pumped-water discharge flows range between 1 and 100 liters per minute (lpm) from individual wells and may extend for 20 years (Wheaton and Metesh, 2002). The current regulatory environment establishes land application using traditional irrigation water delivery systems as an option for CBNG water management (USDOI-BLM, 2003). Site specific application methods are determined by topography, land use and ownership, soil quality, soil hydrologic characteristics, water application rates and vegetation tolerance to altered environmental conditions (DeJoia and Harvey, 2002; USDOI-BLM, 2003).

In the PRB, CBNG water is often sodic or saline-sodic (Rice et al., 2002; Ganjugunte et al. 2005; McBeth et al., 2003). It is generally dominated by sodium (Na^+) and bicarbonate (HCO_3^-) ions, with pH ranging from 6.8 to 8.9, electrical conductivity (EC) from 0.4 to 4.8 dS m^{-1}, and sodium adsorption ratio (SAR) from 5 to 70 (Rice et al., 2002; Van Voast, 2003; Ganjegunte et al., 2005). Salinity is determined by soluble salt concentrations as measured by EC (U.S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978; Horpestad, 2001). Sodicity is determined by the relative ratio of Na^+ to calcium (Ca^{2+}) and magnesium (Mg^{2+}) as measured by SAR (U.S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978).

Several physical, ecological, chemical and hydrologic soil characteristics are affected by introducing irrigation water into arid environments, including altered natural water balances, waterlogging, increased salinization, and increased sodification (Balba, 1995). Many authors have reported reduced soil permeability associated with the use of elevated SAR irrigation waters (Shainberg and Oster, 1978; Agassi et al., 1981; Shainberg and Letey, 1984; Levy et al., 1998; Mace and Amrhein, 2001; Lebron et al., 2002). Sodic soils are widely associated with degraded soil structure and poor soil-water-air relations (Rengasamy and Olsson, 1991; Jayawardane and Chan, 1994). Consistent exposure to saline-sodic CBNG water has been shown to affect soil chemistry in the PRB by significantly elevating EC and SAR at depths up to 120 cm (Stearns et al., 2004; Ganjegunte et al., 2005; King et al., 2005).

Many investigations have also noted vegetation impacts from altered soil conditions and toxicity related to saline-sodic irrigation water applications (U.S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978; Rogers, 2002; Phelps and Bauder, 2003). Shaw et al. (1998) indicated impacts to plant growth from modifications of soil structure, density, strength for root development, soil water relations, and aeration. In strongly sodic soils, physical properties such as low plant available water capacity, low hydraulic conductivity, increased swelling, high bulk density, and uneven soil wetting can restrict plant growth (Eaton, 1940). However, Ganskopp

(1986) stated that the effects of saline or sodic irrigation on native plant populations are not well known. Indeed, research on the use of salt tolerant native plant species in CBNG remediation is limited (Entech, 2002).

Purposes and Objectives

Given historical evidence that irrigation with saline-sodic waters has the potential to adversely impact soil and vegetation systems, this study was established to specifically examine effects from land applications with saline-sodic CBNG water on associated PRB soil/plant ecosystems. It is hypothesized that land application with saline-sodic CBNG water will not alter soil physical/chemical properties and native vegetation communities (H_o). Effects from up to four seasons of land applications with CBNG water on soil physical and chemical properties and the resulting impacts (from up to five seasons of applications) to native vegetation community structure, composition and diversity were examined. These investigations will help to provide essential understandings needed to enhance management and reclamation potentials on these lands.

Materials And Methods

Geographic Study Area

The PRB is located in northeast WY and southeast MT. It is characterized by rolling uplands and hills with rough, eroded and broken terrain in the north (USDOI-BLM, 2003). Land generally slopes northward from higher elevations in WY towards the Yellowstone River in MT, draining mainly via the Tongue and Powder Rivers to the north and the Belle Fourche and Cheyenne Rivers to the east. Annual precipitation averages 380-430 mm along the periphery of the Basin, decreasing to a low of 330 mm near its center. Most precipitation comes between March and July. The climate is arid and semi-arid with long, cold winters and short, hot summers. Soils are influenced by dominant local geologic conditions and vary in texture and quality, accordingly. They are generally alkaline, low in organic matter content, and often dominated by smectitic clays (USDOI-BLM, 2003).

Study Sites

Six original study sites representing up to three seasons of CBNG water applications were established in June-July, 2003. Two additional sites were added in 2004 to enhance evaluations of impacts on native plant communities. Sites are located in Sheridan, Johnson and Campbell Counties (Fig. 1). At each site, data were collected from a treated area (lands receiving applications of CBNG water) and a representative control area (lands not receiving land applications of CBNG water). Control areas were chosen to represent characteristics of each site's treated area. However, seasons of CBNG water application, soil types/textures, dominant vegetation, CBNG water qualities/application rates, chemical treatment strategies (soil and water), precipitation zones, and land uses varied among study sites (Tables 1 and 2). Ganjegunte et al. (2005) has compiled soil type descriptions and CBNG water application rates for these study sites.

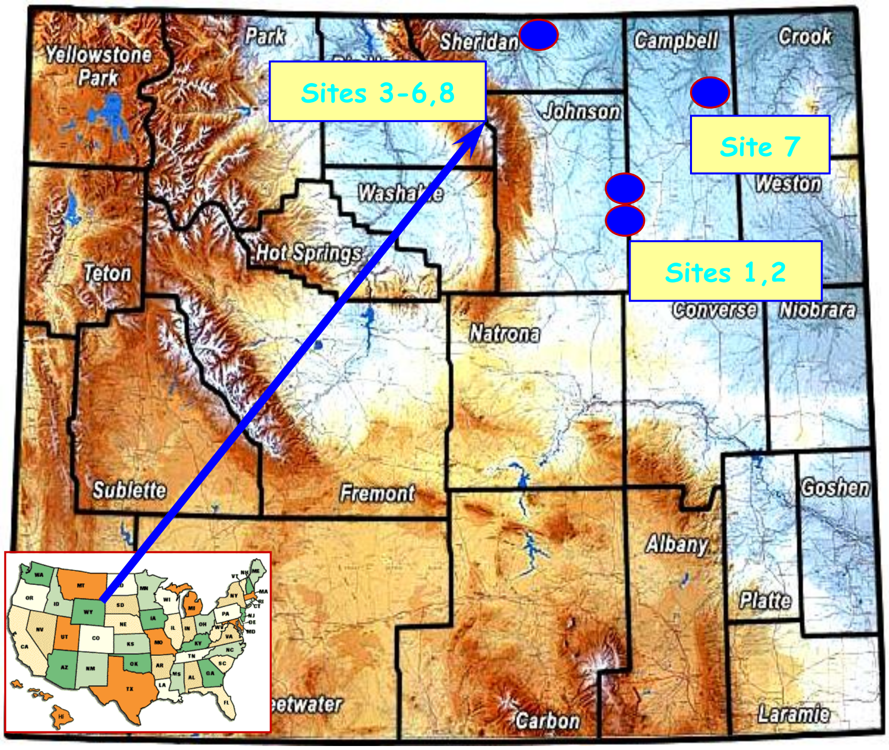

Figure 1. Wyoming study site locations in the Powder River Basin relative to counties.

Table 1. Study site general information: county, seasons of water application, general vegetation type, precipitation zone, texture and water application methods**.**

Site No.	County	Seasons CBNG water applied through 2005	General vegetation & Precipitation zone	Texture[1] to 30 cm	Water application method
1	Johnson	5	seeded grassland 250-380 mm	CL, C	center-pivot
2	Johnson	1.5	seeded alfalfa-oats 250-380 mm	CL, SiCL, L	center-pivot
3	Sheridan	5	mixed grass prairie 380-430 mm	SCL, CL	side-roll
4	Sheridan	4	seeded alfalfa 380-430 mm	L,CL,	center-pivot
5	Sheridan	4	seeded grass pasture 380-430 mm	CL, C	side-roll
6	Sheridan	5	mixed grass prairie 380-430 mm	SCL,CL,C	side-roll
7	Campbell	2[2]	mixed grass prairie 250-380 mm	SL,CL,SCL	misters
8	Sheridan	5	mixed grass prairie 380-430 mm	SCL,C	side-roll

[1]CL=clay loam, C=clay, SCL=sandy clay loam, SiCL=silty clay loam, L=loam.
[2]Received CBNG water only in 2001 & 2002.

Table 2. CBNG water treatment, soil amendments and land use on study sites.

Site No	Water Treatment Before Irrigation	Soil Amendments	Land Use
1	None	multiple seasonal surface applications of gypsum and elemental S	winter cattle grazing, cut for hay in 2004
2	None	annual surface application of gypsum and elemental S	cut for hay in 2004
3	Sulfur Burner	annual surface application of gypsum and elemental S	seasonal cattle grazing
4	Sulfur Burner	annual surface application of gypsum and elemental S	cut for hay
5	Sulfur Burner	annual surface application of gypsum and elemental S	cut for hay
6	Sulfur Burner	annual surface application of gypsum and elemental S	seasonal cattle grazing
7	None	surface application of gypsum and elemental S	seasonal cattle grazing
8	Sulfur Burner	annual surface application of gypsum and elemental S	seasonal cattle grazing

Water Sampling Methods

Samples of CBNG water were collected from reservoirs and/or sprinklers at Sites 1 to 6 (2003 and 2004 field seasons) and Site 8 (2004 field season). These were stored in refrigerated condition until analyzed for pH, EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR calculations. Land applications of CBNG water had been discontinued at Site 7 in 2002. Therefore, company records were substituted to assess water quality.

Soil Sampling Methods

Soils from 6 original study sites (treated and control areas) were sampled with 5 (early season—2003) or 3 (late season—2003 and early/late season—2004) randomly placed, hand-augered holes per area. Sample depth intervals from each hole were 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm. Soil samples were placed in resealable plastic bags to prevent moisture loss and transported to the laboratory for chemical and texture analyses. Soils from treated and control areas on the 2 additional study Sites (7 and 8) were also sampled in May/June 2004 using 3 randomly located sample holes per area but only at 3 depth intervals (0-5, 5-15, 15-30 cm). Soil data from these 2 sites were used during vegetation community comparisons and were not directly compared to soil data from the original 6 study sites.

Soil subsamples were oven-dried to constant weight at 105°C to determine soil moisture content using the difference between wet weight and oven-dry weight. Soil samples were air dried, passed through a 2 mm sieve and analyzed for physical and chemical properties. Soil textures were determined using the hydrometer method (Gee and Or, 2002). Soil saturation paste extracts were prepared as described by Rhoades (1996). Values for pH and EC were obtained from saturation paste extracts (soil) and CBNG water samples using pH and EC meters/electrodes, respectively (Rhoades, 1996; Thomas, 1996). Soluble Na, Ca, and Mg concentrations in saturation paste extracts and CBNG water samples were determined using inductively coupled plasma spectrophotometry (Suarez, 1996). SAR of saturation paste extracts and irrigation water samples was calculated as:

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

where Na^+, Ca^{2+}, and Mg^{2+} represent millimolar concentrations (mmol L^{-1}) of the respective ions.

Soil bulk densities were determined at 3 random locations within each area (treated and control) from 3 depths (0-5, 5-15 and 15-30 cm) using the core method as described by Grossman and Reinsch (2002). Surface infiltration rates from treated and control areas at each site were determined from 5 random locations within each using the single-ring infiltrometer method (Reynolds et al., 2002). Darcy flux rates were determined from 3 random replications for each of 5 depth intervals (15, 30, 60, 90, and 120 cm). Holes were augered to the appropriate sample depth, filled with water to saturate over-night, and refilled the following day prior to recording readings. Flux was determined at 30 minutes by measuring the drop in water elevation after refilling each hole at 15 minute intervals (based on principles discussed in Hillel, 2004).

<u>Vegetation Sampling Methods</u>

Vegetation measurements included determinations of aboveground biomass production, aerial cover, species frequency and species richness/evenness/diversity. Biomass production was determined by clipping 5 randomly located 0.5 m^2 rectangular plots on treated and control areas. Clippings were separated by life form (perennial grass, annual grass, perennial/biennial forb, annual forb, shrubs/half-shrubs and succulents), oven-dried and weighed. Aerial cover on each site was estimated using 5 randomly located 50 m line transects, read every meter using the point-intercept method (first hit species were recorded). Species frequency data were determined by recording presence/absence in 20 randomly located, 20 cm x 50 cm rectangular frames. Sampling was conducted on 2 Sites (1 and 3) in 2003 and expanded to 5 Sites (1, 3, 6, 7, and 8) in 2004 and 2005. Species richness, diversity indices, and evenness were evaluated with both cover and frequency data using PC-ORD Version 4.25 (McCune and Medfford, 1999).

<u>Statistical Analysis</u>

Significant differences between treated and control area parameters were determined using 2-group t-tests of means. Equal variances and normal distribution of data were verified. Significance was determined at $P<0.05$, unless otherwise noted.

Results

<u>CBNG Water Chemistry</u>

Average EC and SAR values of CBNG water reported from these study sites (Table 3) exceed maximum values (EC of 0.75 dS m^{-1}; SAR of 10) generally considered suitable for irrigation water use with sensitive crop species (U. S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978; Hillel, 2000). Although water qualities from these study sites are generally within ranges previously reported for CBNG waters in the PRB (Rice et al., 2002; McBeth et al., 2003; USDOI-BLM, 2003), salinity values at Site 2 were elevated (Table 3).

<u>Soil Physical Properties</u>

<u>Soil Texture.</u> Soil textures on these study sites are typical of those reported from the PRB (USDOI-BLM, 2003). Clay and clay loams predominate at most sample depths (Table 4). Inter-

bedded sandstone parent material influences coarse textures at Sites 3 and 4. Average clay content is 20% or greater for all sample depths at all sites, exceeding 25% at all locations except treated Site 3 (0-5 cm), and exceeding 30% in 60 out of 72 sample depths across all sites to 120 cm (Table 4). Every site had several sample depths with greater than 30% clay.

Table 3. Average CBNG water quality (pH, EC and SAR) on study sites.

Year	**pH**	**EC ($dS\ m^{-1}$)**	**SAR ($mmol^{1/2}\ L^{-1/2}$)**
	Site 1		
2003	8.2	2.9	30.9
2004	7.9	3.2	32.2
	Site 2		
2003	Water source not available for sample		
2004	9.1	4.8	56.1
	Site 3		
2003	8.0	2.0	24.2
2004	7.2	2.0	30
	Site 4		
2003	7.9	2.2	32.8
2004	7.1	2.0	34.5
	Site 5		
2003	7.7	2.9	17.2
2004	7.4	1.6	19.7
	Site 6		
2003	8.0	2.0	24.2
2004	7.2	2.0	30
	Site 7		
2001/2002	Water source not available for sample		
	Site 8		
2004	Water source similar to Sites 3 & 6		

<u>Bulk Density and Soil Moisture.</u> Bulk density values from 2003 indicate no apparent trends within the top 30 cm of these study sites (data not shown). However, by 2004, 14 of 18 sample depths had greater bulk densities on treated (vs. control) areas and 11 of those differences were significant ($P<0.10$) (Table 5). The accompanying gravimetric soil moisture data varied by horizon and sample date and was highly dependent on irrigation application volume/timing/frequency and the frequency/magnitude of natural precipitation events (Table 5).

Table 4. Soil textures and clay content (%) from 6 sample depths to 120 cm (treated vs. control areas from 6 original study sites).*

Depth (cm)	Site 1 Trtd./Cont. % clay	Site 2 Trtd./Cont. % clay	Site 3 Trtd./Cont. % clay	Site 4 Trtd./Cont. % clay	Site 5 Trtd./Cont. % clay	Site 6 Trtd./Cont. % clay
0-5	CL/CL	CL/SiCL	SL/L	L/CL	CL/C	SCL/CL
	37/30	36/37	20/26	24/36	33/42	22/36
5-15	C/C	CL/L	SL/CL	CL/CL	C/C	SCL/CL
	49/41	33/27	28/33	27/40	41/47	32/40
15-30	C/CL	CL/CL	SCL/CL	CL/C	C/C	C/C
	48/36	35/37	32/32	35/48	42/44	50/48
30-60	C/CL	L/CL	SL/CL	CL/C	C/CL	C/C
	41/35	38/40	31/33	38/51	39/39	52/53
60-90	CL/CL	CL/CL	SL/CL	SCL/C	CL/CL	C/C
	37/40	32/33	30/29	30/56	38/39	52/56
90-120	CL/CL	L/CL	SL/CL	SL/C	CL/CL	C/C
	32/38	26/40	22/29	22/43	36/36	56/43

*Textures: CL-clay loam, C-clay, SiCL-silty clay loam, L-Loam, SL-sandy loam, SCL-sandy clay loam.

Table 5. May 2004 bulk density (BD) (g cm^{-3}) from the top 3 sample depths (0-30 cm).

Site	Sample Depth (cm)	TREATED		CONTROL	
		Bulk Density (g cm^{-3})	% Water Content	Bulk Density (g cm^{-3})	% Water Content
1	0-5	1.71$^{\lozenge}$	29.8 ± 5.7	1.43	2.0 ± 1.2
	5-15	1.71*	19.3 ± 2.8	1.46	2.6 ± 0.3
	15-30	1.70*	15.0 ± 4.9	1.45	2.4 ± 0.5
2	0-5	1.44*	13.6 ± 4.9	1.36	5.9 ± 0.6
	5-15	1.55$^{\lozenge}$	11.2 ± 5.5	1.34	3.6 ± 3.6
	15-30	1.57	13.6 ± 1.5	1.57	1.9 ± 0.7
3	0-5	1.29	1.3 ± 0.6	1.34	6.8 ± 0.8
	5-15	1.54$^{\lozenge}$	2.3 ± 2.1	1.29	4.9 ± 1.9
	15-30	1.52	3.4 ± 2.7	1.57	3.0 ± 0.5
4	0-5	1.37	11.0 ± 6.6	1.33	8.8 ± 3.7
	5-15	1.50	15.8 ± 3.9	1.55	5.2 ± 0.7
	15-30	1.76*	15.7 ± 1.2	1.39	3.9 ± 0.7
5	0-5	1.38$^{\lozenge}$	10.1 ± 2.7	1.19	3.6 ± 1.3
	5-15	1.60	6.4 ± 3.6	1.50	4.3 ± 1.1
	15-30	1.67$^{\lozenge}$	5.4 ± 7.9	1.55	4.9 ± 0.7
6	0-5	1.40	2.0 ± 1.0	1.33	8.8 ± 3.7
	5-15	1.79*	3.4 ± 4.1	1.55	5.2 ± 0.7
	15-30	1.73*	5.6 ± 5.5	1.39	3.9 ± 0.7

* BD significant (treated vs. control) @ P<0.05. $^{\lozenge}$BD significant (treated vs. control) @ P<0.10.

Infiltration. Soil infiltration rate (cm hr^{-1}) is volume flux of water flowing into a soil profile per soil surface unit area (Levy et al., 1998). Average infiltration rates were determined for treated and control areas on all 6 study sites for early-season 2003 (beginning of study) and late-season 2004 (end of study). Site 2 was not treated until October 2003. In 2003, average treated area infiltration rates (not shown) were significantly slower ($P<0.10$) than control area rates on only 1 site (Site 5). Infiltration rates on treated areas on Sites 3, 4, and 5 did not decrease in 2004 (vs. 2003) despite continued applications of sodic and saline-sodic CBNG water. However by late-season 2004, all 6 treated areas had significantly slower infiltration rates than their representative control areas and 3 treated areas had infiltration rates averaging < 0.1 cm hr^{-1} (Table 6).

Table 6. Comparisons of average (± one standard deviation) infiltration rates (cm hr^{-1}) between sites receiving saline-sodic CBNG production water (treated) and representative untreated sites (control). Data are from late season 2004.

Late season 2004	**TREATED Average Infiltration rate (cm hr^{-1})**	**CONTROL Average Infiltration rate (cm hr^{-1})**	**Probability level***	**t value**
Site 1	0.0* ± 0.0	10.7 ± 4.1	P=<0.001	5.90
Site 2	0.2*± <0.1	5.3 ± 1.2	P=<0.001	9.06
Site 3	7.1* ± 2.9	9.4 ± 1.3	P=0.071	1.62
Site 4	3.1* ± 0.7	11.9 ± 8.8	P=0.020	2.44
Site 5	9.0* ± 6.7	14.4 ± 2.7	P=0.067	1.66
Site 6	0.4* ± 0.7	11.9 ± 8.8	P=0.007	3.13

*Significance @ P<0.10.

Flux. Flux (q) indicates a specific water flow discharge rate given as volume of water (V) flowing through a unit cross-sectional area (A) of soil per unit time (t) (Hillel, 2004) and mathematically indicated by:

$$q=V/At \quad \textbf{(2)}$$

Average flux rates (cm hr^{-1}) were measured on treated and control areas under saturated conditions from 4 depth intervals to 90 cm (2003) and 5 depth intervals to 120 cm (2004). In 2003, only Site 1 had treated area flux rates that were significantly slower ($P<0.05$) than those of the corresponding control area (King et al., 2004). However, 2004 data indicated significantly slower flux rates on all treated (vs. control) areas at all depth intervals to 120 cm except Site 3 (15 cm) and Site 4 (90 and 120 cm) (Fig. 2).

Soil Chemical Properties

Results of a companion study comparing treated and control areas on study sites in 2003 (Ganjegunte et al., 2005) indicated multiple years of CBNG water land application produced notable trends of salt and Na accumulation in surface horizons. These trends continued into 2004, with CBNG water land applications significantly ($P<0.05$) increasing soil EC to depths of 120 cm (Sites 1, 4, and 6), and to 60 & 90 cm, respectively, on Sites 3 and 5 (Table 7). One and one-half seasons of CBNG water application on Site 2 significantly increased EC to 30 cm depth (Table 7). Multiple years of CBNG water land application also significantly increased SAR to depths of 120 cm (Sites 4, 5, and 6) and to 60 cm depth at Site 1 (Table 7). At Site 2, a single season of CBNG water application significantly increased SAR to 30 cm depth. No differences (treated vs. control) were found in late season 2004 SAR values at any depth at Site 3, which is predominantly coarse textured (sandy loams and sandy clay loams to 30 cm) (Table 7).

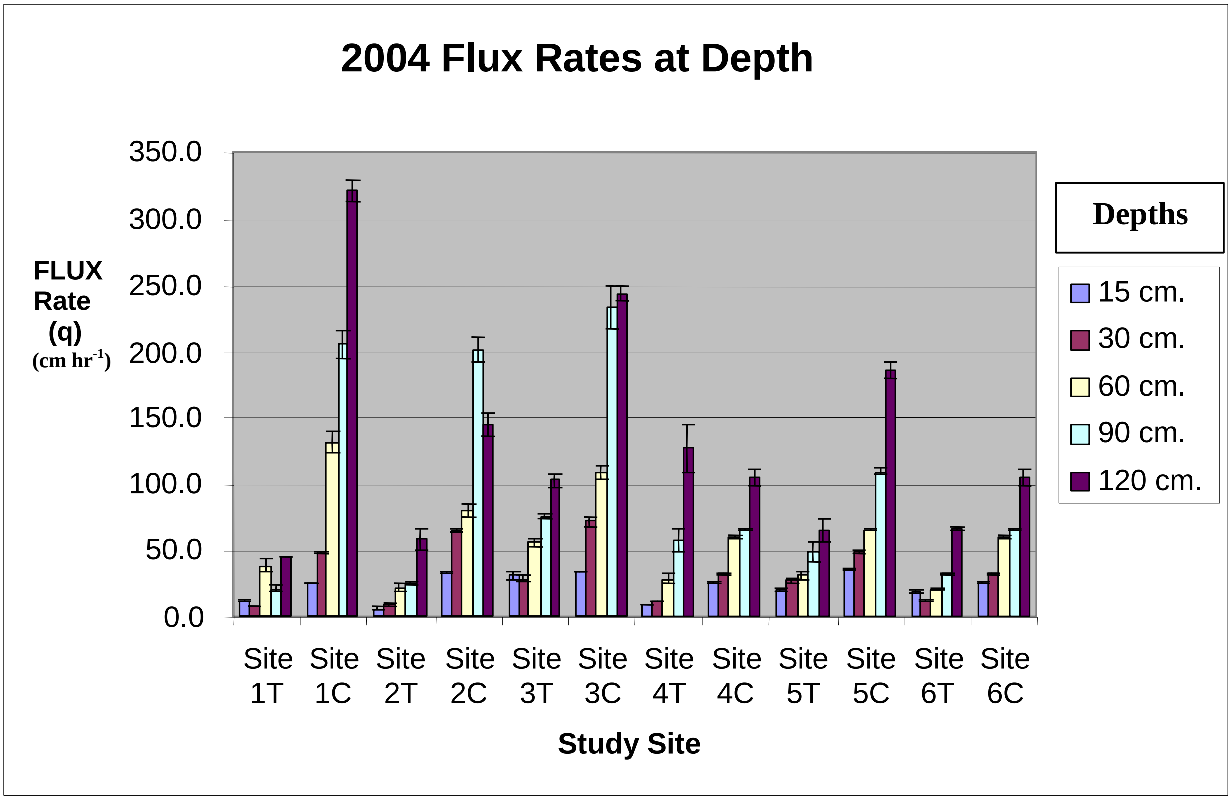

Figure 2. 2004 flux rate (cm hr^{-1}) comparisons by depth interval in treated (T) and control (C) areas. Flux was significantly slower on all T (vs. C) areas at all depths except Site 3 (15 cm) and Site 4 (90 and 120 cm). Error bars indicate standard error.

<u>Vegetation</u>

Vegetation analyses are summarized for treated vs. control area comparisons on study Sites (1, 3, 6, 7 and 8). These sites are dominated by native perennial grassland vegetation communities.

<u>Biomass Production</u>**.** Perennial grasses produced consistently greater biomass on treated areas than on respective non-irrigated control areas. These differences were significant on all sites in all years, except Site 3 in 2003 and 2005 (Table 8). Total vegetation biomass production was significantly greater on all treated areas (vs. control) in 2004 (Sites 1, 3, 6 and 7). This pattern was repeated in 2005, but differences were not significant on all sites (Table 8). Total biomass production was variable on any given site between years, reflecting amounts and patterns of applied water and precipitation.

Table 7. Late season 2004 soil pH, EC (dS m^{-1}) and SAR parameters by depth.

Site & parameter	Treated Areas (cm)						Control Areas (cm)					
	0-5	**5-15**	**15-30**	**30-60**	**60-90**	**90-120**	**0-5**	**5-15**	**15-30**	**30-60**	**60-90**	**90-120**
Site 1												
pH	6.2	7.5	7.5	7.4	7.3	7.2	7.3	7.4	7.4	7.6	7.6	7.7
EC	13.5[a]	10.6[a]	10.6[a]	7.7[a]	3.8[a]	4.7[a]	1.6	0.7	0.5	0.5	05	1.1
SAR	19.5[a]	21.3[a]	20.1[a]	9.8[a]	3.9	3.8	1.3	0.8	0.4	0.6	3.1	7.1
Site 2[1]												
pH	8.1	8.0	8.0	7.9	7.6	7.4	7.9	8.0	7.8	7.8	7.5	7.5
EC	12.3[a]	8.8[a]	3.8[a]	1.7	7.6	12.1	1.1	0.9	0.8	1.5	6.7	10.6
SAR	28.0[a]	22.0[a]	8.5	5.1	10.4	12.5	0.5	0.3	0.4	2.0	6.4	12.2
Site 3												
pH	7.5	7.2	7.3	7.3	7.2	7.6	7.9	8.2	8.3	8.0	8.0	7.7
EC	4.8[a]	2.6[a]	2.3[a]	3.0[a]	3.0	2.9	1.4	1.2	0.8	0.8	3.7	6.3
SAR	7.7	8.7	7.9	6.7	4.7	4.8	3.1	10.0	6.5	2.1	4.9	8.2
Site 4												
pH	7.6	7.7	7.5	7.1	7.0	7.1	7.9	8.1	7.8	7.7	7.6	7.7
EC	5.1[a]	3.1[a]	2.4[a]	4.5[a]	4.6[a]	2.9[a]	1.3	0.9	0.9	0.6	0.5	0.4
SAR	7.6[a]	12.7[a]	11.8[a]	7.9[a]	4.9[a]	1.2[a]	1.8	4.2	3.4	0.9	0.5	0.6
Site 5												
pH	7.8	7.4	7.7	7.7	7.3	7.4	7.5	7.7	7.5	7.4	7.4	7.4
EC	3.1[a]	2.3[a]	1.7[a]	2.9[a]	2.5[a]	2.5	1.4	0.9	0.7	0.6	0.6	0.6
SAR	12.2[a]	12.3[a]	9.5[a]	7.0[a]	3.3[a]	2.6[a]	0.1	0.2	0.5	0.6	0.7	0.6
Site 6												
pH	7.8	7.7	7.6	7.3	7.5	7.5	7.9	8.1	7.8	7.7	7.6	7.7
EC	3.8[a]	1.8[a]	2.2[a]	2.2[a]	3.1[a]	4.5[a]	1.3	0.9	0.9	0.6	0.5	0.4
SAR	14.6[a]	10.7[a]	9.1[a]	6.5[a]	4.0[a]	4.7[a]	1.8	4.2	3.4	0.9	0.5	0.6

[1] CBNG water application delayed until Oct. 2003.
[a] Indicates significance ($P<0.05$)at common depths between corresponding treated and control areas.

Aerial Cover. Percent aerial cover of perennial grasses was significantly greater on treated areas at 4 of 5 study sites (vs. control) in 2004 (Table 9). This pattern was repeated in 2005, with treated areas on 3 of 5 sites producing significantly greater ($P<0.05$) aerial cover (vs. control) of perennial grasses. The additional 2 sites were significantly greater at $P<0.10$ (Table 9). However, non-perennial grass cover was significantly greater on control areas at Sites 1, 3 and 6 (vs. treated) during both 2004 and 2005 (Table 9). Non-perennial grass cover was significantly greater on the treated area (vs. control) at Site 8, which began receiving CBNG waters in 2004 and no differences were detected on Site 7, which had received CBNG waters for 2 seasons in 2001 and 2002 and then terminated (Table 9). Total vegetation cover was consistently higher on treated areas (vs. control) with the notable exception of Site 1 in 2005 (Table 9).

Table 8. Vegetation Biomass Production (kg ha^{-1}).

SITE	Life Form	2003		2004		2005	
		Treated	Control	Treated	Control	Treated	Control
Site 1	per. gr.	5077*	388	4099*	199	4150*	678
	non-per. gr.	1	239	6	79*	47	708*
	Total	5078*	627	4105*	278	4197*	1386
Site 3	per. gr.	1460	1370	933*	311	1294	950
	non-per. gr.	153	625	78	123	436	373
	Total	1613	1995	1011*	434	1730	1323
Site 6	per. gr.	na	na	604*	150	1827*	471
	non-per. gr.	na	na	33	122*	162	1423 *
	Total	na	na	637*	272	1989	1894
Site 7	per. gr.	na	na	550*	340	1797*	1042
	non-per. gr.	na	na	1270	91	463	260
	Total	na	na	1821*	431	2260*	1302
Site 8	per. gr.	na	na	na	na	1338*	741
	non-per. gr.	na	na	na	na	1138	686
	Total	na	na	na	na	2476*	1427

Totals exclude Opuntia polyacantha on Site 1; n=3 (2003), n=5 (2004 and 2005)
* Indicates statistically greater than corresponding treated or control value at P<0.05.

Table 9. Aerial Cover (%) by Vegetation Life Form Data for 2003-2005. (± values represent standard deviation).

SITE	Life Form	2003		2004		2005	
		Treated	Control	Treated	Control	Treated	Control
Site 1	per. gr.	95.5±3.2*	46.5±10.2	76.8±13.6*	24.8±6.9	67.2±11.5*	30.8±4.6
	non-per. gr.	0.4±0.9	22.5±9.0*	0.0±0.0	13.6±7.7*	0.0±0.0	36.8±6.3*
	Total	96.0±3.2*	69.0±3.3	76.8±13.6*	38.4±5.5	67.2±11.5	67.6±6.4
Site 3	per. gr.	75.5±6.2*	51.0±14.7	46.8±5.9*	34.8±3.0	61.2±9.7*	38.8±7.7
	non-per. gr.	13.2±7.3	31.2±11.0*	14.0±6.2	29.2±7.6*	21.2±7.7	34.0±4.5*
	Total	88.7±7.6	82.2±5.7	60.8±6.4	64.0±10.2	82.4±4.3*	72.8±4.4
Site 6	per. gr.	ns	ns	51.6±9.4*	17.2±2.3	68.8±5.4*	33.6±13.1
	non-per. gr.	ns	ns	4.80±5.0	14.8±6.9*	12.4±6.1	39.2±12.9*
	Total	ns	ns	56.4±12.8*	32.0±7.1	81.2±1.1*	72.8±6.1
Site 7	per. gr.	ns	ns	47.2±11.0*	32.4±3.8	54.0±8.4¶	47.2±4.6
	non-per. gr.	ns	ns	13.6±8.0	14.8±9.9	20.4±7.1*	9.20±4.8
	Total	ns	ns	60.8±5.2*	47.2±8.4	74.4±6.2*	56.4±7.5
Site 8	per. gr.	ns	ns	37.0±7.6	30.0±6.9	48.4±7.8¶	42.4±5.5
	non-per. gr.	ns	ns	25.6±3.3*	12.8±11.1	27.6±6.7**	18.4±4.6
	Total	ns	ns	62.8±6.7*	42.8±12.8	76.0±8.0*	60.8±7.6

* indicates statistically > corresponding treated or control value at P<0.05. ¶ indicates statistically > corresponding treated of control value at P<0.10. ** This difference reflects increased shrub cover in treated plot. ± indicates standard deviation. ns indicates "not sampled"

Vegetation species richness, evenness, and diversity. Vegetation cover sampling in 2004 and 2005 recorded 38 and 56 plant species, respectively. The increase in 2005 was influenced by a 70% increase in annual precipitation near Sheridan, WY and a 42% increase near Gillette, WY

(WRCC, 2005). These increases were reflected across most study sites with the exception of areas 8T and 7C (Table 10).

Table 10. Number of vegetation species encountered by life form from cover data (2004-2005), Treated (T) vs. Control (C) Areas.

LIFE FORM	SITE 1				SITE 3				SITE 6				SITE 7				SITE 8			
	2004		2005		2004		2005		2004		2005		2004		2005		2004		2005	
	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C
Perennial Grasses	2	6	3	6	6	7	5	7	3	3	4	5	5	6	6	7	9	9	9	9
Annual Grasses	0	2	0	2	2	2	2	2	3	3	3	3	2	2	2	2	2	2	2	2
Annual Forbs	0	2	2	4	0	0	1	2	2	3	5	3	1	5	4	0	1	0	0	1
Perennial & Biennial Forbs	0	1	0	2	5	0	9	2	0	0	1	2	0	4	3	8	4	1	3	10
Shrubs, 1/2 Shrubs And Succulents	0	1	0	2	4	2	4	3	0	1	0	2	4	2	4	2	3	4	2	3
Total No. Species	2	12	5	16	17	11	21	16	8	10	13	15	12	19	19	19	19	16	16	25

This pattern of increased species numbers in 2005 was also reflected in vegetation frequency sampling which recorded 49 and 68 plant species in 2004 and 2005, respectively. These increases were again reflected across most study sites except for areas 1T and 7C (Data not shown). Overall comparisons of species richness from native grassland communities showed no consistent response to CBNG water applications between treated and control areas using either vegetation cover or vegetation frequency data (Table 11). However, some trends were apparent when comparing evenness values from treated areas with representative control areas. Except for Site 8 (2004), evenness calculated using aerial cover data was greater on control areas (vs. treated) from all sites in both 2004 and 2005 and on most Sites (1, 2, and 7 in 2004 and Sites 1, 2, and 6 in 2005) using frequency data (Table 11).

Shannon's diversity indices calculated using aerial cover data were higher on control areas (vs. treated) on Sites 1, 6 and 7 in 2004 and on all 5 study sites in 2005 while frequency data results indicated no strong trends (Table 11). Simpson's diversity indices had similar trends (Table 11).

Discussion

By late season 2004, all 5 treated (vs. control) areas receiving saline-sodic CBNG water for 2 or more seasons had significant ($P<0.05$) increases in soluble salt accumulations in soil surface horizons to at least 60 cm. Indeed even Site 2, which had received only 1.5 seasons of CBNG water application, had significant soluble salt accumulations to 30 cm. Several sites experienced significant increases to 120 cm. A similar trend was evident with treated area (vs. control) SAR values, with consistent significant increases to depths of 60 cm (30 cm at Site 2).

Table 11. Summary of species Richness, Evenness, Shannon's diversity index, and Simpson's diversity index by site and treatment. Both Frequency and Aerial Cover data are summarized for 2004 and 2005.

Site & Trmt	Richness, species number				Evenness				Shannon's Diversity Index				Simpson's Diversity Index			
	aerial cover		frequency		aerial cover		frequency		aerial cover		frequency		aerial cover		frequency	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
1-T	2	3	8	6	0.084	0.703	0.571	0.779	0.058	0.773	1.19	1.40	0.021	0.450	0.506	0.703
1-C	12	15	19	22	0.858	0.773	0.881	0.876	2.13	2.09	2.59	2.71	0.857	0.836	0.910	0.919
3-T	16	19	17	28	0.770	0.679	0.828	0.833	2.14	2.00	2.35	2.78	0.835	0.797	0.878	0.916
3-C	10	15	15	29	0.844	0.825	0.884	0.876	1.94	2.23	2.39	2.95	0.836	0.864	0.894	0.930
6-T	7	13	14	23	0.485	0.516	0.823	0.819	0.943	1.32	2.17	2.57	0.476	0.608	0.835	0.895
6-C	8	16	11	17	0.711	0.721	0.814	0.848	1.48	2.00	1.95	2.40	0.715	0.797	0.836	0.892
7-T	11	18	18	26	0.565	0.638	0.865	0.873	1.36	1.85	2.50	2.85	0.624	0.717	0.891	0.919
T-C	18	18	25	23	0.795	0.728	0.866	0.825	2.30	2.10	2.79	2.59	0.851	0.828	0.922	0.901
8-T	18	15	24	28	0.787	0.791	0.891	0.872	2.28	2.14	2.83	2.91	0.866	0.849	0.931	0.931
8-C	15	24	21	31	0.774	0.805	0.885	0.869	2.10	2.56	2.69	2.98	0.836	0.894	0.918	0.933

Significant infiltration rate reductions were also measured on all treated (vs. control) areas on our study sites following multiple seasons of saline-sodic CBNG water applications. Reduced infiltration rates likely result from surface seal formation, chemical clay dispersion, plugging of soil pores, and swelling from increased SAR in soil solutions. Indeed the impacts to soil water movement appear to extend into soil profiles at these study sites to depths of at least 120 cm, regardless of management strategies or treatment efforts employed. All of these impacts are attributable to Na^+ and soluble salt accumulations. Although it is likely that rates of surface seal formation are reduced at our study sites with surface chemical applications of gypsum ($CaSO_4 \bullet H_2O$) and elemental sulfur (S), it is apparent that this effect is not adequate to prevent negative impacts to infiltration rates. These impacts are enhanced by the high clay content within the upper 120 cm of soil profiles on our study sites, which increases likelihood of restricted soil water flows and reduces potential for leaching Na^+ out of plant rooting zones.

Although these negative soil chemical and physical impacts are consistent and predictable with applications of saline-sodic CBNG waters, it is somewhat less clear as to the impact on native vegetation communities. Indeed, although 2 of our study sites developed EC and SAR values in excess of those considered suitable for plant growth in reclamation efforts by WY-DEQ/LQD (1994), all 5 study sites evaluated for vegetation impacts had significantly greater perennial grass biomass and aerial cover on treated areas (vs. control). Biomass and aerial cover of non-perennial grass species however were negatively impacted. Species richness did not display any consistent response to saline-sodic CBNG water applications but species diversity as measured by evenness was generally reduced. It was not clear whether differential impacts to vegetation species comprising native grasslands on these study sites resulted from increased saline-sodic soil conditions or aggressive competitive abilities of perennial grasses for increased water availability. Either way, the net result will be reduced diversity of these grassland communities with saline-sodic CBNG water applications and altered abilities to adjust and adapt to condition changes when CBNG water applications cease.

Conclusions

Land application with saline-sodic CBNG water on study sites in the PRB has resulted in consistent trends of increased electrolyte and Na^+ accumulations within impacted soil profiles. Associated with these accumulations and CBNG water application are:

- Consistent significant increases in soil EC and SAR to soil depths of at least 60 cm.
- Consistent significant decreases in surface infiltration rates.
- Consistent significant decreases in Darcy flux rates at depths to 120 cm.
- Diminished water and solute movement into and through affected soil profiles and reduced leaching potential for removing Na^+ ions from soil exchange sites.
- Consistently greater biomass production and aerial cover of perennial grass species.
- Consistently reduced species diversity as measured by evenness.

These results indicate that, on these study sites, current management strategies designed to both dispose of and make beneficial use of CBNG water have resulted in development of soil chemical and physical conditions that tend to limit soil water movement. Although surface accumulations of soluble salts and Na^+ are apparent, it is not clear how these have altered anticipated salt flushing at deeper depths throughout soil profiles (and underlying parent materials) or what overall impacts will be with respect to reclamation potential following cessation of CBNG water applications.

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