Soil solution and exchange complex response to repeated wetting–drying with modestly saline–sodic water

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Abstract Coal bed natural gas (CBNG) extraction in the Powder River (PR) Basin of Wyoming and Montana produces modestly saline-sodic wastewater, which may have electrical conductivity (EC) and sodium adsorption ratios (SAR) exceeding accepted thresholds for irrigation ($EC = 3$ dS m^{-1}, $SAR = 12$ $(mmol_c\ l^{-1})^{1/2}$. As an approach to managing large volumes of CBNG-produced water, treatment processes have been developed to adjust produced water salinity and sodicity to published irrigation guidelines and legislated in-stream standards. The objective of this laboratory study was to assess acute and chronic soil solution EC and SAR responses to various wetting regimes simulating repeated flood irrigation with treated CBNG product water, followed by single rainfall events. Fifty-four soil samples from irrigated fields in southeast Montana were subjected to simulated PR water or CBNG water treated to EC and SAR values accepted as thresholds for designation of saline × sodic water, in a single wetting event, five wetting–drying events, or five wetting–drying events, followed by leaching with distilled water. Resultant saturated paste extract EC (ECe) and SAR of soils having <33% clay did not differ from one another, but resulting ECe and SAR were all less than those for soil having >33% clay. Repeated wetting with PR water having EC of 1.56 dS m^{-1} and SAR of 4.54 led to SAR <12, but brought ECe near 3 dS m^{-1}. Repeated wetting with water having salinity = 3.12 dS m^{-1} and SAR = 13.09 led to ECe >3 dS m^{-1} and SAR near 12. Subsequent inundation and drainage with distilled water, simulating rainfall-quality leaching, reduced ECe and SAR more often in coarse-textured, high salt content soils than in finer-textured, lower salt content soils. Decreases in ECe upon leaching with distilled water were of greater magnitude than corresponding decreases in SAR, reinforcing supposition of sodium-induced dispersion of fine-textured soils as a consequence of rainfall following irrigation with water having salinity and sodicity levels equal to previously published thresholds.

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Introduction

Growing attention to domestic energy production in the US has resulted in aggressive development of a novel and economically profitable approach to recovering natural gas, i.e., methane, from water-saturated coal seams at below-surface depths of as much as 1,000 m. Confinement of water-saturated coal seams creates hydrostatic pressure that can trap biogenic methane within these coal seams (Rice 1997). In order to extract methane, this pressure must be relieved by removing large quantities of water from confining coal seams. The pumped water is generally surface discharged as a waste product. Extensive reserves of methane and water of varying qualities and quantities are present in coal seams in the Powder River Basin of Montana and Wyoming.

Since commencement of coal bed natural gas (CBNG) development in PRB, annual methane production has increased from 11.4×10^6 m^3 in 1987 to 9.8×10^9 m^3 in 2006 (Wyoming Oil and Gas Conservation Commission (WOGCC), 2006, *Coal bed methane production statistics*, http://wogcc.state.wy.us/coalbedMenu.cfm?Skip = 'Y'&oops = 49). In 2003, CBNG wells discharged 89.9×10^6 m^3 of wastewater within the PRB (WOGCC, 2004); estimates for 2006 are comparable to 2003 water discharges.

Current strategies for wastewater management include containment in infiltration and evaporation ponds, land spreading, limited irrigation, subsurface shallow and deep injection, and discharge to existing streams. Because of environmental concerns about direct discharge of CBNG production water into ephemeral and perennial streams of the basin, concerns about perceived waste of the water resource, and concerns about loss of native rangeland to evaporation ponds, increasing attention is being given to proposals for beneficial use of CBNG-produced water for irrigation.

Salinity, measured in terms of electrical conductivity (EC), and sodicity, measured as sodium adsorption ratio (SAR), are two parameters used to assess irrigation water quality. Salinity, which represents total soluble ion concentration, becomes problematic when osmotic forces resulting from high ion concentrations restrict ability of plants to withdraw water from soil (Hanson et al. 1999; Bauder and Brock 2001). Reductions in crop growth occur when average root zone salinity exceeds the crop's threshold level. The commonly accepted threshold used to define water as saline from the perspective of suitability for irrigation is 3 dS m^{-1} (Hanson et al. 1999). According to the Western Fertilizer Handbook (1995), soil saturation paste extract (ECe) equilibrates at approximately 1.5–3 times that of irrigation water, assuming a 15% leaching factor. While salinity can be detrimental to crop growth, it promotes aggregation of fine soil particles, resulting in structurally stable soil with enhanced permeability and hydraulic conductivity and low susceptibility to shrinking, swelling, and cracking (Mitchell and van Genuchten 1992; Buckland et al. 2002).

Numerically, SAR is defined as $[Na^+/((Ca^{2+} + Mg^{2+})/2)^{1/2}]$, where Na^+, Ca^{2+}, and Mg^{2+} are ion concentrations of $mmol_c\ l^{-1}$ or meq l^{-1} (Ayers and Westcot 1976; Miller and Gardiner 2001; Harron et al. 1983). The actual SAR units are $(mmol_c\ l^{-1})^{1/2}$ or $(meq\ l^{-1})^{1/2}$ (Miller and Gardiner 2001); however, the units are ignored in typical usage, as is the case in this reporting. SAR is generally considered a reliable and more easily measured surrogate for soil exchangeable sodium percentage (ESP). An ESP of 15% is the accepted threshold for dispersion of fine-textured soil (Miller and Gardiner 2001; Hanson et al. 1999). ESP of 15% is approximated by SAR = 12.

From the perspective of use of PRB CBNG product water for irrigation, salinity and sodicity hazards of product water range from modest to severe (Rice et al. 2002) and vary considerably throughout the basin (McBeth et al. 2003). In the north and western portions of the basin, salinity and sodicity of CBNG wastewater increasingly exceed established in-stream standards (Fig. 1; J. Wheaton, 2001, Personal communication, Montana Bureau of Mines and Geology, 1300 N. 27th St., Billings, MT 59101), which limit irrigation season maximum in-stream EC to 2.5 dS m^{-1} and maximum SAR to 6. During the non-irrigation season, the SAR standard is 9.75, while the in-stream EC standard is unchanged. As a consequence of establishment of permitted discharge standards, treatment of CBNG product water, either to reduce sodium concentration or elevate calcium concentration, with the objective of lowering the SAR, is a compliment of expanding use in conjunction with irrigation with CBNG product water.

In contrast, Wyoming relies on a narrative standard to manage CBNG production water, the standard stating that degradation of surface waters shall not be of such an extent to cause measurable decrease in crop or livestock production. Wyoming DEQ is in the process of implementing a complex, three-tiered decision making process, subject to substantial interpretation and data gathering, to establish appropriate effluent limits for EC and SAR whenever a proposed discharge will likely reach irrigated lands. Tier 1 establishes default EC and SAR limits in situations where the irrigated crops are salt-tolerant and/or the discharge water quality is relatively good. Tier 2 establishes default limits to equal background water quality conditions and is intended to be used in situations where the background EC and SAR are worse (i.e., greater) than the effluent quality. Tier 3 applies where background EC and SAR is better (i.e., less) than the effluent quality, and provides a mechanism to justify effluent limits that are of a lower quality than the pre-discharge background conditions.

The PRB's structural geology consists mostly of tertiary sandstones and shales (De Bruin and Lyman 2000; Rice

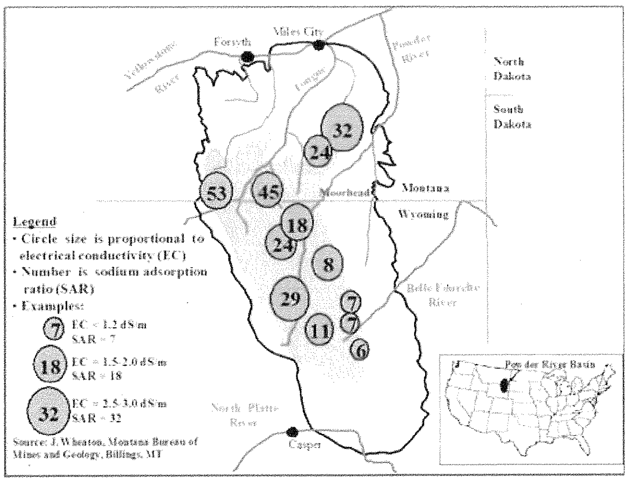

Fig. 1 The *shaded area* shows the region of potential CBNG development within the Powder River Basin of Montana and Wyoming. *Circle* size is proportional to EC, and *numbers* indicate SAR

271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
Journal	Article	MS Code	LE ☐ TYPESET ☐	CP ☑ DISK ☑

et al. 2002). The region has a growing season evapotranspiration requirement of approximately 80 cm, yet the region receives less than 35 cm of precipitation annually. This combination of factors results in inherently high salt content in Powder River flows, particularly during periods of low flow in early spring and late summer (Fig. 2).

Soils along the Powder River consist primarily of silt loams, silty clay loams, and silty clays (USDA 1971), approximately 4,500 ha of which receive Powder River irrigation water annually. Discharge of CBNG product water to streams, as well as product water contributions to base flow, have potential to affect irrigation suitability of already marginal quality water within the irrigated and flooded corridor of the Powder River.

Soils in arid and semi-arid regions often contain high amounts of exchangeable Na^+ (Quirk and Schofield 1955), which, if found in amounts excessive to Ca^{2+} and Mg^{2+}, can have deleterious effects on soil physical properties. The large size, single charge, and hydrated radius of Na^+ ions make them agents of physical separation of soil particles. This separation occurs when hydrated Na^+ ions dominate the diffuse double layer around the clay platelets to which they are adsorbed, resulting in high swelling pressures and creating single clay platelets which persist in solution (Keren and Shainberg 1981). Increasing smectite clay content results in increasing potential for sodium-induced dispersion. Once clay domains swell or become dispersed, soil pore geometry changes (Bresler et al. 1982), resulting in reduced pore size, bond weakening, and particle separation (Curtin et al. 1994). This physical disintegration leads to reduced soil hydraulic conductivity as macroaggregates slake into microaggregates and soil particles become small enough to be carried by water and deposited in soil pores (So and Aylmore 1993; Mace and Amrhein 2001).

Because both salinity and sodicity influence how soils respond to wetting, interaction between the two must be examined in order to assess suitability of irrigation water. In general, flocculating effects of increased ECe counteract the physically deleterious effects of elevated SAR (Curtin et al. 1994). Many factors, including presence of organic matter, inorganic aggregate stabilizing agents, and mechanical disturbance, can influence soil infiltration in accordance to the ECe by SAR interaction (Quirk and Schofield 1955). Figure 3 displays projections of reductions in infiltration expected from a variety of ECe by SAR combinations across a range of soil textures. Historically, SAR of 12 was considered the threshold for soil deterioration as a result of sodicity (U.S. Salinity Laboratory Staff 1954; Hanson et al. 1999). However, Fig. 3 reveals that reduction in infiltration can occur at SAR values well below 12 if salinity is low. Because rainfall and non-saline irrigation water lack sufficient concentrations of Ca^{2+} and Mg^{2+} ions necessary to counteract exchangeable Na^+, such water sources reduce soil solution EC to a greater extent than the associated reduction in SAR (Oster 1994). Suarez (2006), based on rainfall simulation studies, reported significant reductions in infiltration due to deleterious effect of rainfall events at SAR of 2–4.

Because of the modestly saline and typically highly sodic nature and widespread geographical distribution of PRB CBNG product water, water treatment to reduce SAR is becoming a common practice. Correspondingly, development of the CBNG industry in the PRB has provided opportunity to re-evaluate acute and chronic soil responses to repeated wetting and drying with modestly saline-modestly sodic water. Thus, specific objectives of this study were to: (1) assess effects of single and multiple wetting events with simulated Powder River and CBNG water treated to permitted in-stream standards on post-treatment ECe and sodicity of four textural groups; and (2) determine potential risk of dispersion of soils as a consequence of repeated wetting with modestly saline × modestly sodic water, followed by simulated rainfall.

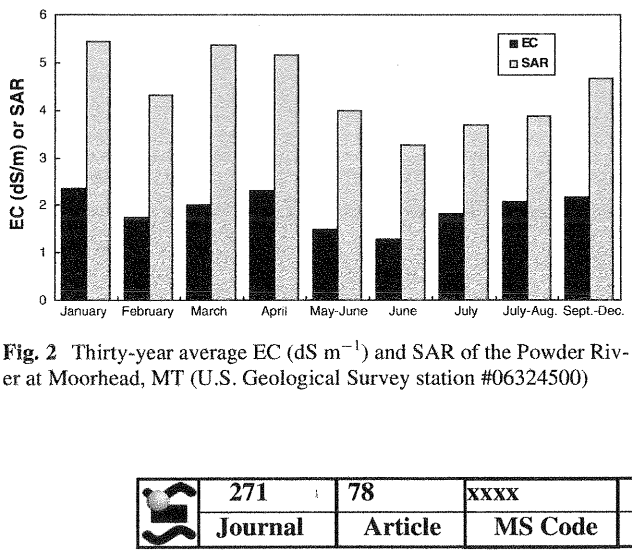

Fig. 2 Thirty-year average EC (dS m^{-1}) and SAR of the Powder River at Moorhead, MT (U.S. Geological Survey station #06324500)

Materials and methods

Baseline soil characterization

An assessment of currently and potentially irrigated soils along the Powder and Yellowstone Rivers in Powder River, Custer, Prairie, and Dawson counties of Montana identified six predominant soil series, representing four predominant textural classes of soil material (S. Van Fossen, 2001, USDA-NRCS Miles City, MT, Personal communication; USDA 1971, 1976, 1996, 2003, Table 1). Within each county, a site representative of each of the four textural classes was excavated to 75 cm, and 25 kg of soil was gathered from each horizon within that depth. Horizonation was initially defined by published taxonomic description for each sampling site. Horizonation was validated in the field at time of sampling using visual and textural assessments in

271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
Journal	Article	MS Code	LE ☐ TYPESET ☐ CP ☑ DISK ☑	

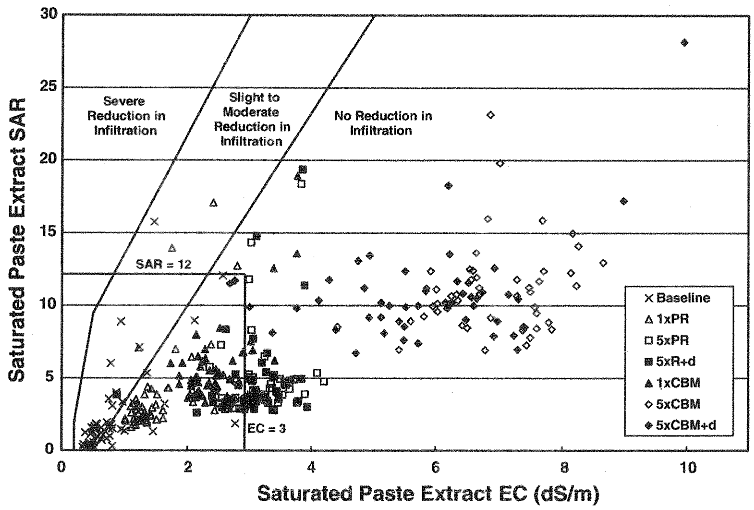

Fig. 3 ECe versus soil solution SAR of soil material prior to treatment (baseline) and following various wetting regimes with either Powder River or treated CBNG water. The 1× wetting regime consisted of a one time application of treatment water, while soils receiving the 5× treatment were wetted and dried five times. The 5× + *d* wetting regime was identical to the 5× treatment, except treatment soils were leached with distilled water following 5× treatment. *Diagonal lines* classify EC × SAR combinations according to risk of infiltration rate reduction for a variety of soil textures (adapted from Ayers and Westcot 1976). *Vertical* and *horizontal* lines at EC = 3 dS m^{-1} and SAR = 12, respectively, represent salinity and sodicity thresholds reported by Hanson et al. (1999), Richards et al. (1954)

Table 1 Predominant currently and potentially irrigated soil series along the Powder and Yellowstone Rivers in Powder River, Custer, Prairie, and Dawson counties of Montana

Soil series	Soil taxonomy[a]	Texture
Cherry	Fine-silty, mixed, frigid Typic Ustochrept	sicl
Marias	Fine, smectitic, frigid Chromic Haplustert	sic
Spinekop	Fine-loamy, mixed, superactive, frigid Aridic Haplustept	sicl
Trembles	Coarse-loamy, mixed, calcareous, frigid Typic Ustifluvent	fsl/l
Havre	Fine-loamy, mixed (calcareous) frigid Ustic Torifluvent	sil/sicl
Busby	Coarse-loamy, mixed Borollic Camborthid	fsl

Source: S. Van Fossen, USDA-NRCS, Miles City, MT, Personal communication; USDA (1971, 1976, 1996, 2003)

si silt; *c* clay; *l* loam; *fs* fine sandy

[a] Soil Survey Staff (1975)

concert with published profile descriptions. Material sampled from a total of 54 horizons at 16 sites underwent baseline chemical analysis by an independent laboratory and particle size analysis, using the hydrometer method described by Gee and Bauder (1986). Using particle size analysis results, samples were classified into four textural groups based on clay content, with textural group #1 containing 0–11% clay ((g clay/100 g soil) × 100%), textural group #2 containing 12–22% clay, textural group #3 containing 23–33% clay, and textural group #4 containing >33% clay. Using baseline chemical characterization data, outliers were removed from the study, leaving 9 soil samples in textural group #1, 13 in group #2, 16 in group #3, and 11 in group #4. Outliers were considered to be any soils which had baseline salinity or SAR values resulting in the soil being initially classified as saline or sodic; thus, these soils were considered to be 'non-irrigable'.

X-ray diffractometry characterization of six sub-samples, ranging in clay content from 33 to 56%, identified smectite as the dominant clay mineral present. Free limestone content ranged from 0.5 to 2.0% [(g $CaCO_3$/100 g dry soil) × 100%] by weight in all subsamples.

Experimental design

Two water quality treatments and three wetting regimes were arranged in a complete factorial of six treatments, each consisting of an applied water quality and a specific wetting × drying schedule. Simulated PR water chemistry (EC = 1.56 dS m^{-1}, SAR = 4.54, pH 8.03) was based on 30-year average salinity and sodicity at Moorhead, MT (U.S. Geological Survey station #06324500). Simulated post-treatment CBNG water (EC = 3.12 dS m^{-1}, SAR = 13.09, pH 8.22) represented CBNG discharge water treated or blended to meet published thresholds for salinity and sodicity. Multiple runs of MINTEQA2 (Allison et al. 1991) were completed to identify appropriate reagent combinations needed to synthesize control (PR) and post-treatment (CBNG) water qualities. Reagents used to constitute intended chemistries were $NaHCO_3$, K_2SO_4, NaCl, $MgSO_4$, $CaCO_3$, and $CaCl_2$.

The first wetting regime, referred to as "1×," consisted of a one time application of water followed by drying,

271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
Journal	Article	MS Code	LE □ TYPESET □	CP ☑ DISK ☑

while soils receiving the "5×" treatment were repeatedly wetted with treatment water and dried a total of 5×. The third wetting regime, referred to as "5× + *d*," was identical to the "5×" treatment, except these soils received a final leaching treatment with distilled water, simulating a rainfall event. Throughout this paper, treatments are abbreviated by combining their wetting regime notation and water quality; for example, 5× wetting and drying with treated CBNG water is denoted as "5×CBNG." For purposes of simplicity in presentation, "CBNG" is used to refer to the modestly saline × modestly sodic water quality resulting from treatment of CBNG product water to reduce SAR to approximately the permitted standard, i.e., SAR = 13.09.

Water quality × wetting regime treatments, which were applied to all 49 soil materials after deleting outliers, were carried out in 266 ml plastic cups lined with cheesecloth to prevent soil from escaping through bottom drain holes. Three hundred and sixty grams of bulk, unsieved, air-dried soil was placed in each cup, after which soil-filled cups were placed in shallow pans containing either CBNG or PR water, and allowed to imbibe water from the bottom for 24 h. The rationale for wetting from the bottom was to: (1) assure saturation while minimizing air entrapment; (2) minimize aggregate destruction that might result from water droplet impact to the surface of the soil (Suarez 2006); and (3) minimize excessive and/or non-uniform leaching caused by unequal or non-uniform surface application. Visual observation confirmed that water content of all samples had equilibrated at saturation, which was the intent of wetting. Each cup was then placed on a screen rack and allowed to drain freely for 24 h. Soils receiving the 1× treatment were then oven dried at 105°C and subsequently analyzed. Soils receiving the 5× treatment were allowed to drain for 24 h after each wetting. Subsequently, the soils dried at 35°C for 24 h, followed by four identical wetting/drying cycles, except that following the fifth wetting event, the soils were allowed to drain for 24 h and then dried at 105°C and analyzed. Cups containing the 5× + *d* treatment were subjected to a similar five-time wetting/draining/drying cycle, except following the fifth wetting cycle, the soils were allowed to drain for 24 h and then dried at 35°C for 24 h. These dried soils were then placed on mesh drainage racks, dosed from the top with 130 ml of distilled water (approximately one pore volume), allowed to drain for 24 h, oven dried at 105°C, and analyzed like the previous treatments. Addition of the distilled water was completed by slowly drip emitting water to the surface, which had been covered with a layer of porous cloth to minimize dispersive effect due to droplet impact.

All post-treatment soil samples were analyzed for EC_e, exchangeable and extractable base forming cation content (Ca^{2+}, Mg^{2+}, and Na^{+}) by an independent laboratory. Cation exchange capacity was approximated by the cation summation method, which generally results in CEC values slightly lower than those obtained by direct measures of CEC. SAR was determined from extractable base cation data, while ESP was determined from exchangeable cation concentrations and cation exchange capacity measurements (Harron et al. 1983).

Statistical analysis

Analyses of variance (ANOVA) and mean separation tests were used to identify significant differences in post-treatment soil solution and exchangeable chemistry at the 95% level of confidence ($P = 0.05$). Data exhibiting non-normal characteristics were either log or square root transformed. Initial statistical analyses were completed by running a two-factor ANOVA with no interactions and textural group

Table 2 Mean post-treatment ECe and SAR for each textural group and water quality treatment

	n	Mean EC (dS m^{-1})	Mean SAR
Textural group			
0–11% clay [(g clay/100 g soil) × 100%]	9	3.08 a	6.06 a
12–22% clay	13	3.39 a	6.04 a
23–33% clay	16	3.28 a	5.34 a
>33% clay	11	3.78 b	7.91 b
Water quality treatment			
Baseline	49	0.82 a	2.56 a
1×PR[a]	49	1.51 b	3.92 b
1×CBNG[b]	49	2.46 c	5.94 b
5×PR[c]	49	3.21 d	4.94 b
5×PR + *d*[d]	49	3.02 e	4.86 b
5×CBNG[e]	49	6.93 f	11.31 c
5×CBNG + d[f]	49	5.73 g	10.85 c

Mean post-treatment ECe and SAR for each textural group was determined by averaging across water quality × wetting regime treatment. Mean post-treatment ECe and SAR for each water quality treatment was determined by averaging across textural groups. Within treatment means in the same column followed by the same letter are not significantly different at $P \leq 0.05$

[a] One time wetting and drying with Powder River water; EC = 1.56 dS m^{-1} , SAR = 4.54, pH 8.03

[b] One time wetting and drying with treated CBNG water; EC = 3.12 dS m^{-1} , SAR = 13.09, pH 8.22

[c] Five times wetting and drying with PR water

[d] Five times wetting and drying with PR water followed by leaching with one pore volume distilled water

[e] Five times wetting and drying with treated CBNG water

[f] Five times wetting and drying with treated CBNG water followed by leaching with one pore volume distilled water

and water quality treatment × wetting regime combination with unequal replications as factors (Table 2). Data were then partitioned by textural group, and one-way ANOVA were run with data from each textural group, with the main factor being water quality × wetting regime. Significant differences at $P \leq 0.05$ were separated using the Student–Newman–Keuls method of pairwise multiple comparison for unequal size data sets (Steel and Torrie 1960). Least squares regression was used to evaluate associations between independent and dependent variables. These analyses were conducted using SigmaStat version 2.0 software (SPSS 1997).

Results

Salinity

Water quality × wetting regime effects on Ece

Averages of ECe across all textural groups (#1, #2, #3, and #4) revealed that all water quality × wetting regime treatments led to ECe significantly greater than baseline and significantly different from one another. Greatest mean ECe among all treatments, averaging 6.93 dS m^{-1}, occurred in soils receiving the 5×CBNG treatment (Table 2).

Individual soils receiving either the 1×PR or 1xCBNG treatments and having high baseline ECe values displayed the smallest increases in ECe over baseline, compared to soils having low baseline ECe values. In soils with baseline ECe < 1 dS m^{-1}, the 1xCBNG treatment led to an increase in ECe of approximately 2 dS m^{-1}. In contrast, for soils with baseline EC_e > 1 dS m^{-1}, the increase in ECe was only approximately 1 dS m^{-1}.

1×PR and 1×CBNG treatments increased mean ECe from 0.82 (baseline) to 1.51 and 2.46 dS m^{-1}, respectively. While significantly greater than baseline, these values did not exceed the commonly accepted salinity threshold of 3 dS m^{-1}. In contrast, the 5×PR treatment led to a final ECe of 3.21 dS m^{-1}, while 5×CBNG treatment resulted in ECe = 6.93 dS m^{-1}. For each of these treatments, ECe equilibrated at approximately twice the EC of the treatment water, a finding consistent with that previously reported by Hanson et al. (1999) and Western Fertilizer Handbook (1995).

Leaching with distilled water following 5× treatments led to significant decreases in ECe for soils treated with either PR or CBNG water but did not lower ECe values below the 3 dS m^{-1} threshold. ECe of soils receiving the 5×PR + *d* averaged 3.02 dS m^{-1}, compared to 3.21 dS m^{-1} prior to leaching. ECe of soils leached with distilled water following 5×CBNG treatment averaged 5.73 dS m^{-1}, significantly less than 6.93 dS m^{-1} prior to leaching.

Textural effects on Ece

When averaged across all water quality × wetting regime treatments, post-treatment ECe did not differ significantly among textural groups #1, #2, and #3. However, mean ECe in textural group #4 was significantly greater than in other groups, averaging 3.78 dS m^{-1} (Table 2). Greater inherent exchange capacities and high percentages of non-readily draining interstitial spaces in these fine textured soils likely resulted in an increased ability to absorb and retain greater concentrations of salts, compared to soils in other textural groups.

In textural group #1 (0–11% clay content), all water quality × wetting regime treatments, except the 1×CBNG and 5×PR + *d* treatments, led to significant differences in ECe compared to one another (Fig. 4). Greatest mean ECe was 6.74 dS m^{-1}, resulting from 5×CBNG treatment. This represented approximately a tenfold increase in ECe over baseline (ECe = 0.60 dS m^{-1}). Distilled water application resulted in significant decreases in ECe following either 5×PR or 5×CBNG treatment.

Salinity of soils in textural groups #2 (12–22% clay) and #3 (23–33% clay) behaved almost identically, differing significantly among all treatments, except the 5×PR and 5×PR + *d* treatments (Fig. 4). In both groups, distilled water application following 5×CBNG treatment led to significant reductions in ECe, while leaching following 5×PR treatment had no significant effects on ECe compared to 5×PR treatment without subsequent leaching.

In textural group #4 (>33% clay), leaching with distilled water had no significant effect following 5×PR or 5×CBNG treatments. Additionally, ECe did not differ among soils receiving 1×CBNG, 5×PR, and 5×PR + *d* treatments (Fig. 4). These results likely reflect the high clay content of textural group #4, which lead to increased exchange capacity and percentage of non-readily draining interstitial spaces, ultimately resulting in an enhanced ability of the soil to absorb and retain high salt concentrations.

Sodicity

Water quality × wetting regime effects on SAR

Averages of SAR across textural groups revealed that mean post-treatment SAR was significantly greater than baseline for all treatments. However, post-treatment SAR did not differ significantly among 1×PR, 1×CBNG, 5×PR, and 5×PR + *d* treatments. 5×CBNG and 5×CBNG + *d* treatments resulted in SAR values significantly greater than other treatments, but not different from one another (Table 2). 5×PR and 5×CBNG treatments resulted in soil solution SAR values equilibrated at approximately applied water SAR.

271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
Journal	Article	MS Code	LE ☐ TYPESET ☐ CP ☑ DISK ☑	

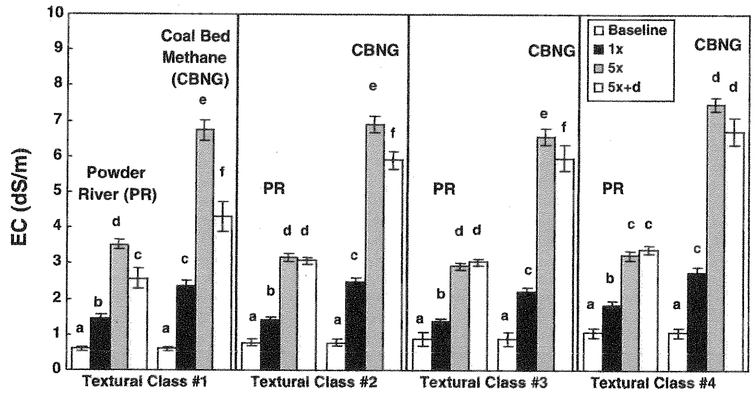

Fig. 4 Mean baseline and post-treatment ECe for each of the 4 soil textural groups (group #1, 0–11% clay; group #2, 12–22% clay; group #3, 23–33% clay; and group #4, >33% clay); means are reported for all water quality × wetting regime treatments. The 1× wetting regime consisted of a one time application of treatment water, while soils receiving the 5× treatment were wetted and dried five times. The 5× + *d* wetting regime was identical to the 5× treatment, except treatment soils were leached with distilled water following 5× treatment. Error bars represent standard error of the mean. *Bars* within the same textural group identified by the *same letter* are not significantly different at $P \geq 0.05$

Similar to trends observed with ECe, individual soils receiving either the 1×PR or 1×CBNG treatments and having high baseline SAR values displayed smaller increases in SAR over baseline compared to soils having low baseline SAR values. In soils with lowest baseline values, SAR increased approximately 2 units with a single wetting with PR water. For soils with baseline SAR values >3, 1×PR and 1×CBNG treatments generally resulted in minimal increases in SAR.

In general, a one time wetting event with either water quality did not increase individual soil sample SAR values above eight, indicating that no soils examined in this study were at risk of becoming sodic from a single application of PR or CBNG water. However, the 5×CBNG treatment caused soil solution SAR to exceed the threshold value of 12 in approximately 15% of all soil samples, regardless of texture.

Textural effects on SAR

Similar to ECe, SAR averaged across water quality × wetting regime treatments was significantly greater in textural group #4 (SAR = 7.91) compared to other groups. Groups #1, #2, and #3 were not significantly different from one another (Table 2).

In textural group #1 (0–11% clay), all water quality × wetting regime treatments led to significant increases in soil solution SAR over baseline (Fig. 5). The 5×CBNG treatment produced the greatest rise in SAR, which increased over tenfold from 1.16 (baseline) to 12.44. Leaching with distilled water lowered SAR from 4.50 to 3.90 following 5×PR treatment and from 12.44 to 11.36 following 5×CBNG treatment. Both reductions were significant (Fig. 5).

Soil solution SAR of textural group #2 (12–22% clay) behaved similarly to ECe in that all treatments led to significant increases in SAR over baseline (SAR = 2.15). Leaching with distilled water following 5×PR treatment led to no significant decrease in post-treatment SAR. 5×CBNG treatment followed by leaching significantly reduced soil solution SAR from 11.53 to 10.65 (Fig. 5).

In textural group #3 (23–33% clay), one wetting with CBNG water resulted in significantly greater SAR values than one wetting with PR water, and all 5× and 5× + *d* treatments led to significantly greater values than 1× treatments. However, leaching with distilled water following 5× treatments had no significant effect on soil solution SAR, regardless of water quality (Fig. 5).

In textural group #4 (>33% clay), 1×CBNG, 1×PR, 5×PR, and 5×PR + *d* treatments led to SAR values significantly greater than baseline SAR but not significantly different from one another. SAR values resulting from 5×CBNG and 5×CBNG + *d* treatments were significantly higher than SAR values resulting from all other treatments but not significantly different from one another (Fig. 5).

Discussion

Study results confirmed previously published relationships between applied water EC and SAR and resultant soil solution ECe and SAR. First, consistent with the Western Fertilizer Handbook (1995), repeated wetting and drying events caused ECe to equilibrate at approximately 2–3 times irrigation water EC. Second, under conditions of this study, post-treatment SAR roughly approximated SAR of the applied water. SAR values following all treatments were approximately related to ESP by the equation

271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
Journal	Article	MS Code	LE ☐ TYPESET ☐ CP ☑ DISK ☑	

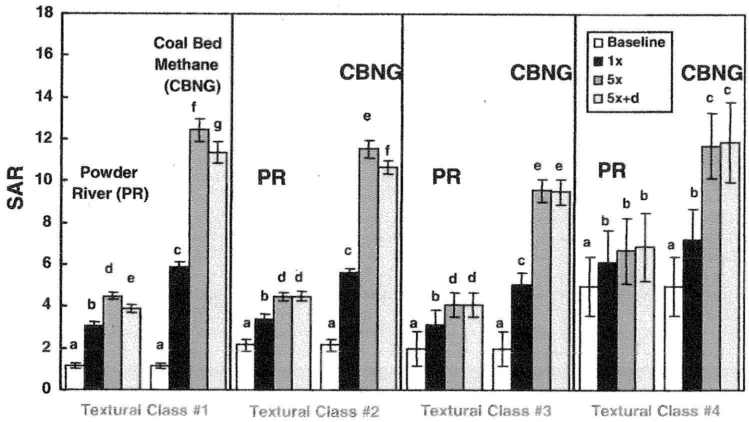

Fig. 5 Mean baseline and post-treatment soil solution SAR for each of the four textural groups (group #1, 0–11% clay; group #2, 12–22% clay; group #3, 23–33% clay; and group #4, >33% clay); means are reported for all water quality × wetting regime treatments. The 1× wetting regime consisted of a one time application of treatment water, while soils receiving the 5× treatment were wetted and dried five times. The 5× + *d* wetting regime was identical to the 5× treatment, except treatment soils were leached with distilled water following 5× treatment. Error bars represent standard error of the mean. *Bars* within the same textural group identified by the *same letter* are not significantly different at $P \geq 0.05$

SAR = 0.80×ESP, reported by the U.S. Salinity Laboratory in 1954 (data not shown). Because this relationship holds true under conditions of this study, land and water managers working under similar conditions can use applied water SAR to approximate resultant soil ESP and SAR.

In terms of salinity, single or infrequent applications of either PR or treated CBNG water posed little risk of causing soil to become saline, as defined by a salinity threshold of 3 dS m^{-1}. However, repeated wetting and drying with PR water brought ECe to values near 3 dS m^{-1}, and repeated wetting and drying with CBNG water, treated to meet permitted in-stream standards, resulted in ECe values more than double the accepted threshold (Figs. 3, 4). While leaching with distilled water following 5×CBNG treatment significantly reduced ECe in textural groups #1, #2, and #3, those reductions did not bring ECe near 3 dS m^{-1}. Additionally, leaching with distilled water following 5×PR led to no significant reductions in ECe in textural groups #2, #3, and #4. Thus, since both PR and treated CBNG water had potential to elevate ECe above the threshold level, and because a single leaching event was incapable of restoring ECe to acceptable levels, care must be taken with repeated application of either water quality, particularly when repeatedly irrigating salt intolerant crops.

5×CBNG and 5×CBNG + *d* treatments in textural groups #1, #2, and #4 resulted in mean soil solution SAR near or exceeding the commonly accepted threshold of 12. All PR treatments resulted in SAR values well below this threshold (Fig. 5). Figure 3 reveals that most of the samples with SAR values exceeding 12 resulted from 5×CBNG to 5×CBNG + *d* treatments. Although these treatments resulted in high SAR values, the treatments correspondingly increased ECe such that reduction in infiltration due to sodium induced dispersion was unlikely, according to guidelines proposed by Ayers and Westcot (1976) (Fig. 3). In terms of soil dispersion, all treatments actually altered soil solution ECe and SAR in a way that reduced the risk of loss of infiltration due strictly to soil solution ECe × SAR combinations, compared to baseline conditions (Fig. 3).

This study was designed to assess only the combination of EC × SAR of source water, followed by introduction of low-cation concentration replacement water, while minimizing the potential confounding effect of raindrop impact or sudden wetting of dry soil of smectite-dominated soil materials. Circumstances associated with actual irrigated field climatic conditions, including substantial leaching of salinity from the zone of wetting during rainfall events, are likely to exacerbate the shift in the ECe × SAR relationship reported here. Additionally, mechanical circumstances associated with irrigation practices and raindrop impact are known to have deleterious effects on soil structure and infiltration. Numerous researchers have reported significant reductions in infiltration consequential to energy associated with raindrop impact (Abo-Ghobar 1993; Mamedov et al. 2000; Suarez 2006). Consequently, results of this study need to be considered somewhat best-case circumstances under conditions of repeated wetting–drying, followed by low-cation concentration wetting of smectite-dominated soils.

Comparison of Figs. 4 and 5 reveals that leaching with distilled water resulted in reductions in ECe proportionately greater than reductions in SAR, particularly in treatments using treated CBNG water. Thus, while risk of sodium-induced dispersion was not high under conditions of this study, repeated wetting with low salinity water or significant rainfall or leaching events with low salinity water

Journal	Article	MS Code	Dispatch: 19.4.07	No. of Pages: 10
271	78	XXXX	LE ☐ TYPESET ☐	CP ☑ DISK ☑

could exacerbate this disproportionate lowering of ECe relative to SAR, reducing the flocculating effects of salinity and increasing the dispersive effects of sodium.

Conclusions

Development of the CBNG industry in the Powder River Basin of Montana and Wyoming, and the necessity of management of modestly saline × highly sodic water associated with natural gas extraction, has necessitated re-examination of the relationship between surface-applied water quality, soil solution chemistry, and risk of sodium-induced dispersion of smectitic soil. Currently promoted practices of treating CBNG produced water to EC and SAR levels published by Richards et al. (1954) and subsequent use as irrigation water on smectite-dominated soils may lead to soil solution ECe and SAR combinations contributing to sodium-induced dispersion. This is especially the case following rainfall events of sufficient amount to induce soluble salt leaching from the upper parts of the soil profile. Additionally, consideration must be given to the dispersive effect of raindrop impact and its relationship to infiltration. Data from this experiment, in combination with previously published thresholds and relationships, provide land managers within the PRB and in similar hydrologic and geologic situations a basis for targeting water treatment and management options and for making informed decisions about water qualities that can safely be applied to their specific soils. Results of this investigation also provide insights into the relationships between salinity, sodicity, soil clay content, and rainfall.

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271	78	XXXX	Dispatch: 19.4.07	No. of Pages: 10
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271	78	xxxx	Dispatch: 19.4.07 No. of Pages: 10
Journal	Article	MS Code	LE ☐ TYPESET ☐ CP ☑ DISK ☑