USE OF COAL BED NATURAL GAS (CBNG) WATERS: SOIL AND PLANT RESPONSES[1]

L.A. King[2], G.F. Vance and G.K. Ganjegunte

Abstract. With about 20,000 coal bed natural gas (CBNG) wells currently permitted or drilled in the Powder River Basin (PRB) of Montana and Wyoming and projections of more than 50,000 future wells, CBNG water production in the PRB over the next 15 years will exceed 366,000 ha-m. Therefore, proper CBNG product water utilization is warranted. Land application using conventional center-pivot and side-roll irrigation systems is a common strategy for managing saline-sodic waters derived from CBNG production within the PRB. Various soil and plant impacts resulting from 1 to 4 years of saline-sodic water (EC = 1.8 to 4.0 dS m^{-1}; SAR =15 to 38) applications were examined during the 2003 and 2004 field seasons on 6 (2003) to 8 (2004) study sites representing native range grasslands, seeded grass hayfields and alfalfa hayfields. Because soil and plant types, water application rates and water and soil treatment strategies were variable across study sites, parameters measured from each treated (irrigated) site were compared directly to those from representative control (non-irrigated) sites. Soil chemical and physical parameters including pH, EC, SAR, texture, bulk density, surface infiltration rate and Darcy flux rates were measured at various depth intervals to 120 cm. Multiple year applications of saline-sodic water produced consistent trends of increased soil EC and SAR values at depths to 30 cm, reduced surface infiltration rates and reduced Darcy flux rates to 120 cm. Significant (P=0.05) differences in EC, SAR, infiltration rates and Darcy flux (P=0.10) were determined at most sites. Up to 4 years of saline-sodic water applications significantly (P=0.05) increased native perennial grass biomass production and cover on treated vs. control sites. However, overall species evenness was reduced. Biological effects were variable and complex, reflecting site specific conditions and management strategies.

Additional Key Words**:** coalbed methane, saline-sodic water; land application; sodium adsorption ratio; soil chemical, physical and biological properties; Powder River Basin; vegetation diversity.

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Introduction

The United States has extensive reserves of coal bed natural gas (CBNG), which is methane gas trapped in coal seams. These reserves are an important supplement to traditional natural gas production and now account for nearly 10% of the Nation's total natural gas production (Pinkser, 2002). The Powder River Basin (PRB) of Wyoming and Montana possesses an important CBNG resource, with about 20,000 CBNG wells currently permitted or drilled (WOGCC, 2003) and more than 50,000 future wells projected (USDOI-BLM, 2003). This activity accounts for nearly 20% of daily U.S. CBNG production (USDE-OFE, 2002).

CBNG production requires extensive water removal to reduce hydrostatic head within coal seams. Therefore, within the PRB, anticipated CBNG production will also generate over 366,000 ha-m of water over the next 15 years (USDOI-BLM, 2003). Normal pumped-water discharge flows from individual wells range between 1 and 100 liters per minute (lpm) which may occur 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, 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 production water is often sodic or saline-sodic. Salinity is determined by soluble salt concentrations as measured by electrical conductivity (EC) (Shainberg and Oster, 1978; Horpestad, 2001). Sodicity is determined by the relative ratio of sodium (Na^+) cations to calcium (Ca^{2+}) and magnesium (Mg^{2+}) as measured by sodium adsorption ratio (SAR) (Shainberg and Oster, 1978; U.S. Salinity Laboratory Staff, 1954). CBNG production water in the PRB is dominated by Na^+ and bicarbonate (HCO_3^-) ions, with pH ranging from 6.8 to 8.9, EC from 0.4 to 4 dS/m and SAR from 5 to 70 (Rice et al., 2002; Ganjegunte et al., 2005). Several ecological, chemical and hydrologic soil characteristics are affected by introducing irrigation water into arid environments including altered natural water balances, waterlogging and increased salinization and sodification (Balba, 1995). Excessive salt concentrations can cause plant water stress from increased osmotic potentials or toxicity (U.S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978). Using salt tolerant halophytes and plant species that promote soil permeability may, in combination with appropriate water management strategies, reduce some negative effects of elevated CBNG product water salinity and sodicity (Phelps and Bauder, 2003). However, research on the use of salt tolerant native plant species in CBNG remediation is limited.

Land applications of saline-sodic CBNG product water can potentially cause significant effects to native soil systems and the vegetation they support. Therefore, the primary study objective was to examine effects from land applications with saline-sodic CBNG product water on associated PRB soil/plant ecosystems. It is hypothesized that land applications of saline-sodic CBNG product water will alter soil physical/chemical properties and native vegetation communities. Effects from up to 4 seasons of land applications with CBNG product water to soil physical and chemical properties and the resulting impacts to native vegetation community structure, composition and diversity were examined. Investigating native plant species' tolerances to modified soil conditions created by CBNG water applications will help to provide essential understandings needed to enhance reclamation potential.

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-broken terrain in the north (USDOI-BLM, 2003). It generally slopes northward from higher elevations in Wyoming towards the Yellowstone River in Montana, 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 and decreases to a low of 330 mm near its center. Most of the precipitation comes between March and July. The climate is arid and semiarid 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.

Study Sites, Soil Sampling and Vegetation Sampling Methods

Six original study sites treated with up to 4 seasons of CBNG water applications and 5 representative non-treated control sites were established in June-July, 2003. Two additional treated sites and 2 representative control sites were added in 2004. Treated site availabilities were limited to deeded properties managed variously by private land owners and control site locations were chosen for generally representative characteristics of treated sites on common landowners. Sites are located in Sheridan, Johnson and Campbell Counties (Fig. 1). Soil types/textures, vegetation dominance, CBNG water qualities/application rates, chemical treatment strategies (soil and water) and land uses vary among sites (Table 1).

Water Sampling

Coal bed natural gas water samples were collected from reservoirs and/or sprinklers at all sites during the 2003 and 2004 field seasons and stored in refrigerated condition until analyzed for pH, EC, and Na^+, Ca^{2+} and Mg^{2+} for SAR calculations.

Soil Field Measurements

Six treated and 5 control sites (sites 1-6) were sampled in 2003 and 2004 with 5 (early season--2003) and 3 (late season—2003, early/late season--2004) randomly located sample holes per site. Six depth intervals (0-5, 5-15, 15-30, 30-60, 60-90, 90-120 cm) were sampled from each hole. Soil samples from 2 additional sites (Sites 7 & 8) were added in early season 2004 with 3 sample holes per site and 3 depth intervals (0-5, 5-15, 15-30). Soil samples were placed in resealable plastic bags to prevent moisture loss and transported to the laboratory for chemical and texture analyses. Soil bulk densities were determined in 3-5 locations within each site from 3 depths (0-5, 5-15 and 15-30 cm) using the core method as described by Grossman and Reinsch (1999). Surface infiltration rates from treated and control sites were determined at 5 random locations within each site using the single-ring infiltrometer method (Reynolds et al., 1999). Darcy flux rates from treated and control sites were determined from 3 random locations at each site from 5 depth intervals (15, 30, 60, 90, 120 cm). Holes were 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, 1982).

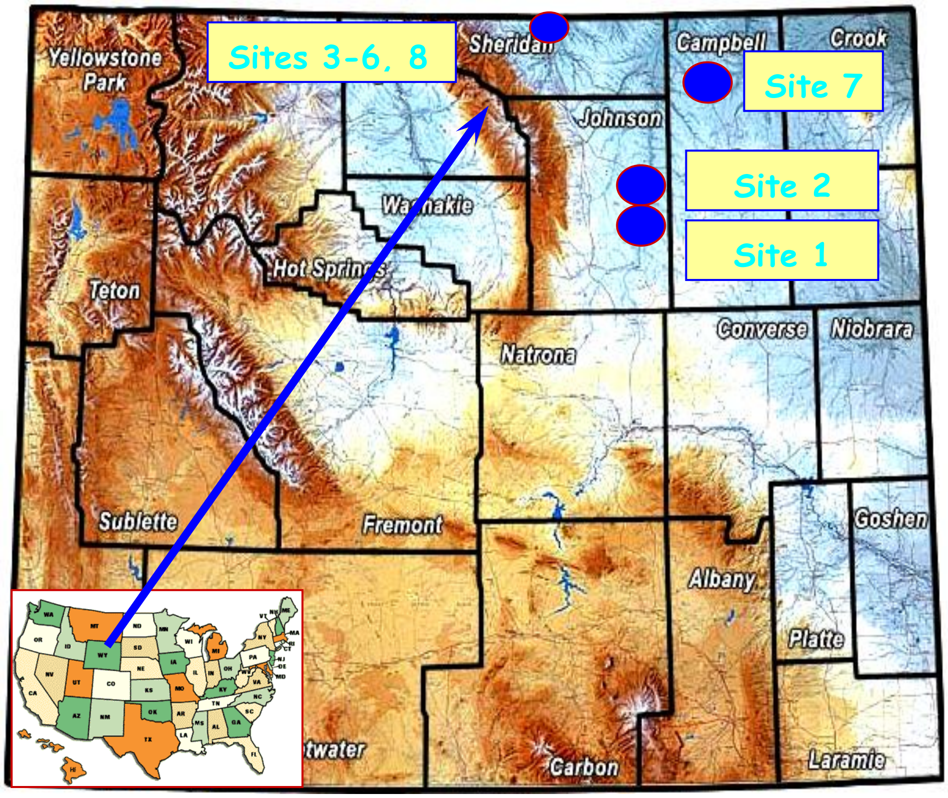

Figure 1. Wyoming study site locations in the Powder River Basin relative to counties.

<u>Laboratory Analyses</u>

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 Bauder, 1986). Soil saturation paste extracts were prepared as described by Rhoades (1999). Values for pH and EC were obtained from saturation paste extracts (soil) and CBNG water samples using pH and EC meters/electrodes, respectively (Thomas, 1999; Rhoades, 1999). Soluble Ca, Mg, and Na concentrations in saturation paste extracts and CBNG water samples were determined using inductively coupled plasma spectrophotometry (Suarez, 1999).

The SAR of saturation paste extracts and irrigation water samples was calculated using:

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

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

Table 1. Study Site and Control Site Descriptions. Each site was represented by a treated area (irrigated with CBNG product water) and a control area (representative soil and vegetation but without CBNG water applications).

Site No.	Seasons CBNG water applied through 2004	General Vegetation & Precipitation zone	Texture[6] to 120 cm	Water application method
1	4[1]	Western Wheatgrass 250-380 mm	CL, C, SCL	Center-Pivot
2	1[2]	Alfalfa-oats 250-380 mm	CL, SiCL, L	Center-Pivot
3	4[3]	Native grass 380-430 mm	SL,L,SCL, CL	Side-roll
4	3[3]	Alfalfa/grass 380-430 mm	L,CL,C,SCL,SL	Center-Pivot
5	3[3]	Grass-hay 380-430 mm	CL,C	Side-roll
6	4[3]	Native grass 380-430 mm	SCL,CL,C	Side-roll
7	2[4,5]	Native grass 250-380 mm	SL,CL,SCL	Misters
8	1[5]	Native grass 380-430 mm	SCL,C	Side-roll

[1]Multiple annual surface applications of gypsum and sulfur. [2]Annual surface applications of gypsum and sulfur. [3]Annual surface applications of gypsum and sulfur & CBNG water treated with sulfur burner. [4]Received CBNG water only in 2001 & 2002. [5]Soil only sampled to 30 cm. [6]CL=clay loam, C=clay, SCL=sandy clay loam, SiCL=silty clay loam, L=loam, SL=sandy loam.

Vegetation Sampling

Vegetation measurements included aboveground biomass production, aerial cover, 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 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. Species numbers were determined using cover data. Dendrogram cluster classifications and species richness, evenness and diversity indices were determined using PC-ORD Version 4.25 (McCune and Mefford, 1999).

Statistical Analysis

Significant differences between treated and control area parameters were determined using 2-group t-tests of means. Significance was determined at P=0.05, unless otherwise noted.

Results and Discussion

CBNG Water Chemistry

Average chemical properties of CBNG water collected from our study sites in 2003 and 2004 are presented in Table 2. All EC and SAR values 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; Warrence et al., 2003). Tolerances of native vegetation to these water qualities are less well known (EnTech, 2002). Water qualities are consistent with those previously reported for CBNG waters in the PRB (Rice et al., 2002; USDOI-BLM, 2003). It is important to consider that land application can differ from traditional irrigation water management because it emphasizes water disposal over plant growth. This altered emphasis can limit the degree to which land application practices with saline-sodic CBNG product waters can be compared to traditional irrigation practices in the region.

Table 2. Chemical properties of CBNG water samples from study sites in 2003 & 2004.

Year	EC (dS m^{-1})		SAR		pH	
	Average	Range	Average	Range	Average	Range
2003	2.5	2.0-4.0	27.2	15-38	8.1	7.0-8.8
2004	3.2	1.9-3.9	31.0	18-57	8.1	7.4-8.9

Soil Physical Properties

Soil Texture. Soil texture data and average percent clay content from 6 depth intervals to 120 cm at the 6 original sites were previously reported by King et al. (2004). Data from sites 7 and 8 (not shown) from 3 depth intervals down to 30 cm were added in 2004. Except for treated site 3 (0-5 and 5-15 cm), treated site 4 (90-120 cm), control site 6 (0-5 cm) and control site 7 (0-5 cm), all sample depths at all sites had > 20% clay indicating increased likelihood of restricted water permeability and reduced leaching potential for Na^+ applied with CBNG water (Levy et al., 1998).

Soil Moisture and Bulk Density. Gravimetric soil moisture content (data not shown) varied by horizon and sample date and was highly dependent on irrigation timing and frequency. Consistent impacts to bulk density are not apparent among sites in the early season 2004 values reported in Table 3. Further data analyses are required to examine potential relationships between depth of wetting front, Na^+ leaching effectiveness and bulk density.

Table 3. May 2004 (Early Season) bulk density values (g/cm^3) from 3 sample depths (0-5, 5-15, 15-30 cm).

Depth	treated BD (g/cm-3)	control BD (g/cm-3)	Probability level*	t value
Site 1				
0-5 cm	1.71	1.43	P=0.084	1.68
5-15 cm	1.71	1.46	P=0.015	3.32
15-30 cm	1.70	1.45	P<0.005	4.66
Site 2				
0-5 cm	1.44	1.36	P<0.002	6.24
5-15 cm	1.55	1.34	P=0.068	1.85
15-30 cm	1.57	1.57	P=0.065	1.90
Site 3				
0-5 cm	1.29	1.34	P=0.446 NS	0.14
5-15 cm	1.54	1.29	P=0.055	2.05
15-30 cm	1.52	1.57	P=0.348 NS	0.42
Site 4				
0-5 cm	1.37	1.33	P=0.303 NS	0.56
5-15 cm	1.50	1.55	P=0.217 NS	0.87
15-30 cm	1.76	1.39	P<0.001	3.81
Site 5				
0-5 cm	1.38	1.19	P=0.097	1.56
5-15 cm	1.60	1.50	P=0.239 NS	0.78
15-30 cm	1.67	1.55	P=0.052	2.09
Site 6				
0-5 cm	1.40	1.33	P=0.123 NS	1.36
5-15 cm	1.79	1.55	P=0.012	3.53
15-30 cm	1.73	1.39	P=0.029	2.65

*NS: not significant at P=0.10.

Infiltration Rates. Average infiltration rates measured on the 6 original treated and 5 original control sites established in 2003 indicate a significant (P=0.10) decrease in infiltration rates on all treated (vs. control) sites by October, 2004 (Table 4). Infiltration tests were not conducted on sites 7 and 8. Applications of water with high Na^+ content can result in clay dispersion and clogging of soil pores which leads to reduced soil permeability and water infiltration (U.S. Salinity Laboratory Staff, 1954; Aggasi et al., 1981; Bauder and Brock, 1992; Hergert and Knudsen, 1997). However, infiltration rates did not decrease on treated sites 3, 4 and 5 from 2003 to 2004 despite continued applications of sodic and saline-sodic CBNG product water.

Table 4. Comparisons of average infiltration rates (cm/hr) between sites receiving saline-sodic CBNG production water (treated) and representative untreated sites (control). Data are from early season 2003 and late season 2004.

Early season 2003	Average Infiltration Treated		Average Infiltration Control		Probability level*	
SITE	cm/hr	standard deviation	cm/hr	standard deviation		t value
1	1.3	1.4	5.6	4.6	P=0.256 NS	0.68
2	6.0	2.8	3.3	2.7	Not Yet Treated	NA
3	3.7	2.5	4.6	1.9	P=0.284 NS	0.60
4	2.3	1.3	6.0	9.6	P=0.233 NS	0.76
5	8.4	5.4	25.9	19.5	P=0.043	1.96
6	3.8	2.3	6.0	9.6	P=0.073	1.61
Late season 2004	Average Infiltration Treated		Average Infiltration Control			
SITE	cm/hr	SD	cm/hr	SD[1]	P Value	t value
1	0.0	0.0	10.7	4.1	P<0.001	5.90
2	0.2	<0.1	5.3	1.2	P<0.001	9.06
3	7.1	2.9	9.4	1.3	P=0.071	1.62
4	3.1	0.7	11.9	8.8	P=0.020	2.44
5	9.0	6.7	14.4	2.7	P=0.067	1.66
6	0.4	0.7	11.9	8.8	P=0.007	3.13

*NS: not significant at P=0.10.

Flux. Flux (q) indicates a specific discharge rate given as the volume of water (V) flowing through a unit cross-sectional area (A) per unit time (t) and mathematically indicated by q=V/At (Hillel, 1982). Comparisons of q between treated and control sites in 2003 under saturated conditions from 4 depth intervals to 90 cm indicated only site 1 with significant differences (P =0.05) (King et al., 2004). However, comparisons in 2004 from depths to 120 cm indicated significantly slower flux on all treated (vs. control) sites at all depths except site 3 (15 cm) and site 4 (90 and 120 cm) (Fig. 2). Clay swelling, dispersion and downward migration from saline-sodic CBNG water applications is suspected to be responsible for the reduced q on treated sites. These tests were not conducted on sites 7 and 8.

Soil Chemical Properties

Data from end of season 2003 indicate that salt accumulations (EC) were elevated on all treated sites within the upper 60 cm of the soil profile and Na^+ accumulations (SAR) were elevated in the top 30 cm (Ganjegunte et al., 2005) (Table 5). Site 1 is operated under an intense management strategy that annually applies about 90 cm of CBNG product water (compared to about 45 cm for sites 3-6). This high application rate is accompanied by an intense regime of surface chemical applications of gypsum ($CaSO_4$) and elemental sulfur (S) that provide Ca^{2+} ions and an acidifying soil environment. The later promotes $CaSO_4$ dissolution, encouraging Ca^{2+}/Na^+ exchange on the soil complex and Na^+ leaching from the soil profile. However, data from 2003 (Table 5) indicate that soluble salt and Na^+ accumulations in the upper part of the profile reflect restricted water flows that limit the ability to leach Na^+ and soluble salts to deeper depths.

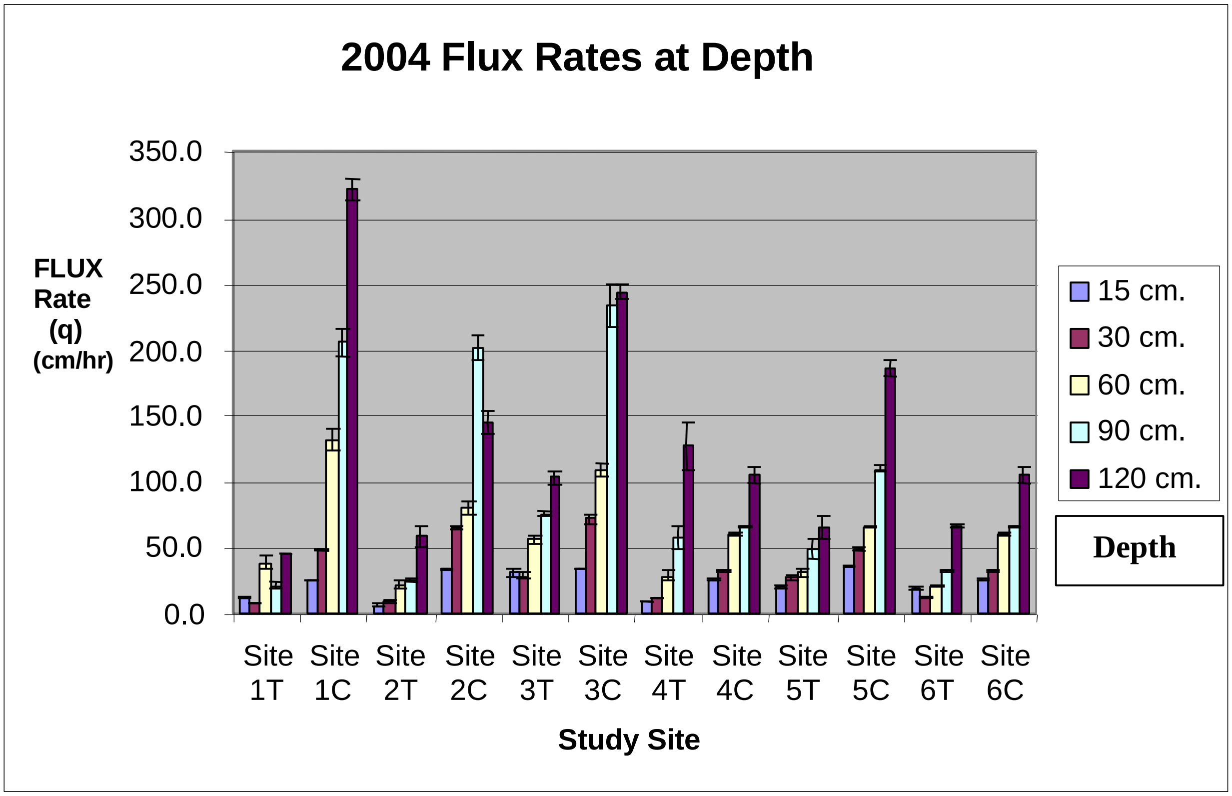

Figure 2. 2004 flux rate (cm hr^{-1}) comparisons by depth interval in treated (T) and control (C) areas. Flux was significantly slower on all treated (vs. control) sites at all depths except site 3 (15 cm) and site 4 (90 and 120 cm). Sites 7 and 8 were not evaluated. Error bars indicate standard error.

Vegetation

Vegetation data are presented from those study sites (treated and control) dominated by native vegetation communities (Sites 1, 3, 6, 7 and 8).

Biomass Production and Aerial Cover. Perennial grasses responded positively to increased water availability as reflected by significantly greater perennial grass cover (except site 8T) (Table 6) and perennial grass production (Table 7) on treated sites in 2004. However, total non-perennial grass cover was greater on control sites 1C, 3C and 6C (vs. treated sites), although differences in non-perennial grass cover were not detected on sites 7C and 8C (Table 6). Site 7 had received only 2 seasons of CBNG water application and site 8 less than one. Total vegetation biomass production was significantly greater on treated sites 1T, 3T, 6T and 7T (vs control sites). Reduced biomass production in 2004 (vs. 2003) at control sites 1 and 3 (Table 7) probably reflects amount and patterns of precipitation, while decreased biomass at treated sites 1 and 3 may reflect soil and water chemistry. This trend will be examined further with a third sampling season.

Table 5. Soil chemical properties of sites 1-6 (treated and control), October 2003 (Ganjegunte et al., 2005).

	pH		EC (dS m^{-1})		SAR		ESP (%)	
Site 1	Control	Irrigated	Control	Irrigated	Control	Irrigated	Control	Irrigated
0-5 cm	7.0±0.1	7.5±0.1*	0.67±0.19	9.09±0.50*ψ	1.4± 0.9	16.6±1.1*	1.1±0.4	9.6±0.3*
5-15 cm	7.3±0.2	7.4±0.1	0.39±0.05	6.83±1.39*	1.1± 1.3	19.7±2.8*	1.2±0.4	14.9±1.4*
15-30 cm	7.2±0.1	7.3±0.2	0.41±0.06	6.38±0.73*	0.6± 0.4	12.4±2.3*	1.2±0.4	8.3±3.4*
30-60 cm	7.3±0.1	7.3±0.2	0.47±0.02 ψ	4.43±1.64*	0.3± 0.3	4.9±2.2*	1.2±0.3	1.9±0.7
60-90 cm	7.3±0.1	7.4±0.2	0.44±0.05	2.78±1.90*	0.9± 0.8	2.3±0.4	2.0±0.2	0.7±0.5*
90-120 cm	7.4±0.1	7.3±0.2	0.76±0.40	2.41±1.18	2.2± 1.1	2.9±0.3	2.0±0.6	1.3±0.4
Site 2								
0-5 cm	7.9±0.4	7.5±0.1	0.87±0.01	1.41±0.34	0.3± 0.1	4.9±3.0	0.8±0.0	3.6±1.2*
5-15 cm	8.1±0.5	7.5±0.4	0.58±0.04	2.26±1.14	0.3± 0.2	6.2±9.0	0.8±0.2	4.3±4.6
15-30 cm	7.8±0.6	7.3±0.2	0.64±0.06	4.37±6.35	0.5± 0.05	8.7±13.7	1.1±0.1	7.7±10.0
30-60 cm	7.8±0.5	7.4±0.5	1.58±1.55	6.09±8.78	0.7± 0.3	9.7±13.2	0.9±0.3	12.9±15.6
60-90 cm	7.6±0.3	7.1±0.3	2.88±1.92	7.86±7.00	1.7± 1.1	13.7±13.6	1.5±0.2	5.9±4.1
90-120 cm	7.8±0.3	6.9±0.1*	8.21±3.36	11.69±5.89	9.3± 6.9	15.9±10.0	5.2±5.0	10.7±7.5
Site 3								
0-5 cm	7.3±0.0	7.4±0.3	0.86±0.08	2.45±0.16*	5.7± 2.5	5.5±5.6	3.2±0.8	9.4±4.5
5-15 cm	7.4±0.1	7.5±0.4	0.82±0.04	1.69±0.89	6.5± 2.9	5.0±5.9	2.8±1.2	5.6±5.3
15-30 cm	7.3±0.1	7.5±0.5	0.57±0.04 ψ	1.63±0.97	2.0± 1.0	2.7±2.4	1.8±0.5	6.5±4.6
30-60 cm	7.4±0.0	7.6±0.2	0.52±0.02	1.52±0.77	1.7± 0.4	1.7±1.9	1.7±0.2	1.5±0.7
60-90 cm	7.6±0.0	7.6±0.2	1.79±0.88	2.72±3.23	8.6± 4.1	1.7±1.8	3.7±1.5	3.1±1.7
90-120 cm	7.1±0.2	7.7±0.3*	6.68±0.18 ψ	2.36±1.79*	9.5± 4.8	1.0±0.8*	10.2±11.6	4.6±2.8
Site 4								
0-5 cm	7.4±0.2	7.5±0.2	0.97±0.25	4.12±0.77*	3.8± 3.4	14.6±5.4*	2.3±1.1	7.3±2.8*
5-15 cm	7.5±0.2	7.5±0.1	0.67±0.14	2.28±0.40*ψ	4.5± 4.0	11.8±1.1*	3.0±1.8	4.8±2.6
15-30 cm	7.4±0.1	7.3±0.2	0.60±0.07 ψ	2.07±0.61*	3.2± 1.9	7.5±0.7*	2.4±1.7	2.9±0.7
30-60 cm	7.4±0.1	7.4±0.3	0.49±0.06	2.43±0.87*	1.0± 0.8	2.6±1.0	1.3±0.6	0.8±0.6
60-90 cm	7.5±0.1	7.6±0.1	0.45±0.01	1.55±0.17*ψ	0.4± 0.1	3.3±1.5*	1.1±0.1	1.7±0.2*
90-120 cm	7.6±0.1	7.5±0.1	0.40±0.03	1.72±0.89	0.4± 0.1	4.1±2.8	1.3±0.4	2.1±0.8
Site 5								
0-5 cm	7.4±0.2	7.4±0.1	1.11±0.27	3.28±0.74*ψ	0.1± 0.02	10.4±2.0*	0.8±0.3	7.9±2.0*
5-15 cm	7.5±0.1	7.7±0.1	0.68±0.06	1.62±0.28*	0.4± 0.2	9.4±1.9*	0.9±0.4	7.7±3.2*
15-30 cm	7.5±0.2	7.7±0.3	0.63±0.07	1.45±0.09*	0.4± 0.1	7.4±0.6*	1.4±0.3	5.7±2.3*
30-60 cm	7.6±0.2	7.6±0.2	0.65±0.03	1.24±0.24*	0.5± 0.1	4.7±1.2*	1.8±0.3	3.6±1.4
60-90 cm	7.4±0.2	7.5±0.2	0.98±0.68	1.85±1.40	0.6± 0.2	1.7±0.4*	2.7±0.9	1.8±0.5
90-120 cm	7.3±0.2	7.4±0.4	0.89±0.65	2.91±1.42	0.6± 0.3	1.3±0.3*	2.3±0.4	1.9±0.8
Site 6								
0-5 cm	7.4±0.2	7.5±0.2	0.97±0.25	2.85±0.60*	3.8± 3.4	7.5±6.4	2.3±1.1	5.4±4.1
5-15 cm	7.5±0.2	7.5±0.2	0.67±0.14	1.69±0.45*	4.5± 4.0	6.7±6.3	3.0±1.8	7.6±4.5
15-30 cm	7.4±0.1	7.4±0.1	0.60±0.07 ψ	1.63±0.46*	3.2± 1.9	4.6±1.4	2.4±1.7	6.4±3.6
30-60 cm	7.4±0.1	7.7±0.1*	0.49±0.06	1.52±1.12	1.0± 0.8	4.4±2.4	1.3±0.6	3.7±2.7
60-90 cm	7.5±0.1	7.5±0.7	0.45±0.01	2.72±5.09	0.4± 0.1	4.2±2.9	1.1±0.1	4.9±3.6
90-120 cm	7.6±0.1	7.4±0.6	0.40±0.03	2.36±4.09	0.4± 0.1	5.2±2.8	1.3±0.4	3.6±0.7*

* indicates differences between early and end of season irrigated soil values were significant at P =0.05.

ψ indicates significant differences between late season and early season values for the same site/depth.

± values reflect standard errors.

Vegetation species richness, evenness, and diversity. Thirty-eight plant species were recorded during cover sampling. Comparison of species richness from native plant communities showed no consistent response to CBNG water applications between treated and control sites. Evenness, however, was greater on all control (vs. representative treated) sites, except for site 8C which had received < 1 year of CBNG water application. Additionally, both Shannon's and Simpson's diversity indices were higher on control sites 1C, 6C and 7C (vs. representative treated sites), whereas sites 3C (low clay) and 8C did not reflect this difference (Table 8). Analyses of the various vegetation diversity parameters (PCORD) indicate evenness decreased on all treated (vs. representative control) sites except site 8T. However, treated sites also had consistently higher average vegetation cover as moderate increases in soil salinity from land application of saline-sodic CBNG water have not reached thresholds limiting growth of dominant perennial grasses (favoring increased biomass and cover with supplemental water). Effects on other species however, have been less favorable and resulted in a decrease in their relative importance and overall community evenness. A continuation of this trend would predict an overall decrease in species diversity (evenness) with continued land applications, even though total species numbers (richness) may not be impacted.

Table 6. Vegetation cover comparisons by life form on sites (1, 3, 6, 7 & 8; treated vs. control) dominated by native plant communities.

2004 Vegetation Cover (%)				
Life Form	Treated ± standard deviation	Control ± standard deviation	Probability level*	t value
SITE 1 Perennial Grasses	76.8±13.6	24.8±6.90	P<0.001	7.6
Non-Perennial Grasses	0.00±0.00	13.6±7.70	P=0.004	4.0
Total Vegetation Cover	76.8±13.6	38.4±5.50	P=0.001	5.8
SITE 3 Perennial Grasses	46.8±5.90	34.8±3.00	P=0.004	4.0
Non-Perennial Grasses	14.0±6.20	29.2±7.60	P=0.008	3.5
Total Vegetation Cover	60.8±6.40	64.0±10.2	P=0.569 NS	0.6
SITE 6 Perennial Grasses	51.6±9.40	17.2±2.30	P<0.001	7.9
Non-Perennial Grasses	4.80±5.00	14.8±6.90	P=0.030	2.6
Total Vegetation Cover	56.4±12.8	32.0±7.10	P=0.006	3.7
SITE 7 Perennial Grasses	47.2±11.0	32.4±3.80	P=0.022	2.8
Non-Perennial Grasses	13.6±8.00	14.8±9.90	P=0.210 NS	0.8
Total Vegetation Cover	60.8±5.20	47.2±8.40	P=0.015	3.1
SITE 8 Perennial Grasses	37.0±7.60	30.0±6.90	P=0.155 NS	1.6
Non-Perennial Grasses	25.6±3.30	12.8±11.1	P=0.039	2.5
Total Vegetation Cover	62.8±6.70	42.8±12.8	P=0.015	3.1

*NS: not significant at P=0.05.

Table 7. Perennial grass and non-perennial grass life form production (kg/ha) on treated and control sites dominated by native plant communities (1, 3, 6 & 7). Total biomass production values are also included.

SITE	Life Form	Treated -2003 kg/ha	Control -2003 kg/ha	Treated -2004 kg/ha	Control -2004 kg/ha
Site 1	perennial grass	5077*	388	4099*	199
	non-perennial grass	1	239	6	79
	Total biomass	5078*	627	4105*	278
Site 3	perennial grass	1460	1370	933*	311
	non-perennial grass	153	625	78	123
	Total biomass	1613	1995	1011*	434
Site 6	perennial grass	na	na	604*	150
	non-perennial grass	na	na	33	122
	Total biomass	na	na	637*	272
Site 7	perennial grass	na	na	550*	340
	non-perennial grass	na	na	585	91
	Total biomass	na	na	1135*	431

Totals for Sites 1 and 7 excluded *Opuntia polyacantha*
* indicates statistically greater than control value at P=0.05

Table 8. Summary of vegetation species richness, evenness, and diversity indices from cover data on sites dominated by native plant communities (1, 3, 6, 7 & 8). N=38 species.

SITE	Richness (no. species)	Evenness	Shannon's Diversity	Simpson's Diversity
1T	2	0.084	0.058	0.0206
1C	12	0.858	2.131	0.8570
3T	16	0.770	2.135	0.8348
3C	10	0.844	1.942	0.8363
6T	7	0.485	0.943	0.4761
6C	8	0.711	1.478	0.7153
7T	11	0.565	1.356	0.6239
7C	18	0.795	2.298	0.8506
8T	18	0.787	2.275	0.8656
8C	15	0.774	2.097	0.8364

Dendrogram classification. Dendrogram classification using cover data clustered sites 1T, 6T, and 7T with about 60% of the information remaining (Figure 3). This is a relative indicator reflecting site similarities using less than 50% of site information. Sites 3T and 8T were grouped with control sites. Site 3T (low clay) clustered with 6C and 7C with about 50% information remaining, while site 8T (1 season of CBNG water application) grouped closely with 3C and 1C (Fig. 3).

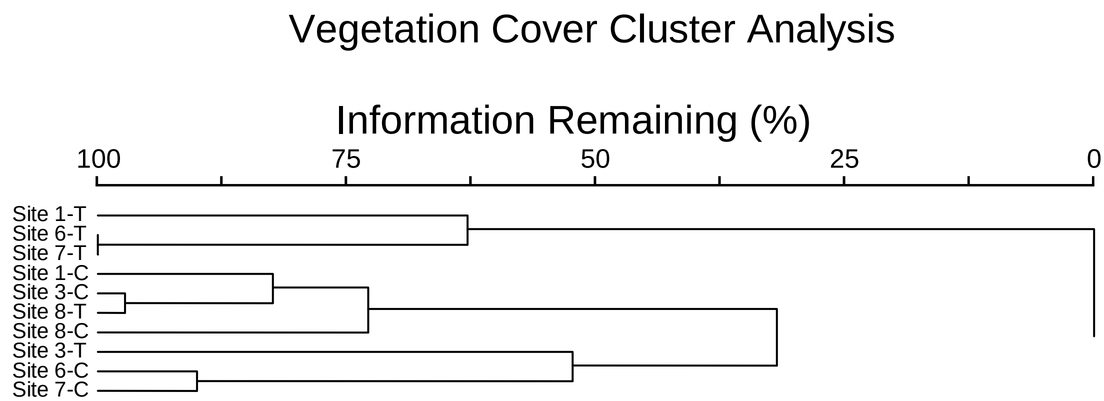

Figure 3**.** Cluster dendrogram of 5 treated and 5 control sites using individual vegetation species cover data. Classified with Sorensen distance and farthest neighbor methods.

Dendrogram classification using cover data reflects impacts from saline-sodic CBNG water applications on native vegetation communities. Although treated sites 1T, 6T and 7T grouped together, treated sites 3T and 8T, were classified with non-treated control sites. Classification of site 3T is influenced by its low soil clay content (< 22% above 30 cm in the profile), which promotes increased water infiltration and percolation, increased salt leaching from surface horizons, and decreased moisture holding capacity. Site 8T has greater clay content (> 43%) but received less than 1 full season of CBNG water applications prior to sampling, which was not sufficient to reflect impacts on soil and vegetation. Treated site vegetation communities have responded to increased available water from land applications with significantly higher average cover values (Table 6). It is this response that is reflected in the dendrogram classification.

Conclusions

Preliminary analyses from this study suggest 4 apparent trends associated with applications of saline-sodic CBNG product water to native soils and vegetation, including:

- Consistent trends of increased soil EC and SAR values at depths to 60 cm (EC) and 30 cm (SAR). The degree of impact varies according to site specific environmental conditions and management practices.
- Decreasing surface infiltration rates and Darcy flux rates at depths to 120 cm.
- Increasing overall vegetation production and cover, mainly through significant positive responses of perennial grass species.
- Decreasing vegetation species diversity (evenness).

The complex and variable responses of various biological parameters reflect site specific conditions and management strategies that should continue to be monitored over time. This is particularly true when consideration is given to the impacts on native vegetation communities (differential tolerances between species to saline-sodic CBNG water applications) and the resulting impacts on long-term reclamation potentials of lands supporting native communities once CBNG water application is discontinued.

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