Cumulative Soil Chemistry Changes from Land Application of Saline–Sodic Waters

Girisha K. Ganjegunte Texas A&M University System
Lyle A. King Shell Valley Consulting
George F. Vance* University of Wyoming

Management of large volumes (60,000 ha-m) of co-production water associated with coal bed natural gas (CBNG) water extraction is a potential concern in the Powder River Basin (PRB) of Wyoming and Montana due to elevated water salinity and sodicity levels. Land application of saline–sodic CBNG water is a common water management method being practiced in the PRB, which can result in deterioration in soil quality. The objective of this study was to evaluate effects from 1 to 4 yr of land application with CBNG water on soil chemical properties at six study sites (fine to loamy, mixed to smectitic, mesic, Ustic Ardisols and Entisols) in the Wyoming PRB region. Changes in chemistry of soils collected from six depths irrigated with CBNG water were compared with representative nonirrigated soils. Applications of CBNG water significantly increased soil EC, SAR, and ESP values (up to 21, 74, and 24 times, respectively) compared with nonirrigated soils. Differences in soil chemical properties between an irrigated and nonirrigated coarse-textured soil were less than that of fine-textured soils, emphasizing texture as an important factor for salinity buildup. Pretreatment of CBNG water using a sulfur burner and application of gypsum and elemental S soil amendments reduced soil pH but did not prevent the build-up of salts and sodium. Study results suggest that current CBNG water management strategies are not as effective as projected. Additional research is needed to develop management strategies appropriate for mitigating adverse effects of CBNG water irrigation.

Driven by growing national demand for energy, substantial coal bed natural gas (CBNG) reserves in the Powder River Basin (PRB) of Wyoming and Montana are being actively developed. Wyoming's portion of the PRB has over 16,000 producing wells with up to 100,000 total wells projected (U.S. Department of Interior, Bureau of Land Management, 2003, Wyoming Coal Bed Natural Gas Task Force, 2006). Wyoming's PRB annual CBNG production represents approximately 2% of the total U.S. natural gas production (Ruckelshaus Institute of Environment and Natural Resources, 2005; U.S. Energy Information Administration, 2006), with estimates of a cumulative 50 billion m^3 of natural gas (Wyoming Coal Bed Natural Gas Task Force, 2006). The PRB is also the fastest growing CBNG development area in the United States (U.S. Department of Energy, Office of Fossil Energy, 2002; U.S. Energy Information Administration, 2006).

Production of CBNG requires removal of co-produced water (hereafter referred to as CBNG water) to reduce hydrostatic head within coal seams. Water extraction from CBNG operations in the PRB is extensive, reaching an annual rate of approximately 750 ha-m in 2003 with about 4500 ha-m produced between 1987 and 2005 (Wyoming Coal Bed Natural Gas Task Force, 2006). An additional 60,000 ha-m are projected over the next 20 yr (Ruckelshaus Institute of Environment and Natural Resources, 2005). Water discharge flows from a single CBNG well can range between 1 and 100 L min^{-1} and may extend for 20 yr (Wheaton and Metesh, 2002).

Major concerns associated with CBNG water quality are salinity (measured by total dissolved solids [TDS] or electrical conductivity [EC]), sodicity (measured by sodium adsorption ratio [SAR]), and high carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations (Rice et al., 2002; McBeth et al., 2003; Ganjegunte et al., 2005; Jackson and Reddy, 2007a, 2007b). Coal bed natural gas water quality is variable across the PRB. Its water chemistry is dominated by Na^+ and bicarbonate ions, with pH ranging from 6.8 to 9.1, EC from 0.4 to 5.0 dS m^{-1}, and SAR from 5 to 70 $mmol^{1/2}$ $L^{-1/2}$ (Rice et al., 2002; McBeth et al., 2003; Van Voast, 2003; Ganjegunte et al., 2005; Jackson and Reddy, 2007a, 2007b).

Copyright © 2008 by the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Published in J. Environ. Qual. 37:S-128–S-138 (2008).
doi:10.2134/jeq2007.0424
Received 12 Aug. 2007.
*Corresponding author (gfv@uwyo.edu).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

G.K. Ganjegunte, El Paso AgriLife Res. and Ext. Ctr., Texas AgriLife Res., Texas A&M Univ. System, El Paso, TX 79927-5020; L.A. King, Shell Valley Consulting, P.O. Box 867, Basin, WY 82410 (former soil science Ph.D. graduate student, Dep. of Renewable Resources, Univ. of Wyoming); G.F. Vance, Dep. of Renewable Resources, Univ. of Wyoming, Laramie, WY 82072-3354.

Abbreviations: BLM, Bureau of Land Management; CBNG, coal bed natural gas; CEC, cation exchange capacities; EC, electrical conductivity; ESP, exchangeable sodium percentage; PRB, Powder River Basin; SAR, sodium adsorption ratio; TDS, total dissolved solids.

In the PRB, several management options have been considered including: (i) direct discharge to existing waterways, (ii) construction of infiltration/evaporation reservoirs, (iii) aquifer-injection, and (iv) direct land application using conventional irrigation systems (U.S. Department of Interior, Bureau of Land Management, 2003). Several regulatory, environmental, and economic considerations affect these options (U.S. Energy Information Administration, 2006). However, land application of CBNG water using traditional sprinkler irrigation systems is common (U.S. Department of Interior, Bureau of Land Management, 2003). At present several management strategies such as applying adequate water to prevent salt accumulation and maintain high available water, addition of soluble Ca^{2+} in the form of gypsum to replace Na^{+}, and applications of elemental S to neutralize alkalinity are being practiced to minimize adverse effects of land disposal of saline–sodic CBNG water (Vance et al., 2004; Johnston et al., 2008). 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 (U.S. Department of Interior, Bureau of Land Management, 2003; King et al., 2004).

Smectite clays dominate the mineralogy of soils in the PRB with nearly 41% of the basin area characterized as poorly drained (U.S. Department of Interior, Bureau of Land Management, 2003). Application of poor quality CBNG water on these lands can have adverse impacts on sensitive plant growth and soil quality due to salinity and Na^{+} buildup (Bauder and Brock, 2001; Rice et al., 2002; Dahiya et al., 2004; Ganjegunte et al., 2005; King et al., 2005; Stearns et al., 2005; Vance et al., 2008). Long-term land application of CBNG water, if not managed properly, can irreversibly damage soil productivity in the disposal sites. Evaluating changes in soil chemistry is therefore critical for developing appropriate management practices. The objective of this study was to evaluate cumulative effects from 1 to 4 yr of CBNG water land application on soil chemical properties. Results of this study can be used to evaluate current management practices and provide essential information needed to develop appropriate management practices to prevent permanent damage to lands impacted by CBNG water applications.

Materials and Methods

Powder River Basin

The PRB is located in northeast Wyoming and southeast Montana. It is characterized by rolling uplands and hills with rough, eroded, and broken terrain in the north. Land generally slopes northward from higher elevations in Wyoming toward 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 to 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 semiarid with long, cold winters and short, hot summers. Soils are influenced by dominant local geologic strata that influence chemical and physical properties. Basin soils are generally alkaline, low in organic matter content, and often dominated by smectitic clays (U.S. Department of Interior, Bureau of Land Management, 2003).

Study Sites

Areas irrigated with CBNG water and representative nonirrigated areas were established at six study sites (Fig. 1) in June–July, 2003 with data collection through October 2004. Study sites were located in Johnson and Sheridan counties of Wyoming (Fig. 1). Different CBNG producers have been managing these sites, and land application of CBNG water occurs from April through November. Various CBNG water treatments (i.e., sulfur burner) and soil amendments (i.e., gypsum and elemental S) were used on the irrigated sites. Ownership and access issues limited possible study site locations. Six sites were selected because representative nonirrigated areas with similar soil series and topographies were available in proximity to irrigated areas. Soil classification details for irrigated and nonirrigated sites are provided in Table 1. Environmental characteristics are summarized by: seasons of CBNG water application by October 2004 (end-of-study), general vegetation, precipitation zone, soil profile textures, and water application methods. Various water and soil amendments being used in these study sites are summarized in Table 2. The details provided by different CBNG producers managing these sites, on the amount of CBNG water, gypsum, and S that have been added to irrigated site soils, are given in Table 3. The amount of S does not include that used in sulfur burners.

Coal Bed Natural Gas Water Sampling

Multiple grab water samples were periodically obtained throughout the 2003–2004 field seasons from reservoirs associated with the study sites and also from side-roll and center-pivot irrigation sprinklers used for CBNG water application. Samples were collected in plastic bottles that were filled to eliminate headspace, capped, placed in ice-filled coolers, and transported to the laboratory for analyses of pH, EC, and Na^{+}, Ca^{2+}, and Mg^{2+} concentrations.

Soil Sampling

Soil samples from irrigated and nonirrigated areas in study sites were collected during 2003 and 2004. Sample dates were early-season (June or July) and late-season (October) for both years. Five (early-season 2003) or three (late-season 2003; early and late-season 2004) random samples were collected from each experimental area using a hand-auger. Soil samples were collected at six depth intervals (0–5, 5–15, 15–30, 30–60, 60–90, and 90–120 cm), placed in resealable plastic bags to prevent moisture loss, and transported to the laboratory for further analyses. Soil subsamples were dried at 105°C until constant weight was obtained and gravimetric soil moisture contents calculated. Soil samples were air-dried, passed through a 2.0-mm sieve, and analyzed for particle-size distribution and chemical properties. Particle analyses were determined using the hydrometer method (Gee and Or, 2002).

Soil Solution Sampling

To monitor salt and Na^{+} buildup, two to four nests of soil solution lysimeters (Johnson 1 and 2, four lysimeter nests; Sheridan

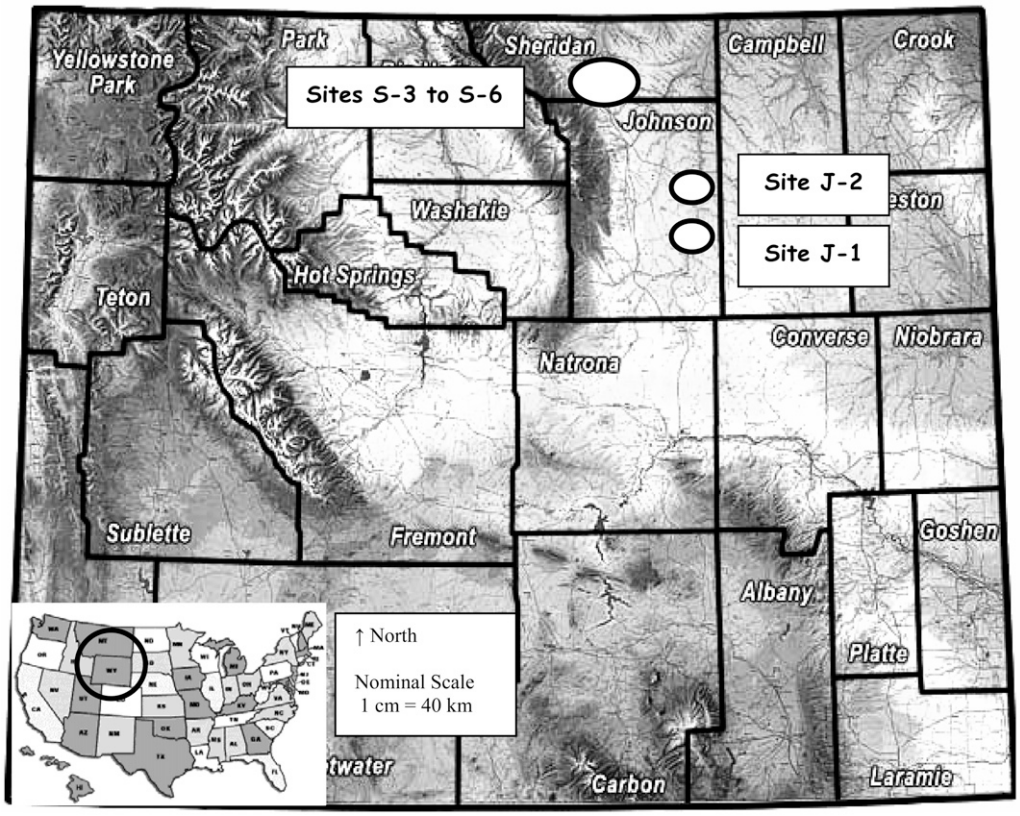

Fig. 1. Wyoming study sites examined for coal bed natural gas (CBNG) water application impacts on soil chemistry. J = Johnson County and S = Sheridan County.

3, 4 and 6, three lysimeter nests; and Sheridan 5, two lysimeter nests) were installed in irrigated areas of study sites at 15-, 30-, and 60-cm depths during August 2003. Lysimeters were allowed to equilibrate for several months and soil solutions collected late during the 2003 irrigation season were discarded. Lysimeter soil solution samples collected in August 2004 were stored in plastic

Table 1. Taxonomical classification information for the coal bed natural gas (CBNG) water-irrigated and nonirrigated soils at six study sites.

	Irrigated		Nonirrigated	
Site	Classification by soil map unit or (soil series)	Area	Classification by soil map unit or (soil series)	Area
		ha		ha
Johnson-1	Map unit—data not available for north Johnson County fine-loamy, mixed, superactive, mesic Ustic Haplocambid (Zigweid)	17	Map unit—data not available for north Johnson County fine-loamy, mixed, superactive, mesic Ustic Haplocambid (Zigweid)	1
Johnson-2	Map unit—Kishona fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthent	15	Map unit—Kishona fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthent	2
Sheridan-3—coarse-texture	Map unit—Shingle-Worf Complex loamy, mixed, superactive, calcareous, mesic, shallow Ustic Torriorthent (Shingle) loamy, mixed, superactive, mesic, shallow Ustic Haplargid (Worf)	17	Map unit—Cushman-Worf Association fine-loamy, mixed, superactive, mesic Ustic Haplargid (Cushman) loamy, mixed, superactive, mesic, shallow Ustic Haplargid (Worf)	2
Sheridan-4—center pivot	Map units—Bidman-moist-Ulm loam and Parmleed-Bidman Association fine, smectitic, mesic Ustic Paleargid (Bidman) fine, smectitic, mesic Ustic Haplargid (Ulm) fine, smectitic, mesic Ustic Paleargid (Parmleed)	12	Map units—Parmleed-Worfka and Parmleed-Bidman Associations fine, smectitic, mesic Ustic Paleargid (Parmleed) clayey, smectitic, mesic, shallow Ustic Haplargid (Worfka) fine, smectitic, mesic Ustic Paleargid (Bidman)	1
Sheridan-5—fine-texture/grass hay	Map unit—Wyarno clay loam fine, smectitic, mesic Ustic Haplargid (Wyarno)	8	Map unit—Wyarno clay loam fine, smectitic, mesic Ustic Haplargid (Wyarno)	1
Sheridan-6—fine-texture/native grass	Map unit—Parmleed-Worfka Association fine, smectitic, mesic Ustic Paleargid (Parmleed) clayey, smectitic, mesic, shallow Ustic Haplargid (Worfka)	2	Map units—Parmleed-Worfka Association and Parmleed-Bidman Association fine, smectitic, mesic Ustic Paleargid (Parmleed) clayey, smectitic, mesic, shallow Ustic Haplargid (Worfka) fine, smectitic, mesic Ustic Paleargid (Bidman)	1

Table 2. Study site general information, coal bed natural gas (CBNG) water treatment, soil amendments, and land use on CBNG irrigated areas.

Site name county-number—feature (if any)	Seasons CBNG water application (end-of-study/October 2004)	General vegetation and precip. zone	Texture† (0–120 cm)	Water application method	Water treatment before irrigation	Soil amendment type and application strategy	Land use
Johnson-1	4	seeded grassland 250–380 mm	CL, C	center-pivot	none	multiple annual surface applications of gypsum and elemental S	winter cattle grazing, cut for hay in 2004
Johnson-2	1.5	seeded alfalfa-oats 250–380 mm	CL, SiCL, L	center-pivot	none	annual surface application of gypsum and elemental S	cut for hay in 2004
Sheridan-3—coarse-texture	4	mixed grass prairie 380–430 mm	SL, L, SCL, CL	side-roll	sulfur burner	annual surface application of gypsum and elemental S	seasonal cattle grazing
Sheridan-4—center pivot	3	seeded alfalfa 380–430 mm	L, CL, C, SCL, SL	center-pivot	sulfur burner	annual surface application of gypsum and elemental S	cut for hay
Sheridan-5—fine-texture/grass hay	3	seeded grass pasture 380–430 mm	CL, C	side-roll	sulfur burner	annual surface application of gypsum and elemental S	cut for hay
Sheridan-6—fine-texture/native grass	4	mixed grass prairie 380–430 mm	SCL, CL, C	side-roll	sulfur burner	annual surface application of gypsum and elemental S	seasonal cattle grazing

† CL, clay loam; C, clay; SiCL, silty clay loam; L, loam; SL, sandy loam; SCL, sandy clay loam.

bottles and transportation to the laboratory for further analyses. Insufficient irrigation during 2003 resulted in the lack of equilibration in the soil solution of samples from Johnson-2, so they were not analyzed. Insufficient soil solution sample sizes also occurred at Sheridan-6 site at 30- and 60-cm depths. These samples required dilution and only EC was determined.

Chemical Analyses

The pH and EC values were determined using a glass electrode and conductivity cell (Rhoades, 1996; Thomas, 1996). Soluble Na^+, Ca^{2+}, and Mg^{2+} concentrations in soil saturated paste extracts and CBNG water samples were determined using inductively coupled plasma spectrometry (Suarez, 1996). Sodium adsorption ratios (SAR) were calculated as:

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

where Na^+, Ca^{2+}, and Mg^{2+} represent millimolar concentrations (mmol L^{-1}) of respective ions (Essington, 2004). Limited volumes of lysimeter soil solution samples allowed for only EC and SAR analyses, using the methods described above.

Table 3. Details of coal bed natural gas (CBNG) water, gypsum, and S applied over 4 yr to study sites managed by different CBNG producers.†

Site name	2001 (September–November)	2002 (April–November)	2003 (April–November)	2004 (April–November)	Total
Johnson-1					
Water, ha-m	0.22	0.55	0.55	0.78	2.10
Gypsum, Mg ha^{-1}	8.03	13.30	21.30	21.30	63.93
Sulfur, Mg ha^{-1}	3.08	9.38	16.30	16.30	45.06
Johnson-2					
Water, ha-m			0.39	0.78	1.17
Gypsum, Mg ha^{-1}			10.65	21.30	31.95
Sulfur, Mg ha^{-1}			8.15	16.30	24.45
Sheridan-3—coarse-texture					
Water, ha-m	0.30	0.30	0.30	0.30	1.20
Gypsum, Mg ha^{-1}	4.25	4.25	4.25	4.25	17.00
Sulfur, Mg ha^{-1}	2.50	2.50	2.50	2.50	10.00
Sheridan-4—center pivot					
Water, ha-m		0.30	0.30	0.30	0.90
Gypsum, Mg ha^{-1}		4.25	4.25	4.25	12.75
Sulfur, Mg ha^{-1}		2.50	2.50	2.50	7.50
Sheridan-5—fine-texture/grass hay					
Water, ha-m		0.30	0.30	0.30	0.90
Gypsum, Mg ha^{-1}		4.25	4.25	4.25	12.75
Sulfur, Mg ha^{-1}		2.50	2.50	2.50	7.50
Sheridan-6—fine-texture/native grass					
Water, ha-m	0.30	0.30	0.30	0.30	1.20
Gypsum, Mg ha^{-1}	4.25	4.25	4.25	4.25	17.00
Sulfur, Mg ha^{-1}	2.50	2.50	2.50	2.50	10.00

† The above data are obtained from management records of coal bed natural gas (CBNG) producers maintaining the study sites and based on mass balance calculations performed in an earlier study on the same sites (Ganjegunte et al., 2005); these data were found to be fairly accurate.

Table 4. Coal bed natural gas (CBNG) water quality (pH, electrical conductivity [EC], and sodium adsorption ratio [SAR]) used to irrigate study sites in 2003 and 2004.

Site name	Sample year	pH	EC	SAR
			dS m^{-1}	$mmol^{1/2}$ $L^{-1/2}$
Johnson-1	2003	8.2	2.9	30.9
	2004	7.9	3.2	32.2
Johnson-2	2003	Water source not available to sample		
	2004	9.1	4.8	56.1
Sheridan-3—coarse-texture†	2003	8.0	2.0	24.2
	2004	7.2	2.0	30.0
Sheridan-4—center pivot	2003	7.9	2.2	32.8
	2004	7.1	2.0	34.5
Sheridan-5—fine-texture/ grass hay	2003	7.7	2.9	17.2
	2004	7.4	1.6	19.7
Sheridan-6—fine-texture/ native grass†	2003	8.0	2.0	24.2
	2004	7.2	2.0	30.0

† Sheridan-3 and Sheridan-6 have the same reservoir water source.

Soil cation exchange capacity (CEC) was determined using sodium acetate (NaOAc) buffered at pH 8.2 and 1 M ammonium acetate (NH_4OAc) (Sumner and Miller, 1996). Soil water-soluble Na^+ concentrations from saturated paste extracts were subtracted from Na^+ concentrations determined with NH_4OAc extracts to calculate exchangeable Na^+ concentrations (Helmke and Sparks, 1996) and to calculate exchangeable sodium percentage (ESP), which is the percentage Na^+ on the exchange complex. Ammonium acetate–extractable Na^+ represented the sum of soil water-soluble and exchangeable Na^+.

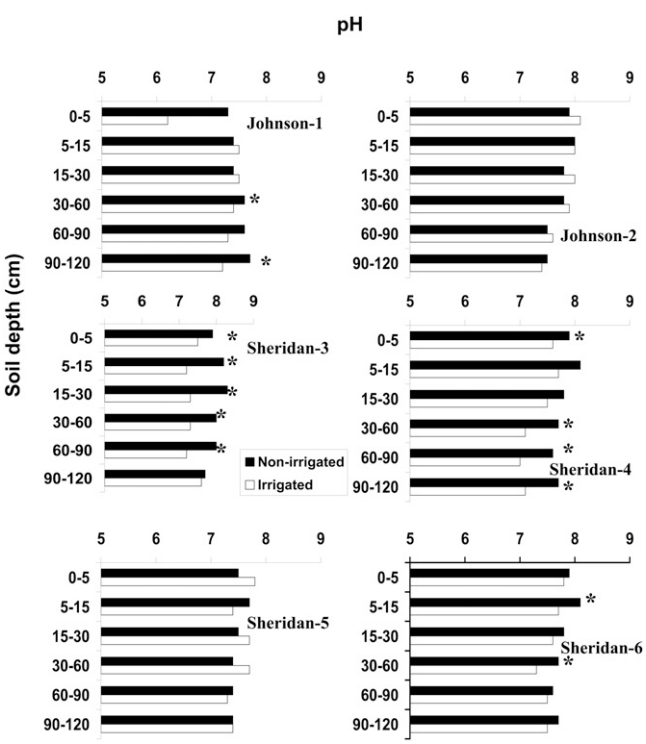

Fig. 2. Late-season 2004 comparison of soil pH in nonirrigated and coal bed natural gas (CBNG) water-irrigated areas at six study areas in the Powder River Basin, WY. The asterisks (*) represent significant differences at the $p \leq 0.05$ level.

Statistical Analyses

Significant differences between sample parameters were determined with two-group *t* tests of means (SAS Institute, 2002). Variances were evaluated for equality and log(*x*) data transformations performed when necessary. Satterthwaite (1946) approximation was used to evaluate *t* test results for unequal variances. Significance was determined at the $p < 0.05$ or $p < 0.10$ levels (one-tailed).

Results

Chemical properties of CBNG water collected from our study sites in 2003 and 2004 indicate all EC and SAR exceeded values (EC of 0.75 dS m^{-1}; SAR of 10 $mmol^{1/2}$ $L^{-1/2}$) generally considered suitable for sensitive crop species (U.S. Salinity Laboratory Staff, 1954; Shainberg and Oster, 1978; Hillel, 2000) (Table 4). Values of SAR also exceeded Montana's Legislated in-stream standards (Powder River $\leq$7.5 and $\leq$9.75 $mmol^{1/2}$ $L^{-1/2}$ during irrigation and nonirrigation seasons and Tongue River $\leq$4.5 and $\leq$7.5 $mmol^{1/2}$ $L^{-1/2}$ during irrigation and nonirrigation seasons, respectively) (Montana State University, 2003). Water qualities from these study sites were generally within ranges previously reported for CBNG waters in the PRB with Johnson-2 water salinity and sodicity levels approaching the higher end of reported ranges (Rice et al., 2002; McBeth et al., 2003; U.S. Department of Interior, Bureau of Land Management, 2003; Jackson and Reddy, 2007a, 2007b) (Table 4).

Clay and clay loam soil textures dominated most sample depths on the six study sites (Table 2). Inter-bedded sandstone parent material influenced texture throughout the profile of Sheridan-3 and the 60- to 120-cm depth of Sheridan-4. Clay content exceeded 250 g kg^{-1} at most depths at all locations except the irrigated areas at Sheridan-3 (0–5 and 90–120 cm), Sheridan-4 (0–5 and 90–120 cm), and Sheridan-6 (0–5 cm) sites. Clay content exceeded 300 g kg^{-1} in 60 of 72 study site samples. Soil chemical properties were evaluated by comparing end-of-study (late-season 2004) irrigated vs. nonirrigated areas and beginning-of-study (early-season 2003) irrigated area data to end-of-study irrigated area data. Beginning-of-study does not necessarily imply no treatment with CBNG water as some sites (Johnson-1 and Sheridan-3) had received up to two prior seasons of CBNG water applications by 2003.

Late-season 2004 responses of both irrigated and nonirrigated area pH values were variable (Fig. 2). Soils from Johnson-2 and Sheridan-5 showed no significant differences in pH values (irrigated vs. nonirrigated). However, the Johnson-1 irrigated area had two soil depths (30–60 and 90–120 cm) and irrigated areas at Sheridan-3, -4, and -6 each had several sample depths with significantly lower pH values than their respective nonirrigated areas. Comparisons of irrigated area pH values between beginning- and end-of-study indicated five of six study sites had at least four sample depths with significantly lower pH values by end-of-study (Table 5).

End-of-study (2004) soil ECs were significantly greater (up to 21 times that of nonirrigated soil at 15–30 cm in Johnson-1) on irrigated areas at four of six study sites to depths of 120 cm

Table 5. Selected soil chemical properties at different depths in the irrigated areas of six study sites in the beginning (early-season 2003) and end of the study (late-season 2004). Bold numbers indicate irrigated soils differed between 2003 and 2004 at the $p \leq 0.05$ level unless otherwise noted.

	Johnson-1		*Johnson-2†*		*Sheridan-3*		*Sheridan-4*		*Sheridan-5*		*Sheridan-6*	
Depth	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
cm												
				pH								
0–5	**7.6**	**6.2**	8.1	8.1	7.9	7.5	**7.7**	**7.6 ‡**	7.9	7.8	7.9	7.8
5–15	7.6	7.5	8.1	8.0	**8.2**	**7.2**	7.7	7.7	**8.4**	**7.4**	**8.2**	**7.7‡**
15–30	7.5	7.5	8.1	8.0	**8.2**	**7.3**	7.6	7.5	**8.2**	**7.7**	**8.1**	**7.6**
30–60	**7.6**	**7.4‡**	8.1	7.9	**8.2**	**7.3**	**7.6**	**7.1**	**8.3**	**7.7**	**8.2**	**7.3**
60–90	**7.8**	**7.3**	**8.0**	**7.6‡**	**8.1**	**7.2**	**7.9**	**7.0**	**8.2**	**7.3**	**8.1**	**7.5**
90–120	**7.9**	**7.2**	**7.9**	**7.4**	**8.0**	**7.6‡**	**8.0**	**7.1**	**8.2**	**7.4**	**8.1**	**7.5**
				Electrical conductivity, dS m^{-1}								
0–5	**7.1**	**13.5**	**1.0**	**12.3**	**1.9**	**4.8**	**3.8**	**5.1**	2.8	3.1	**1.9**	**3.8**
5–15	**5.9**	**10.6**	**0.8**	**8.8**	**1.0**	**2.6**	**1.4**	**3.1**	**1.5**	**2.3‡**	**1.1**	**1.8**
15–30	**5.4**	**10.6**	**0.8**	**3.8**	**1.0**	**2.3**	**1.3**	**2.4**	**0.9**	**1.7**	**1.1**	**2.2**
30–60	**2.5**	**7.7**	1.4	1.7	**1.5**	**3.0**	**1.2**	**4.5**	**0.8**	**2.9**	1.7	2.2
60–90	**1.1**	**3.8**	3.9	7.6	4.1	3.0	**0.6**	**4.6**	**0.8**	**2.5**	4.2	3.1
90–120	2.2	4.7	5.7	12.1	5.0	**2.9**	**0.4**	**2.9**	**0.8**	**2.5**	5.5	4.5
				Sodium adsorption ratio, $mmol^{1/2}\ L^{-1/2}$								
0–5	**15.0**	**19.5**	**1.6**	**28.8**	7.3	**7.7**	**4.5**	**7.6**	**7.8**	**12.2**	9.0	14.6
5–15	**20.3**	**21.3**	**1.2**	**22.3**	**6.3**	**8.7 ‡**	**3.5**	**12.7**	**7.3**	**12.3**	9.1	10.7
15–30	**13.0**	**20.1**	**2.0**	**8.5**	**5.9**	**7.9‡**	**3.6**	**11.8**	**5.7**	**9.5**	8.2	9.1
30–60	**4.1**	**9.8**	3.4	5.1	4.5	6.7	**0.7**	**7.9**	5.3	7.0	4.5	6.5
60–90	4.2	3.9	7.4	10.4	5.3	4.7	**0.6**	**4.9**	3.1	3.3	4.1	4.0
90–120	5.1	3.8	8.6	12.5	7.1	4.8	**0.4**	**1.2**	2.9	2.6	6.2	4.7
				Exchangeable sodium percent								
0–5	**11.4**	**34.4**	**1.6**	**26.8**	**5.7**	**14.9**	**2.1**	**25.1**	**11.1**	**16.1**	**6.4**	**28.0**
5–15	**13.9**	**45.2**	**2.4**	**29.7**	**3.5**	**16.0**	**3.2**	**30.3**	**4.5**	**17.2**	**10.9**	**27.5**
15–30	**10.0**	**38.5**	**2.2**	**31.4**	**4.3**	**22.4**	**2.6**	**29.2**	**6.3**	**18.6**	**6.9**	**24.9**
30–60	7.7	13.9	**3.0**	**22.2**	**5.1**	**19.8**	**2.0**	**4.5**	**8.1**	**18.7**	**4.1**	**17.3**
60–90	**3.8**	**9.2**	**7.2**	**24.3**	10.1	12.0	**4.8**	**11.3**	5.6	8.2	**5.4**	**10.0**
90–120	**3.9**	**12.0**	**6.2**	**20.6**	9.0	11.1	**5.6**	**8.4‡**	**3.4**	**9.5**	**8.6**	**19.9**

† CBNG water application initiated in October 2003.

‡ Irrigated 2004 differed from irrigated 2003 at $p \leq 0.10$ level.

compared with their respective nonirrigated areas (Fig. 3). The remaining two sites had significantly greater irrigated area ECs to depths of 60 cm (Sheridan-3) and 30 cm (Johnson-2) than their respective nonirrigated areas. Thirty-one of 36 sample comparisons had significantly higher irrigated area ECs. Most irrigated area samples (26 of 36) had significantly higher ECs in late-season 2004 than corresponding values from early-season 2003 (Table 5). Sheridan-4 had uniformly significant EC increases (late-season 2004 vs. early-season 2003) to 120 cm. Sheridan-5 had significantly higher (late-season 2004 vs. early-season 2003) ECs at all but the 0- to 5-cm sample depth (Table 5). All other sites had significant increases (late-season 2004 vs. early-season 2003) in EC to at least 30 cm (Table 5). Sheridan-3 had higher EC on its nonirrigated area at 60- to 90- and 90- to 120-cm sample depths than on its respective irrigated area (Fig. 3). Based on saturated paste extract EC values, soils at Johnson-1 (0–60 cm), Johnson-2 (0–15 and 90–120 cm), Sheridan-3 (0–5 cm), Sheridan-4 (0–5, 30–60, and 60–90 cm), and Sheridan-6 (60–90 cm) are classified as saline (EC > 4 dSm^{-1}). Lysimeter soil solution EC values also confirmed that the upper 60 cm soils in Johnson-1, Sheridan-3, and Sheridan-4 were saline, whereas Sheridan-6 contained high salt concentrations at 30- and 60-cm depths.

Late-season 2004 irrigated area SARs were significantly greater than those of respective nonirrigated areas at depths to 120 cm on four study sites (Johnson-1 and Sheridan-4, -5, and -6) (Fig. 4). The SAR increases of irrigated soils ranged from double the representative nonirrigated Sheridan-3 surface soil to 74 times greater than the representative nonirrigated site at the 5- to 15-cm depth of Johnson-2. The irrigated area at Johnson-2 had significantly increased SARs to 60 cm compared with its nonirrigated area after only 1.5 seasons of saline–sodic CBNG water application. Results from Sheridan-3 were variable with significantly greater irrigated area SARs at 0- to 5-cm and 30- to 60-cm sample depths than those of its nonirrigated area, but significantly lower SARs at the 90- to 120-cm depth (Fig. 4). Differences in other sample depths at Sheridan-3 were not significant. Comparisons of beginning-of-study and end-of-study irrigated area SARs indicate significant increases in Na^+ accumulations to at least 30 cm at five of the six study sites (Table 5). Increases were significant to depths of 120 cm on Sheridan-4, 60 cm on Johnson-1, and 30 cm on Johnson-2 and Sheridan-5. Based on saturated paste soil SAR values, soils at Johnson-1 (0–5, 5–15, and 15–30 cm), Johnson-2 (0–5 and 5–15 cm), and Sheridan-6 (0–5 cm) were considered sodic (Fig. 4). However,

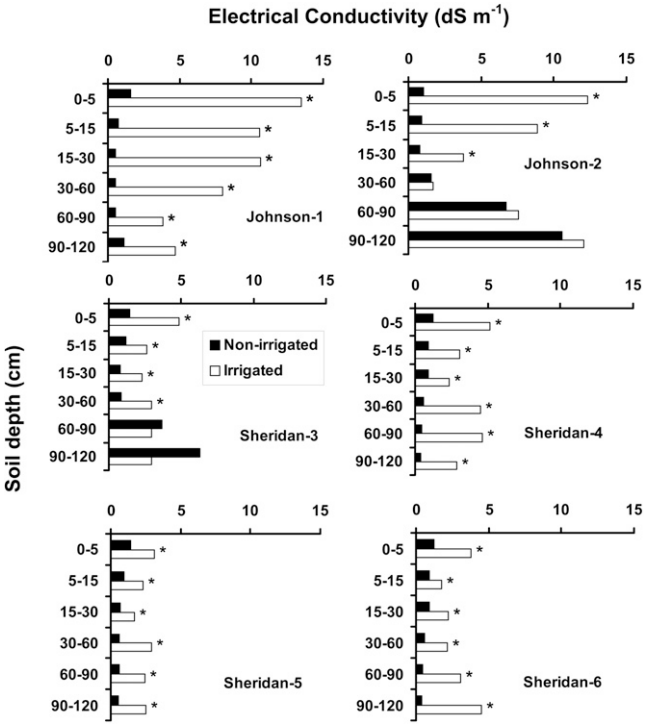

Fig. 3. Late-season 2004 comparison of soil electrical conductivity (EC) (dS m^{-1}) in nonirrigated and coal bed natural gas (CBNG) water-irrigated areas at six study sites in the Powder River Basin, WY. The asterisks (*) represent significant differences at the $p \leq 0.05$ level.

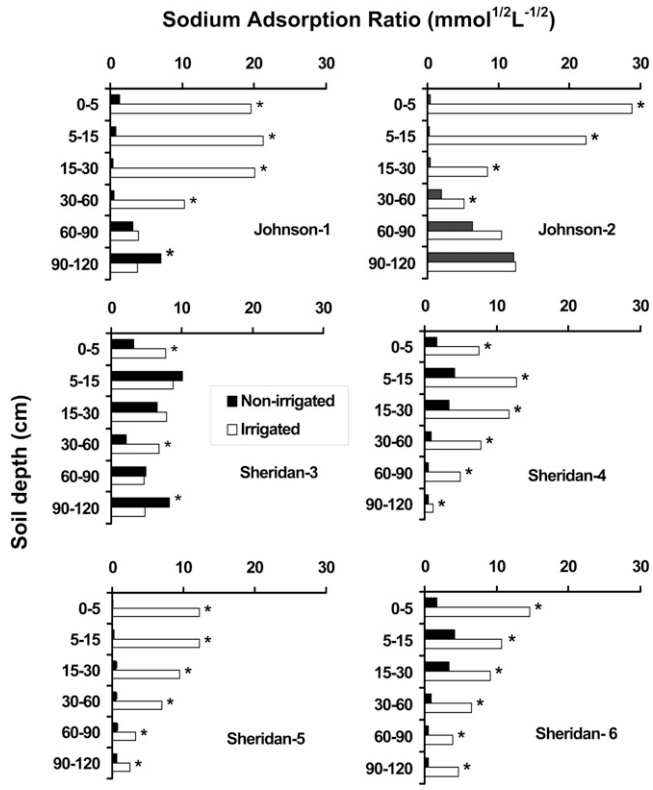

Fig. 4. Late-season 2004 comparison of soil sodium adsorption ratio (SAR) (mmol$^{1/2}$ $L^{-1/2}$) in nonirrigated and coal bed natural gas (CBNG) water-irrigated areas at six study sites in the Powder River Basin, WY. The asterisks (*) represent significant differences at the $p \leq 0.05$ level.

lysimeter solution SAR values indicated only the 15-cm depth of Johnson-1 site to be sodic (Fig. 5).

Beginning-of-study vs. end-of-study irrigated area ESP comparisons indicated increased accumulations of exchangeable Na^+ on soil exchange sites to depths of 120 cm at five of six study sites. Increases were significant for 32 of 36 samples (Table 5). Differences in ESP values from intermediate depths at Johnson-1 (30–60 cm), Sheridan-3 (60–120 cm), and Sheridan-5 (60–90 cm) were not significant (Table 5). Irrigated soil ESPs were significantly higher at most depths than nonirrigated soils in all study sites for late-season 2004 samples (data not shown). The ESP values of irrigated soils at 60- to 90-cm depth in Johnson-2 were 24 times greater than nonirrigated areas after only 1.5 seasons of saline–sodic CBNG water application. However, Sheridan-3 and Sheridan-4 had a combined total of five intermediate sample depths with ESPs that were not significantly elevated. Sheridan-3 had variable results with significantly greater ESPs (irrigated vs. nonirrigated) at 0- to 5-, 15- to 30-, and 90- to 120-cm sample depths, but no significant differences at 5- to 15- or 30- to 90-cm depths. Sheridan-4 also had no significant increase in irrigated area ESPs compared to its nonirrigated area in the 30- to 90-cm depth range.

Concentrations of Na^+ (mg L^{-1}) significantly increased to depths of 30 cm on irrigated areas at all six study sites between early-season 2003 and late-season 2004 (Table 6). However, results at depths below 30 cm were inconsistent. Concentrations of Ca^{2+} and Mg^{2+} were variable, reflecting amounts, timing, and quality of surface amendments and CBNG water, as well as in situ mineral concentrations. Increases and decreases in both ions were evident across sites and with depth (Table 6). Only Johnson-1 had significant end-of-study (vs. beginning-of-study) increases in Ca^{2+} and Mg^{2+} at most sample depths (Table 6).

Discussion

Site specific management practices are influencing soil pH on irrigated areas of the CNBG water application study sites. Coal bed natural gas water treated with sulfur burners, which acidify CBNG water by burning elemental S to produce sulfurous or sulfuric acids that reduces HCO_3^- concentrations, lowered soil pH on Sheridan-3, Sheridan-4, Sheridan-5 and Sheridan-6. Relatively large volumes of low pH CBNG water applied in 2004 to Sheridan-3 and Sheridan-6 compared with Sheridan-5 could have resulted in significantly lower pH values in these two sites. Although Sheridan-4 and Sheridan-5 received the same amount of CBNG water and elemental S, the pH of CBNG water applied at the Sheridan-4 site was lower than Sheridan-5. This could explain the lower pH values observed at some depths in Sheridan-4 soils. Reduction in pH values observed at Johnson-1 was a continuation of trends observed for the same site reported by Ganjegunte et al. (2005) and could be due to the application of greater amounts of CBNG water and S. Sulfur burner treatments appear to favorably influence pH, maintaining values throughout soil profiles

of irrigated areas that improve dissolution of in situ calcite (Yu et al., 2003; Johnston et al., 2008). Late-season 2004 Ca^{2+} concentrations were also influenced by heavy surface applications of gypsum. In fact, 10 of 12 samples from sites not irrigated with sulfur burners (Johnson-1 and Johnson-2) had significantly increased Ca^{2+} accumulations (late-season 2004 vs. early-season 2003) compared with 8 of 24 samples on sites receiving sulfur burner treatment (Table 5). Johnson-1 received the heaviest applications of CBNG water and chemical amendments of all six study sites and the irrigated area surface horizon had the lowest pH value (6.2) measured. Decrease in pH values from early 2003 to late 2004 at depths to 120 cm on irrigated sites reflect the influence of soil chemical amendments and amount of CBNG water applied. It is likely, however, that this trend will not continue following cessation of CBNG water applications and soil or water treatments. Over time, soil pH equilibria will be reached by leaching effects driven only by natural precipitation events (e.g., rainfall and snowmelt) and the accumulated soluble salts and Na^+ from CBNG water and chemical treatment applications.

Tedeschi and Menenti (2002) reported that salts accumulated in arid soils from solubilization of soil salts when irrigated with saline water ($EC_w > 0.75$ dS m^{-1}). On our study sites, late-season 2004 irrigated area soil ECs were significantly greater (up to 21 times) than those from respective nonirrigated areas to depths of at least 30 cm. These increases are much higher compared with EC values reported for the same sites (except Johnson-2) by Ganjegunte et al. (2005). In fact, only Johnson-2 and Sheridan-3 were significantly impacted at depths less than 120 cm. Johnson-2 (impacted to 30 cm) had only received CBNG water

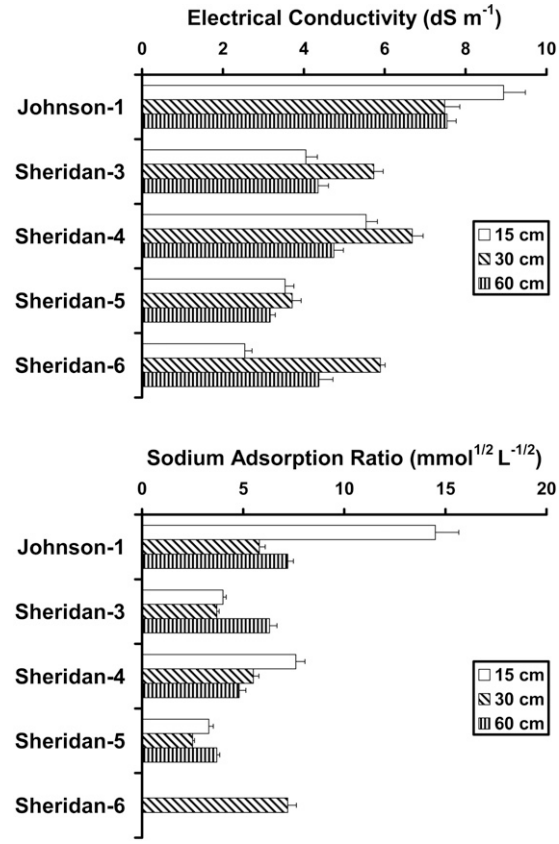

Fig. 5. Electrical conductivity and sodium adsorption ratio (SAR) (error bars show standard deviation of means) of soil solutions collected using lysimeters during 2004 from coal bed natural gas (CBNG) water-irrigated areas at six study sites in the Powder River Basin, WY.

Table 6. Saturation paste extract Na, Ca, and Mg concentrations in the beginning-of-study (early-season 2003) and end-of-study (late-season 2004) CBNG water-irrigated areas soil samples. Bold values indicate significant differences ($p \leq 0.10$) in ion concentrations at common depths between sample years

	Johnson-1		*Johnson-2†*		*Sheridan-3*		*Sheridan-4*		*Sheridan-5*		*Sheridan-6*	
Depth	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
cm												
				Na, mg L^{-1}								
0–5	**1548**	**2539**	**58**	**2797**	**221**	**745**	**447**	**654**	**447**	**696**	**272**	**817**
5–15	**1461**	**2235**	**46**	**1887**	**108**	**478**	**161**	**545**	**268**	**564**	**210**	**404**
15–30	**1142**	**2069**	**75**	**538**	**105**	**395**	**155**	**420**	**165**	**343**	**237**	**454**
30–60	**322**	**1113**	189	220	**169**	**462**	**46**	**637**	**144**	**475**	255	332
60–90	**154**	**327**	792	1408	712	369	**24**	**493**	**99**	**266**	514	345
90–120	350	407	1026	2159	845	377	**13**	**107**	95	218	736	546
				Ca, mg L^{-1}								
0–5	**537**	**496**	**147**	**538**	**138**	**702**	685	558	176	202	277	344
5–15	**259**	**453**	**113**	**402**	**88**	**273**	164	141	104	104	**43**	**114**
15–30	**369**	**432**	**105**	**280**	**77**	**179**	145	88	43	61	**46**	**119**
30–60	**246**	**497**	120	109	73	290	221	380	**35**	**184**	78	159
60–90	**48**	**289**	257	337	148	190	**79**	**513**	**45**	**261**	231	161
90–120	**111**	**420**	**361**	**647**	252	96	**51**	**332**	50	308	298	310
				Mg, mg L^{-1}								
0–5	156	509	20	136	**17**	**31**	**39**	**27**	56	31	17	17
5–15	**81**	**230**	**21**	**93**	25	13	31	14	**17**	**35**	16	12
15–30	**127**	**218**	**22**	**54**	18	22	30	17	15	25	28	53
30–60	**114**	**281**	43	27	**26**	**74**	**44**	**78**	**15**	**106**	94	106
60–90	**51**	**199**	169	247	168	178	**19**	**153**	**22**	**157**	421	289
90–120	154	256	272	550	316	219	**20**	**158**	25	162	521	461

† Coal bed natural gas (CBNG) water application initiated in October 2003.

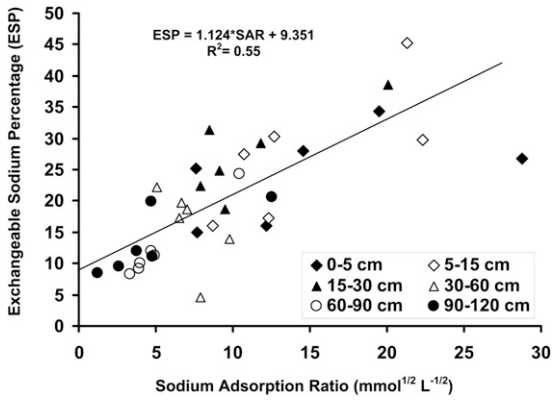

Fig. 6. Relationship between sodium adsorption ratio (SAR) (mmol$^{1/2}$ L$^{-1/2}$) and exchangeable sodium percentage (ESP) (%) for late-season 2004 samples from coal bed natural gas (CBNG) water-irrigated areas at six study sites in the Powder River Basin, WY.

applications for 1.5 seasons and Sheridan-3 (impacted to 60 cm) was dominated by coarse soil textures. Significant accumulations of soluble salts were found at consistently deeper depths on all study sites in 2004 than those reported from these sites in 2003 (Ganjegunte et al., 2005). It is evident that land application with saline–sodic CBNG water has resulted in significant increases in soluble salt accumulations in these soil profiles and the effects have been cumulative over time. It is also apparent that both chemical amendments and CBNG water applications are contributing to these surface accumulations. Impacts to 14 of 36 irrigated area samples have increased ECs to levels that qualify as saline soils ($\geq$4.0 dS m^{-1}, U.S. Salinity Laboratory Staff, 1954); however, other factors such as soil texture, clay mineralogy, sodicity, and soil moisture content can influence the effect of salinity of a specific soil. Three soil salinity ratings for CBNG development in the PRB have been proposed by the U.S. Department of Interior, Bureau of Land Management (2003): slightly saline (0–8 dS m^{-1}), moderately saline (8–16 dS m^{-1}), and strongly saline (>16 dS m^{-1}) (U.S. Department of Interior, Bureau of Land Management, 2003). Salinity hazard ranking systems based on these factors have been developed to help predict salinity effects. Because this ranking system does not include a nonsaline category, it is more restrictive at low concentrations and less restrictive at high concentrations than implied by the standard definition. Significant increases in EC values of upper depth soils at irrigated areas suggest that leaching has not been adequate to remove excess salt accumulations from effective root-zones

Land applications of saline–sodic CBNG water significantly increased SAR values to levels much higher than those reported by Ganjegunte et al. (2005) for the same sites. Increases in SAR occurred throughout the soil profiles of irrigated areas compared with respective nonirrigated areas on study sites, especially in the sites dominated by fine-textured soils. Significant increases in both SARs and ESPs to 120 cm were common. The irrigated area at Sheridan-3 had variable and inconclusive SAR and ESP responses compared with the nonirrigated areas, with no increases at some intermediate sample depths. Patterns of increased Na^+ accumulation in irrigated areas during the study are similar to those noted for ECs, with significantly increasing SARs (to at least 60 cm) on all but coarse-textured Sheridan-3 and significantly increasing ESPs to 120 cm on four of six irrigated areas. Accumulations of Na^+ in 10 of 36 irrigated area samples increased SARs to levels defined as sodic (12 mmol$^{1/2}$ L$^{-1/2}$) and 24 of 36 irrigated area samples had increased ESPs to sodic levels (15%) compared with respective nonirrigated areas (U.S. Salinity Laboratory Staff, 1954). In fact, some portion of the top 30 cm of the soil profiles on all irrigated areas was either sodic or approaching sodic. The sodicities of these sample depths would also make them unsuitable or marginally suitable for topsoil use in mine land reclamation as rated by the Wyoming DEQ-LQD mining soil salvage guidelines (Wyoming Department of Environmental Quality–Land Quality Division, 1994). In addition, six sample depths in the upper 30 cm of soil profiles on three irrigated areas (Johnson-1, Johnson-2, and Sheridan-4) had soluble salt and Na^+ concentrations defined as saline–sodic. These trends were also observed for EC and SAR values of soil solutions obtained from suction lysimeters (Fig. 5). Lysimeter soil solution EC and SAR values were different than saturated paste extracts, indicating steady state equilibrium between soil and soil solution has not been reached in the irrigated areas.

The relationship between SAR and ESP for the end-of-season irrigated sites is shown in Fig. 6. There was a positive correlation (R^2 of 0.55) between SAR and ESP for the end-of-season irrigated sites, suggesting addition of CBNG waters increased the amount of Na^+ on the exchange complex and in the soil solution. This was expected to occur over time; however, Ganjegunte and Vance (2006) reported that direct measurements of ESP using NH_4OAc in saline soils of the PRB might yield erroneous results due to overcorrection for water-soluble Na^+ concentrations. They reported that SAR values were often below the expected SAR-ESP empirical relationship provided by the U.S. Soil Salinity Laboratory Staff (1954). One reason for this appreciable error in the estimation of exchangeable Na^+ may be related to smectite being the dominant clay mineral in these soils. Therefore, SAR values were suggested by Ganjegunte and Vance (2006) to be the best indicator for relating Na^+ status to plant growth.

The SAR values of irrigated soils at Sheridan-4, Sheridan-5, and Sheridan-6 significantly increased to 120-cm soil depths, indicating increases in Na^+ accumulation at deeper depths of these sites. However, SAR values at the deepest sample depth (90–120 cm) on irrigated areas of the other three sites were not significantly different than those of respective nonirrigated areas. In addition, disproportionate Na^+ accumulations were found in the upper horizons (vs. deeper sample depths) on all irrigated areas. The comparison of Na^+, Ca^{2+}, and Mg^{2+} concentrations (mg L^{-1}) between early-season 2003 and late-season 2004 at these deeper sample depths did not reveal a consistent trend for altered SAR values among sites, emphasizing the need for site specific management plans. These observations indicate inadequate leaching and treatment strategies on all irrigated areas except Sheridan-3. Indeed, it is apparent that current management strategies on these study sites have not prevented the development of sodic soil conditions in at least some portion of the upper 30 cm of soil profiles on irrigated areas, except Sheridan-3. It is also ap-

parent that Na^+ accumulations are increasing with each season of CBNG water application on most sites. It is significant that soluble salt and Na^+ accumulations have not produced sodic conditions at Sheridan-3 (sandy loams and sandy clay loams), thus emphasizing the importance of texture in site response to land applications of saline–sodic CBNG water.

It is evident from the study results that current management practices are not preventing buildup of salts and Na^+ in the CBNG water-irrigated soils. To prevent permanent damage to fragile PRB ecosystems, successful management practices should include selection of appropriate sites that are suited for irrigation with saline–sodic water (well drained, preferably coarse-textured soils), pretreatment of CBNG water to reduce salinity and SAR before irrigation, and appropriate management of irrigated fine-textured soils that could include land preparation and management practices such as deep tillage, mixing with sand to improve permeability, and conditioning with organic matter or polymers. Reduction in salts and Na^+ concentrations in brackish or saline–sodic waters such as CBNG water is possible with expensive reverse osmosis treatment, which is not favored by CBNG companies because of its high cost. In a recent study, Zhao et al. (2008a, 2008b) have shown that treatment of CBNG water with naturally enriched Ca^{2+} zeolites reduced SAR and EC values to acceptable levels at a much reduced cost compared with reverse osmosis. In fine-textured soils, managing salinity using deep tillage or subsoiling is a common practice in the southwest and other parts of the United States (Pearce et al., 1999; Miyamoto, 2002). Assessing feasibility of these suggested practices is urgent and critical to develop alternative management options to avoid permanent damage to soil productive capacity in CBNG water-irrigated areas.

Conclusions

Land application with CBNG water has significantly altered soil chemical characteristics on PRB study sites. Multiple years of CBNG water application has resulted in significant increases in soil EC to 120-cm depths on fine-textured soils and to 60 cm on coarse-textured soils. The SAR values of CBNG water-irrigated soils increased to 120-cm depths on fine-textured irrigated areas compared with their respective nonirrigated areas, suggesting that fine-textured soils are more prone to salt and Na^+ buildup. Pretreating CBNG water with sulfur burners before land application lowered soil pH, but had inconclusive impacts on Ca^{2+} concentrations. Current management strategies and practices designed to mitigate soil Na^+ and soluble salt concentrations by leaching have not prevented significant negative impacts to soil properties. Particularly, these practices have not prohibited development of saline, sodic, and saline–sodic horizons. These results stress the need for alternative site-specific management practices and monitoring to prevent development of extremely difficult saline–sodic conditions with minimal reclamation potential following cessation of CBNG water applications.

Acknowledgments

The authors acknowledge financial support provided by the U.S. Department of Energy (DOE) with a grant administered by the U.S. Bureau of Land Management (BLM). Work was conducted under a cooperating agreement between the University of Wyoming and the U.S. BLM Buffalo, WY, and Miles City, MT, field offices. Study site availability and access were generously provided by J.M. Huber Corporation, Williams Production Company, Anadarko Petroleum Corporation, and Yates Petroleum. We also thank Amitava Chatterjee for assistance with graphics. Dr. Ganjegunte thankfully acknowledges support received from Texas Agrilife Research, Texas A&M University System, in terms of computer resources and time to prepare this manuscript.

References

Bauder, J.W., and T.A. Brock. 2001. Irrigation water quality, soil amendment, and crop effects on sodium leaching. Arid Land Res. Manage. 15:101–113.

Dahiya, I.S., S.B. Phogat, R.S. Hooda, N.K. Sangwan, and S. Kumar. 2004. Efficient use of canal and sodic waters to minimize sodicity hazards to crops and rise in water table level for sustainable agriculture. Ann. Biol. 20:167–172.

Essington, M.E. 2004. Soil and water chemistry: An integrative approach. CRC Press, Boca Raton, FL.

Ganjegunte, G.K., and G.F. Vance. 2006. Deviations from empirical sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) relationship. Soil Sci. 171:364–373.

Ganjegunte, G.K., G.F. Vance, and L.A. King. 2005. Soil chemical changes resulting from irrigation with water co-produced with coalbed natural gas. J. Environ. Qual. 34:2217–2227.

Gee, G.W., and D. Or. 2002. Particle size analysis. p. 255–293. J.H. Dane and G.C. Topp (ed.) *In* Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5, SSSA, Madison, WI.

Helmke, P.A., and D.L. Sparks. 1996. Lithium, sodium, potassium, rubidium, and cesium. p. 551–574. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Hillel, D. 2000. Salinity management for sustainable irrigation: Integrating science, environment, and economics. The International Bank for Reconstruction and Development/The World Bank, Washington, DC.

Jackson, R.E., and K.J. Reddy. 2007a. Geochemistry of CBNG produced water in the Powder River Basin: Salinity and sodicity. Water Air Soil Pollut. 184:49–61.

Jackson, R.E., and K.J. Reddy. 2007b. Trace element chemistry of coal bed natural gas produced water in the Powder River Basin, Wyoming. Environ. Sci. Technol. 41:5953–5959.

Johnston, C.R., G.F. Vance, and G.K. Ganjegunte. 2008. Irrigation with coalbed natural gas co-produced water. Agric. Water Manage. doi:10.1016/j.agwat.2008.04.015.

King, L.A., G.F. Vance, and G.K. Ganjegunte. 2005. Use of coal bed natural gas (CBNG) waters: Soil and plant responses. p. 607–622. *In* R.I. Barnhisel (ed.) Raising reclamation to new heights. Proc. Am. Soc. Mining Recl., Lexington, KY. 19–23 June 2005. Am. Soc. Mining Recl., Lexington, KY.

King, L.A., J.R. Wheaton, G.F. Vance, and G.K. Ganjegunte. 2004. Water issues associated with coalbed methane (natural gas) in Powder River Basin of Wyoming and Montana. Reclam. Matters 2:7–12.

McBeth, I.H., K.J. Reddy, and Q.D. Skinner. 2003. Coalbed methane product water chemistry in three Wyoming watersheds. J. Am. Water Res. Assoc. 39:575–585.

Miyamoto, S. 2002. Guidelines for developing soil and water management programs: Irrigated pecans. Texas Agric. Exp. Stn./Texas Water Res. Inst. Publ. TR-188 March 2002. TAES/TWRI, College Station, TX.

Montana State University. 2003. In-stream EC and SAR standards for streams within the Powder River Basin. Effective 25 Apr. 2003. Dep.

Land Res. Environ. Sci. Montana State Univ., Bozeman, MT. Available at http://waterquality.montana.edu/docs/methane/CBMstandards.shtml (accessed 16 Oct. 2005; verified 26 June 2008). Montana State Univ., Bozeman.

Pearce, A.D., C.R. Dillon, T.C. Keisling, and C.E. Wilson. 1999. Economic and agronomic effects of four tillage practices on rice produced on saline soils. J. Prod. Agric. 12:305–312.

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved solids. p. 417–436. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Rice, C.A., T.T. Bartos, and M.S. Ellis. 2002. Chemical and isotopic composition of water in the Fort Union and Wasatch formations of Powder River Basin, Wyoming and Montana: Implications for coalbed methane development. p. 53–70. *In* S.D. Schwochow and V. Nuccio (ed.) Coalbed methane of North America II. No. 108. Rocky Mountain Assoc. Geol., Denver, CO.

Ruckelshaus Institute of Environment and Natural Resources. 2005. Water production from coalbed methane development in Wyoming: A summary of quantity, quality and management options. Final Report. White paper prepared for the Office of the Governor State of Wyoming by The Ruckelshaus Institute of Environment and Natural Resources. Univ. of Wyoming, Laramie.

SAS Institute. 2002. SAS Learning edition 2.0 for windows. Version 8.2.0. SAS Inst., Cary, NC.

Satterthwaite, F.W. 1946. An approximate distribution of estimates of variance components. Biometrics Bull. 2:110–114.

Shainberg, I., and J.D. Oster. 1978. Quality of irrigation water. Intl. Irrig. Inf. Ctr., Bet Dagan, Israel.

Stearns, M., J.A. Tindall, G. Cronin, M.J. Friedel, and E. Berquist. 2005. Effects of coal-bed methane discharge waters on the vegetation and soil ecosystem in Powder River Basin, Wyoming. Water Air Soil Pollut. 168:33–57.

Suarez, D.L. 1996. Beryllium, magnesium, calcium, strontium and barium. p. 575–602. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. p. 1201–1229. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Tedeschi, A., and M. Menenti. 2002. Simulation studies of long-term saline water use: Model validation and evaluation of schedules. Agric. Water Manage. 54:123–157.

Thomas, G.W. 1996. Soil pH and soil acidity. p. 475–490. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

U.S. Department of Energy, Office of Fossil Energy. 2002. DOE study raises estimates of coalbed methane potential in Powder River Basin. Available at http://www.fossil.energy.gov/news/techlines/2002/tl_cbm_powderriver.html (accessed 30 June 2008; verified 7 July 2008).

U.S. Department of Interior, Bureau of Land Management. 2003. Final environmental impact statement and proposed plan amendment for the Powder River Basin oil and gas project. Vol. 1–3. Buffalo Field Office, Buffalo, WY.

U.S. Energy Information Administration. 2006. Natural gas navigator. Natural gas production and consumption histories. Available at http://tonto.eia.doe.gov/dnav/ng/_cons_sum_dcu_nus_a.htm (accessed 30 June 2008; verified 7 July 2008).

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handb. 60. U.S. Gov. Print. Office, Washington, DC.

Van Voast, W.A. 2003. Geochemical signature of formation waters associated with coalbed methane. AAPG Bull. 87:667–676.

Vance, G.F., L.A. King, and G.K. Ganjegunte. 2004. Coalbed methane co-produced water: Management options. Reflections, June Issue:31–34.

Vance, G.F., L.A. King, and G.K. Ganjegunte. 2008. Soil and plant responses from land application of saline–sodic waters. J. Environ. Qual. 37:S-139–S-148.

Wheaton, J.R., and J.J. Metesh. 2002. Potential ground-water drawdown and recovery for coalbed methane development in the Powder River Basin, Montana. Montana Bureau of Mines and Geology Open-File Rep. 458. Montana Bureau of Mines and Geology, Butte.

Wyoming Coal Bed Natural Gas Task Force. 2006. Interim Report. Available at http://cbm.moose.wy.gov/documents/FinalInterimReport_000.pdf (accessed 30 June 2008; verified 7 July 2008).

Wyoming Department of Environmental Quality–Land Quality Division. 1994. Guideline 1. Topsoil and overburden. Appendix I Section 1 Table 2. p. 20. Available at http://deq.state.wy.us/lqd/guidelns/guide1.pdf (accessed 17 Jan. 2006; verified 26 June 2008). Wyoming Dep. of Environ. Qual., Cheyenne, WY.

Yu, J., L.I. Shainberg, A.I. Mamedov, and G.J. Levy. 2003. Infiltration and erosion in soils treated with dry PAM and Gypsum. Soil Sci. Soc. Am. J. 67:630–636.

Zhao, H., G.F. Vance, G.K. Ganjegunte, and M.A. Urynowicz. 2008a. Use of zeolites for treating natural gas co-produced waters in Wyoming, USA. Desalination 228:263–276.

Zhao, H., G.F. Vance, M.A. Urynowicz, and R.W. Gregory. 2008b. Integrated treatment process using a natural Wyoming clinoptilolite for remediating produced waters from coalbed natural gas operations. Appl. Clay Sci. doi:10.1016/j.clay.2008.03.007.