CHANGES IN SOIL PHYSICAL AND CHEMICAL PROPERTIES OF A CROPLAND IRRIGATED WITH CBNG CO-PRODUCED WATER[1]

Christopher R. Johnston[2], George F. Vance, and Girisha Ganjegunte

Abstract: Significant quantities of water are being produced and discharged as a by-product of coalbed natural gas (CBNG) development in the Powder River Basin (PRB). Elevated salinity and sodicity in CBNG water has become a major concern, particularly with regard to its use or disposal. If land applied, elevated salinity and/or sodicity in CBNG water may adversely affect soil physical properties such as structure, infiltration, permeability, and aeration. Soil chemical properties impacted by CBNG water utilized for irrigation include changes in nutrient supply, modification of the soil exchange complex with dispersion, and pH effects. A sodic soil has been shown to maintain good soil structure if the salinity level is maintained above the threshold electrolyte concentration (TEC). In this study, cropland that was irrigated with Piney Creek (control) and CBNG waters were sampled two years after CBNG water irrigation and compared to baseline and post irrigation data to evaluate changes in soil physical and chemical properties. CBNG water was treated with gypsum ($CaSO_4 \bullet 2H_2O$), sulfur (S) via a S burner, or both, and soils were amended with $CaSO_4 \bullet 2H_2O$, elemental S, or both (GS). Changes in soil physical and chemical properties were monitored using a split plot experiment. Single ring infiltration experiments were conducted within each plot to determine if infiltration rates were affected by water type and/or water and soil treatments. A significant decrease in infiltration rate was observed for plots irrigated with CBNG water without soil amendments or water treatments. Soil samples were taken and analyzed for chemical parameters including pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) before CBNG water application and two seasons following final CBNG water application. Decreases in EC and SAR were determined for most CBNG irrigated plots. Higher EC levels were detected in S and GS plots due to delayed microbial conversion of S. It appears Na^+ is moving through the soil profile with all soil amendment and water treatment combinations; however, CBNG-GSB+GS treatment results in the lowest SAR in the A and Bt_1 horizons.

Additional Key Words: salinity, sodicity, sodium adsorption ratio, gypsum, sulfur, Coalbed Methane, Coalbed Natural Gas

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Introduction

Natural gas production from coal is at an all-time high, currently accounting for 10% of the overall natural gas production in the United States (Ganjegunte et al., 2005). The Powder River Basin (PRB) in northeastern Wyoming and southeastern Montana is widely regarded as the most active coalbed natural gas (CBNG) production region in the United States containing an estimated total reserve of 900 billion m^3 (31.8 trillion ft^3) (U.S. BLM, 2003). Approximately 40,000 CBNG wells have been permitted in the Wyoming portion of the PRB through October, 2006 (WOGCC, 2006) with a total CBNG production in excess of 59.5 billion m^3 (2.10 trillion ft^3) (WOGCC, 2006).

Coalbed natural gas is adsorbed to the coal surface via hydrostatic pressure. Coalbed natural gas production requires the drawdown of water (CBNG water) to decrease hydrostatic pressure in the coal seam and subsequently release CBNG. Coalbed natural gas water is brought to the surface as a by-product where it must be managed because of increased levels of dissolved salts dominated by sodium (Na^+) and bicarbonate (HCO_3^-), often requiring on-site treatment or soil amendments prior to land application. There are numerous CBNG water management methods currently being used in the PRB including, surface discharge into ephemeral and perennial steam channels, infiltration reservoirs, impoundment reservoirs, injection into subsurface aquifers, reverse osmosis (RO), ion exchange, subsurface drip irrigation (SDI), land application for disposal, and managed irrigation to increase forage and cropland production (U.S. DOE, 2002, BeneTerra, 2006, King, 2006).

In Wyoming, the U.S. BLM (2003) estimates that 366,000 hectare-meters (ha-m) of CBNG water will be produced in the PRB over the life of the CBNG development. There has been approximately 62,000 ha-m of CBNG water produced in the PRB through October, 2006 (WOGCC, 2006). The majority of this water has been managed through discharge into ephemeral and perennial stream channels and infiltration reservoirs. However, more stringent Federal and State water regulations have made it much more difficult to manage these waters using these traditional methods.

In a time of extended drought in the PRB the beneficial use of CBNG water via managed irrigation has become more popular as a water management alternative. Managed irrigation as defined by Harvey and Brown (2005) is "the application of soil science, water chemistry, agricultural engineering, and agronomic principles to utilize CBNG water in a beneficial manner to produce forage for livestock and wildlife while protecting soil physical and chemical properties." This is different from land application disposal (LAP) in that LAP is simply a means of land applying CBNG water, usually with soil amendments or water treatments, that relies on the maximum infiltration rate of the soil to dispose of the greatest amount of CBNG water (Harvey and Brown, 2005).

Managed irrigation using CBNG water is currently being conducted on 1,435 ha of private land in the PRB with approximately 1,081 ha-m of CBNG water being applied each irrigation season (Harvey, 2006). The irrigation season in the PRB is between 125-150 days. During the off-season CBNG water is either stored in holding ponds or discharged under WYPDES permits (Harvey, 2006).

Several issues must be addressed in order to successfully manage CBNG water for land application. The physical and chemical properties of the soil and the chemistry of the CBNG water to be used must be understood. Coalbed natural gas waters are typically high in dissolved salts, Na^+ and HCO_3^- and there is evidence land application could cause soil salinity and sodicity problems (Rice et al., 2000, King, 2006). Increased salinity and sodicity in soils makes it more difficult for plants to uptake water and essential nutrients needed to facilitate photosynthesis. As the salinity of the soil increases, plants, depending on their level of salt tolerance, become less able to absorb the amounts of water needed for optimal biomass production due to reduced osmotic potential (Bauder and Brock, 2001). In addition, increased levels of soil Na^+ are associated with degradation of soil structure due to aggregate slaking and clay particle dispersion (U.S. Salinity Laboratory Staff, 1954, McNeal and Coleman, 1966, Arora and Coleman, 1979, Abu-Sharar, 1987). The resulting decrease in soil infiltration and permeability affects the flow of oxygen, water, and nutrients to the plant root system leading to decreased plant productivity, lower microbial biomass, and the destruction of once-productive soils.

Sodium impacts on soil have been shown to be not only dependent on soil texture, clay content, and clay type, but also on the electrical conductivity (EC) of the irrigation water and the soil solution. Ayers and Westcot (1985) and Hanson et al. (1999) showed that if the salinity of the water increases, higher SAR water can be applied without a reduction in infiltration (Fig. 1). This relationship has been expressed as the threshold electrolyte concentration (TEC). The TEC

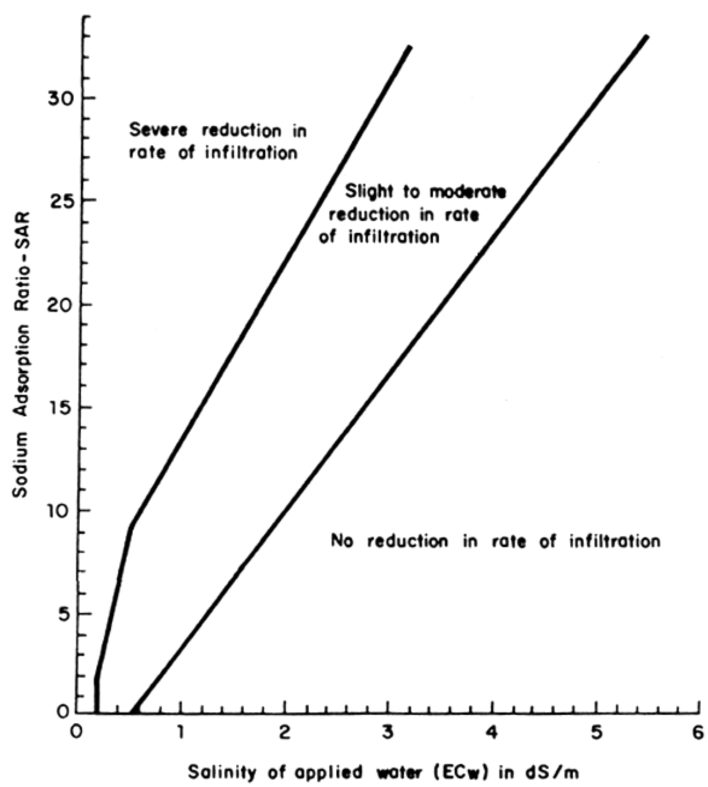


Figure 1. Relationship between EC and SAR as demonstrated by Ayers and Westcot (1985) and Hanson et al. (1999). Note: This relationship is for a particular soil studied by Ayers and Westcot.

is referred to as the minimum EC required to keep the soil flocculated (Quirk and Schofield, 1955, Sumner et al., 1998 and Chaudhari and Somawanshi, 2004). For example, if salt is added to a dispersed clay suspension, the increased EC of the suspension will cause the clay particles to flocculate. If the EC in the soil solution can be maintained at or above the TEC, the soil will remain in a flocculated state at higher SAR levels (Sumner et al., 1998). However, if the EC is below the TEC, a highly sodic soil may slake and disperse and soil structure will deteriorate (Shainberg et al., 1981a). Elevated EC concentrations in CBNG water in conjunction with the addition of soil amendments and water treatments result in EC concentrations above the TEC required to maintain soil flocculation eliminating potential impacts due to increased Na^+ concentrations in CBNG water. It is important, however, to monitor elevated EC levels so that increased salts do not impact plant production.

In addition to the elevated EC concentrations in CBNG water and the addition of soil amendments and water treatments there is evidence that shows EC concentrations can be maintained above the TEC level required to maintain flocculation by weathering and dissolution of soil minerals, including, Ca and Mg carbonates, gypsum, and a few primary minerals including feldspars, plagioclase and hornblendes (Nader et al., 1996 and Shainberg et al., 1981b). In a study conducted using six semi-arid soils, Rhoades et al. (1968) found soil solution EC's were 2.7 to 5.4 meq L^{-1} higher than applied waters with Ca^{2+} and Mg^{2+} accounting for 2.3 to 4.3 meq L^{-1}. More notably, SAR values in the soil solutions were reduced by 30 to 90% compared to applied water SAR's. Similar results for EC were reported in a study by Oster and Shainberg (1979) for three semi-arid soils. In addition, Shainberg et al. (1981a, b) found that a soils susceptibility to decreases in hydraulic conductivity when leached with distilled water was dependant on the rate of mineral dissolution. The use of distilled water in this study simulated rainfall conditions and showed the importance of maintaining TEC levels that help prevent crust formation and decreases in hydraulic conductivity. In addition to soil amendments and water treatments, mineral weathering of the soils is expected to contribute to the overall EC of the soil solution, especially in subsurface horizons, and help maintain TEC levels.

Methods currently being use to manage potential impacts to soil include treating the soil surface or CBNG water with an amendment such as gypsum ($CaSO_4 \bullet 2H_2O$) or sulfur (S). Gypsum is used as a surface amendment to increase Ca^{2+} concentrations in the soil solution. The increased Ca^{2+} competes for available cation exchange sites on clay surfaces, which results in the movement of Na^+ through the soil profile with subsequent irrigation events or with a leaching fraction at the end of the irrigation season. Sulfur is also used as a surface amendment. The oxidation of S, mainly via microbial processes, results in the production of acidity enhancing the dissolution of in-situ $CaCO_3$, which results in the release of Ca^{2+} into the soil solution. Water treatments and/or soil amendments are required for all managed irrigation systems. However, the rate of application is dependent on the EC and SAR of the water being applied. Higher Na^+ concentrations typically require higher treatment and amendment rates resulting in increased costs. Most CBNG water currently being land applied in the PRB is being treated via soil amendments.

Managed irrigation is cost effective when compared to other CBNG water management options. Costs associated with different CBNG water management technologies are shown in Table 1. Costs for managed irrigation technologies are based on a 16.2 ha plot with an application rate of 795,000 L day^{-1} (5,000 bbl day^{-1}). Capital costs for irrigation systems include all installation costs prior to use. Gypsum applicator costs do not include installation costs, but these costs are considered minimal by suppliers. Sulfur burner costs include installation costs.

Table 1. Costs associated with CBNG water management. Source: U.S. DOE, 2002, ALL Consulting, 2004, Paetz et al., 2006, and personal communications with Diamond K, Roughrider Power and J.M. Huber Corp (2006).

Management Technologies	**Capital Costs per well**	**O&M Costs**
Surface Discharge	$1,400	$0.02/bbl
Infiltration/Storage Ponds	$10,300	$0.06/bbl
Shallow Injection	$15,150	$0.06/bbl
Deep Injection	$35,200	$0.14/bbl
Reverse Osmosis	$19,600	$0.03/bbl
Managed Irrigation Systems	**Capitol Costs per system**	**O&M Costs**
Center Pivot System	$58,000	$0.04/bbl
Side Roll Systems	$55,000	$0.12 - $1.20/bbl
Automated Big Gun System	$55,000	$0.04 - $0.08/bbl
Manual Big Gun System	$20,000	$0.20 - $0.40/bbl
Water Treatments		
Gypsum Applicator		
175 gallon	$3,000	$0.04/bbl
325 gallon	$3,000	$0.04/bbl
525 gallon	$3,200	$0.04/bbl
Pump and Metering Box	$2,000	
Sulfur Burner	$30,000	$0.10/bbl
Mixing Tank	$1,500	
Pumps (2)	$400-$600	
Soil Amendments		
Gypsum and Sulfur (delivered) (1.45 Mg/ha)		$0.12 -$0.15/bbl

*Costs for managed irrigation technologies are based on a 16.2 ha plot with a flow of 5,000 bbl/day (1 bbl = 42 gal = 159 L).

The chemistry associated with saline and sodic conditions in soils is complex. The objective of this work was to better understand the chemical interactions taking place between treatment combinations of CBNG water and a semi-arid soil in the PRB used for cropland production. Understanding these interactions may lead to the successful use of CBNG water via managed irrigation to improve plant production on irrigated croplands.

Materials and Methods

Study Area

A 15 ha irrigated mixed gas field near Ucross, WY was revisited two years after an initial CBNG study was completed that examined water and soil impacts with water treatments and soil amendments (Johnston et al., 2006). Additional sampling and field measurements were conducted to ascertain soil chemical and physical changes due to the initial application of CBNG water treatments and soil amendments (Johnston et al., 2006). The site, which has historically been irrigated with Piney Creek water, was irrigated with 31 cm of CBNG water over one irrigation season, and has since only received natural precipitation. Initial field characterization and study area and sample plot establishment were reported by Johnston et al. (2006).

Soil Amendments and Water Treatments

Soil amendment and water treatment combinations were used in the initial study to reduce impacts from land application of CBNG waters. Treatments evaluated at the site included combinations of irrigation waters, soil amendments, and water treatments, as shown in Table 2. Soil amendments included agricultural grade S (90% S and 10% bentonite), $CaSO_4 \bullet 2H_2O$ (87% $CaSO_4 \bullet 2H_2O$), S plus $CaSO_4 \bullet 2H_2O$, and no treatment. Mathematical adjustments were made for the purity of the $CaSO_4 \bullet 2H_2O$ and S to ensure appropriate application rates. Rock $CaSO_4 \bullet 2H_2O$ was sieved to a mesh size of 0.32 cm. Gypsum and S were applied using a drop spreader to ensure even distribution. Soil amendments were initially applied during the first irrigation season (2003); however, due to availability of CBNG water, only one irrigation cycle using Piney Creek water was completed over the entire field. This allowed for initial reaction and dissolution of soil amendments. Soil amendments were reapplied at the same rates prior to the 2004 spring irrigation season.

Coalbed natural gas water treatments included acidification via SO_2 addition with a S burner for HCO_3^- removal, solution grade $CaSO_4 \bullet 2H_2O$ via a $CaSO_4 \bullet 2H_2O$ fertigation applicator, and no treatment. Piney Creek water was used as the control. CBNG water passed through the S burner was oxygenated to facilitate the SO_2 to SO_4^{2-} conversion, resulting in acidification and HCO_3^- removal. A reduction in pH of the CBNG water to 6.5 removed HCO_3^- to levels that resulted in under-saturation of $CaCO_3$. Surface amendment and water treatment requirements were calculated to achieve a final SAR of approximately 8.0 $mmol^{1/2}\ L^{-1/2}$. Irrigation water was applied using a side-roll irrigation system.

Table 2. Irrigation water treatment and surface amendment combinations.

Water Used	Surface Applied Soil Treatment	Water Treatment Before Irrigation	Abbreviations Used
Piney Creek (PC)	none	none	PC+NT
PC	gypsum	none	PC+G
PC	sulfur	none	PC+S
PC	Gypsum & sulfur	none	PC+GS
CBNG	none	none	CBNG+NT
CBNG	gypsum	none	CBNG+G
CBNG	sulfur	none	CBNG+S
CBNG	Gypsum & sulfur	none	CBNG+GS
CBNG	none	gypsum injector	CBNG-G+NT
CBNG	gypsum	gypsum injector	CBNG-G+G
CBNG	sulfur	gypsum injector	CBNG-G+S
CBNG	Gypsum & sulfur	gypsum injector	CBNG-G+GS
CBNG	none	gypsum inj. & sulfur burner	CBNG-GSB+NT
CBNG	gypsum	gypsum inj. & sulfur burner	CBNG-GSB+G
CBNG	sulfur	gypsum inj. & sulfur burner	CBNG-GSB+S
CBNG	Gypsum & sulfur	gypsum inj. & sulfur burner	CBNG-GSB+GS

Soil Samples

Soil samples were taken 2 years after the initial study was completed to determine soil chemical changes due to natural rainfall events following CBNG water application. Soil samples were randomly collected from each plot following the methods used by Johnston et al. (2006). Soil samples were collected from the top three soil horizons within each study plot. Samples were homogenized, air-dried and sieved to <2 mm. Saturated paste extracts were prepared using the method described by Rhoades (1996). Extracts collected from the saturated pastes were then analyzed for pH, EC, Na^+, Ca^{2+} and Mg^{2+}, and SAR was calculated from the base cation data. Quadruplicate samples were determined for each soil amendment and water treatment combination.

Infiltration Study

A falling head over time experiment was used to determine if there were any differences in infiltration rates between soil amendment and water treatment combinations. Triplicate single ring infiltration tests were completed within each study plot. Infiltration rings 20.3 cm long with a 20.3 cm inside diameter (ID) were randomly inserted 10.2 cm into the soil. Rings were filled with Piney Creek water one time and allowed to drain until almost empty. Rings were then refilled to 8 cm and measurements were taken every 5 min minutes until empty.

Statistical Approach

A split-plot in space and time experimental design was used to analyze the data. This design allowed for analysis of effects of different water types, water treatments, and soil amendments on soil chemistry and their interactions. Statistics were run on mean values for pre, post, and spring 2006 data and comparisons were made between horizons, water treatments, and surface amendments. Analyses were performed using the GENSTAT 4.1 statistical software. The model consisted of water quality as the main-plot effect, soil treatments as sub effect, and soil horizons as sub-sub effect. Water quality was a random effect, and all other components were fixed. Differences among treatment means were tested using Fisher’s Least Significant Difference Test (LSD) at $P \leq 0.05$ (Steel and Torrie, 1980).

Irrigated Land Suitability

A preliminary soils suitability analysis was completed on irrigated lands in the Powder River and Tongue River watersheds to determine soil suitability for CBNG managed irrigation. Soil data used for this analysis was at the 1:100,000 scale. Because of the small scale, Soil Matching Units (SMU’s) often contained more than one soil series description. In these cases, the predominant soil series was used to determine suitability.

Soil characteristics were studied from soil series descriptions. Soil texture, clay type, and presence or absence of a calcareous horizon was used to determine soil suitability. Soil texture was used to approximate the clay content of each soil. Soils with a clay content >35% were considered unsuitable for CBNG water managed irrigation. Soils with a clay content <35% were considered for CBNG water managed irrigation and subsequently investigated for clay type. Soils containing 2:1 clays were generally considered unsuitable because of there swelling properties and poor drainage. Soils with <35% clay with a calcareous layer present were considered likely suitable while soils with <35% clay without a calcareous layer were considered possibly suitable.

Results and Discussion

Irrigation Water Chemistry

Two irrigation waters were used in the previous study. Piney Creek water was used as the control and CBNG water obtained from a common wellhead on the property was evaluated in this study. The Piney Creek water is the traditional water used for irrigation at the site and represents a typical irrigation water for the region with Ca^{2+} and HCO_3^- being the most active ions in solution. Sodium and HCO_3^- were the dominant cation and anion in the CBNG water. Coalbed natural gas water was high in HCO_3^- and its application was expected to result in the precipitation of $CaCO_3$ due to supersaturated conditions with respect to Ca^{2+} and HCO_3^- ions. Acidification of the CBNG water by the sulfur burner and the subsequent reduction in HCO_3^- helped maintain higher Ca^{2+} levels in the soil solution. Table 3 lists the water chemistry for both waters used in the previous study.

Table 3. Water chemistry for Piney Creek and CBNG waters used at the study site.

Water Sample	pH s.u.	EC dS/m	TDS mg/L	ALK mg/L	Na^+ mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	SAR $mmol^{1/2}\ L^{-1/2}$
Piney Creek	8.3	0.64	470	207	28.1	74.8	29.5	0.69
CBNG	8.3	1.38	910	802	344	8.90	3.90	24.3

	K^+ mg/L	Fe mg/L	HCO_3^- mg/L	Cl^- mg/L	F^- mg/L	CO_3^{2-} mg/L	SO_4^{2-} mg/L
Piney Creek	5.8	100	237	2.5	0.19	7.5	137
CBNG	3.1	560	853	12.8	0.94	61.5	<1.0

Soil Studies

Soil samples were taken to determine soil chemical changes due to natural watering events following CBNG water application. Statistics were run on mean values for pre, post, and spring 2006 data and comparisons were made between horizons and surface amendments. Post irrigation and spring 2006 data are presented here. Pre-irrigation data was previously reported in Johnston et al. (2006).

Soil saturated paste extracts indicated increases in pH for all CBNG and CBNG-GSB water treatments irrespective of soil amendment except for CBNG-GSB+S in the Bt_1 horizon which was close with a difference of 0.51 compared to the LSD of 0.53 (Table 4). Interestingly, significant decreases in pH were observed in many of the same treatment combinations from pre to post-irrigation (Johnston et al., 2006). Changes are attributed to the leaching of amendments and increased Na^+ concentrations in all horizons. Sodium-affected soils demonstrate an increased pH due to dominance of Na^+ on the soil exchange complex. Comparisons between CBNG and CBNG-GSB water treatments and PC and CBNG-G water treatment indicate more differences in pH for both pre to post irrigation and post irrigation to spring 2006 comparisons for CBNG and CBNG-GSB water treatments (Johnston et al., 2006). Differences in pH for the CBNG-GSB water treatments can be attributed to the addition of the S burner as a water treatment and the subsequent rapid leaching of amendments thought the soil profile, whereas the changes in pH for the CBNG water treatments may have resulted from dilution of the soil solution by natural precipitation.

Table 4. Mean pH values for soil saturated paste extracts of post and spring 2006 Piney Creek and CBNG irrigation treatment sites receiving water and soil amendments. Abbreviations are described in Table 3-2. Spring 2006 irrigation treatment LSD = 0.29. Post and spring 2006 irrigation treatment LSD of A horizon = 0.51, Bt_1 = 0.53, and Bt_2 = 0.45.

Variable	Water Treatment	Soil Horizon	Post Irrigation - Fall 2004				Spring 2006			
			Soil Amendment							
			NT	**G**	**S**	**GS**	**NT**	**G**	**S**	**GS**
pH	PC	A	7.76	**6.80**	**7.34**	**7.28**	8.08	**8.20**	**7.96**	**7.97^{ab}**
		Bt_1	7.79	7.72	7.77	**6.95**	7.86	7.95	7.90	**8.13^{a}**
		Bt_2	7.76	7.67	**7.41**	7.41	7.97	8.00	**7.98**	7.76^{b}
	CBNG	A	**7.13**	**7.15**	**7.10**	**7.00**	**8.23^{A}**	**8.22^{Aab}**	**8.04^{AB}**	**7.92^{B}**
		Bt_1	**7.13**	**7.05**	**7.13**	**7.08**	**8.25**	**8.34^{a}**	**8.20**	**8.11**
		Bt_2	**7.18**	**7.10**	**7.20**	**7.41**	**8.15**	**8.00^{b}**	**8.02**	**8.02**
	CBNG-G	A	**7.03**	**7.39**	7.90	**7.46**	**8.15**	**8.21^{a}**	7.93^{b}	**8.06**
		Bt_1	**7.45**	**7.51**	7.90	7.85	**8.37**	**8.29^{a}**	8.23^{a}	8.18
		Bt_2	**7.13**	7.56	7.77	7.76	**8.10**	7.87^{b}	8.12^{ab}	8.01
	CBNG-GSB	A	**7.03**	**6.88**	**6.98**	**6.93**	**8.24^{A}**	**8.06^{AB}**	**8.02^{AB}**	**7.88^{B}**
		Bt_1	**7.03**	**6.98**	7.49	**7.08**	**8.28**	**8.17**	8.00	**8.14**
		Bt_2	**7.15**	**7.10**	**7.49**	**7.10**	**8.14**	**7.97**	**8.01**	**7.89**

BOLD indicates significant differences between means of post irrigation and spring 2006 samples for each soil amendment and water treatment combination at the same depth ($P \leq 0.05$). Capital letters indicate a significant difference among soil amendment means of spring 2006 samples for each water type at the same depth ($P \leq 0.05$). lower case letters indicate a significant difference among soil horizon means of spring 2006 samples for each soil amendment and water treatment combination ($P \leq 0.05$).

Very few differences were detected in pH among soil amendments. The CBNG and CBNG-GSB water treatments both resulted in lower pH values for GS soil treatments in the A horizon. The GS soil amendment was significantly different from the NT soil amendments; however, GS soil amendments were similar to S soil amendment in the CBNG water treatment and the G and S soil amendments in the CBNG-GSB water treatment. Lower pH values for the GS and S amended plots are attributed to the slower conversion of elemental S via microbial processes and continued acidity produced during the oxidation of S to SO_4^{2-}.

Decreases in EC were observed between post irrigation and spring 2006 data for almost all amendments and soil horizons except for some NT and PC+S treatments (Table 5). Decreases in EC are a result of the leaching of both natural and applied solutes deeper in the soil profile. Comparisons between soil amendments indicate higher EC concentrations in general for S and GS soil amendments. Higher EC concentrations in the S soil amended plots may be due to the delayed microbial conversion of S to SO_4^{2-}. Sulfur oxidation results in the production of acidity enhancing the dissolution of $CaCO_3$ and resulting in the release of Ca^{2+} into the soil solution. Because this conversion mainly occurs via microbial processes, oxidation reactions are generally slow, which is an important reason why the S and GS soil amended plots tend to have higher residual EC values than the NT and G soil amended plots. In addition, it is also important to note that when compared to pre irrigation data, spring 2006 S and GS soil amended plots tend to have significantly higher EC concentrations in the A and Bt_1 horizons while the NT and G plots are similar to pre irrigation among all water types.

Table 5. Mean EC values (dS m^{-1}) for soil saturated paste extracts of post and spring 2006 Piney Creek and CBNG irrigation treatment sites receiving water and soil amendments. Abbreviations are described in Table 3-2. Spring 2006 irrigation treatment LSD = 0.432. Post and spring 2006 irrigation treatment LSD of A horizon = 0.457, Bt_1 = 0.387, and Bt_2 = 0.862.

Variable	**Water Treatment**	**Soil Horizon**	**Post Irrigation - Fall 2004**				**Spring 2006**			
			Soil Amendment							
			NT	**G**	**S**	**GS**	**NT**	**G**	**S**	**GS**
EC	PC	A	0.943	**1.50**	**1.49**	**2.06**	0.649^{C}	**0.677**^{C}	**2.06**^{Aa}	**1.39**^{B}
dS m^{-1}		Bt_1	0.806	**1.42**	1.00	**1.56**	0.490^{B}	**0.669**^{B}	1.09^{Ab}	**1.03**^{A}
		Bt_2	0.755	**2.08**	**2.99**	**2.07**	0.462^{B}	**0.816**^{AB}	**0.734**^{ABb}	**1.07**^{A}
	CBNG	A	**1.52**	**2.08**	**2.43**	**2.84**	**0.684**^{B}	**0.633**^{B}	**1.33**^{Aa}	**1.53**^{Aa}
		Bt_1	0.800	**1.91**	**1.23**	**1.94**	0.711	**0.763**	**1.08**^{ab}	**0.954**^{b}
		Bt_2	0.730	**2.02**	1.12	**2.03**	0.485	**0.891**	0.842^{b}	**0.849**^{b}
	CBNG-G	A	**1.78**	**2.47**	**2.39**	**2.52**	**0.889**^{BC}	**0.588**^{C}	**1.93**^{Aa}	**1.19**^{B}
		Bt_1	**1.32**	**1.84**	**1.55**	**1.92**	**0.530**^{B}	**0.603**^{B}	**1.05**^{Ab}	**1.14**^{A}
		Bt_2	1.02	**2.21**	1.75	**2.24**	0.492	**0.786**	0.939^{b}	**0.942**
	CBNG-GSB	A	**1.99**	**3.90**	**3.12**	**3.72**	**0.660**^{B}	**0.596**^{Bb}	**1.54**^{Aa}	**1.69**^{Aa}
		Bt_1	**1.76**	**3.28**	**2.11**	**2.63**	**0.615**	**0.729**^{b}	**0.983**^{b}	**0.920**^{b}
		Bt_2	**1.75**	**2.57**	**2.07**	2.54	**0.592**^{C}	**1.20**^{Ba}	**0.892**^{BCb}	1.80^{Aa}

BOLD indicates significant differences between means of post irrigation and spring 2006 samples for each soil amendment and water treatment combination at the same depth ($P \leq 0.05$). Capital letters indicate a significant difference among soil amendment means of spring 2006 samples for each water type at the same depth ($P \leq 0.05$). lower case letters indicate a significant difference among soil horizon means of spring 2006 samples for each soil amendment and water treatment combination ($P \leq 0.05$).

Spring 2006 soil chemistry data show significant reductions in SAR in all horizons (Table 6). The lowest SAR was observed for the CBNG-GSB+GS treatment A horizon (0.608 $mmol^{1/2}$ $L^{-1/2}$). Decreases in SAR were observed in the A horizons for all water treatment and soil amendment combinations, indicating the movement of Na^+ from the surface horizon deeper into the profile. Soil amendments of G, S, and GS result in lower SAR values than NT. Surface horizons are often more susceptible to increased Na^+ concentrations because of lower EC levels in irrigation and precipitation water that do not meet TEC requirements for maintaining soil structure. In addition, mechanical forces resulting from raindrop impact, the flow of water at the surface due to flooding, or the use of farm equipment can enhance compaction and surface runoff and result in clay dispersion at the soil surface.

Table 6. Mean SAR values ($mmol^{1/2}\ L^{-1/2}$) for soil saturated paste extracts of post and spring 2006 Piney Creek and CBNG irrigation treatment sites receiving water and soil amendments. Abbreviations are described in Table 3-2. Spring 2006 irrigation treatment LSD = 0.728. Post and spring 2006 irrigation treatment LSD of A horizon = 0.968, Bt_1 = 0.877, and Bt_2 = 0.508.

Variable	Water	Soil	Post Irrigation - Fall 2004				Spring 2006			
			Soil Amendment							
	Treatment	Horizon	NT	G	S	GS	NT	G	S	GS
SAR $mmol^{1/2}L^{-1/2}$	PC	A	0.768	0.536	0.557	0.470	0.412	0.353	0.177	0.274
		Bt_1	0.734	0.522	0.633	0.596	0.518	0.415	0.450	0.436
		Bt_2	0.846	0.62	0.672	0.563	0.893	0.678	0.705	0.960
	CBNG	A	**7.74**	**5.64**	**6.06**	**4.49**	**2.92^Aa**	**1.76^Bb**	**1.74^Bb**	**0.940^Cb**
		Bt_1	**2.29**	2.04	**2.67**	2.40	**3.58^Aa**	2.77^Ba	**3.56^Aa**	2.91^ABa
		Bt_2	**1.25**	**0.942**	**1.09**	**0.924**	**1.98^b**	**1.77^b**	**1.88^b**	**2.46^a**
	CBNG-G	A	**7.50**	**5.56**	**5.69**	**4.97**	**3.08^Ab**	**1.93^Bb**	**1.69^Bb**	**1.39^Bb**
		Bt_1	**2.93**	3.19	**2.72**	2.77	**3.98^Aa**	3.73^Aa	**3.73^Aa**	2.93^Ba
		Bt_2	**1.04**	**0.966**	**0.865**	**0.998**	**1.87^c**	**1.92^b**	**2.30^b**	**2.42^a**
	CBNG-GSB	A	**5.54**	**3.67**	**4.38**	**3.91**	**1.69^Ab**	**1.05^ABb**	**0.641^Bb**	**0.608^Bb**
		Bt_1	**2.68**	2.68	3.66	**3.41**	**3.53^Aa**	2.56^Ba	2.80^BCa	**1.93^Ca**
		Bt_2	**1.06**	**1.08**	**1.20**	**1.18**	**3.08^Aa**	**2.85^ABa**	**2.99^ABa**	**2.34^Ba**

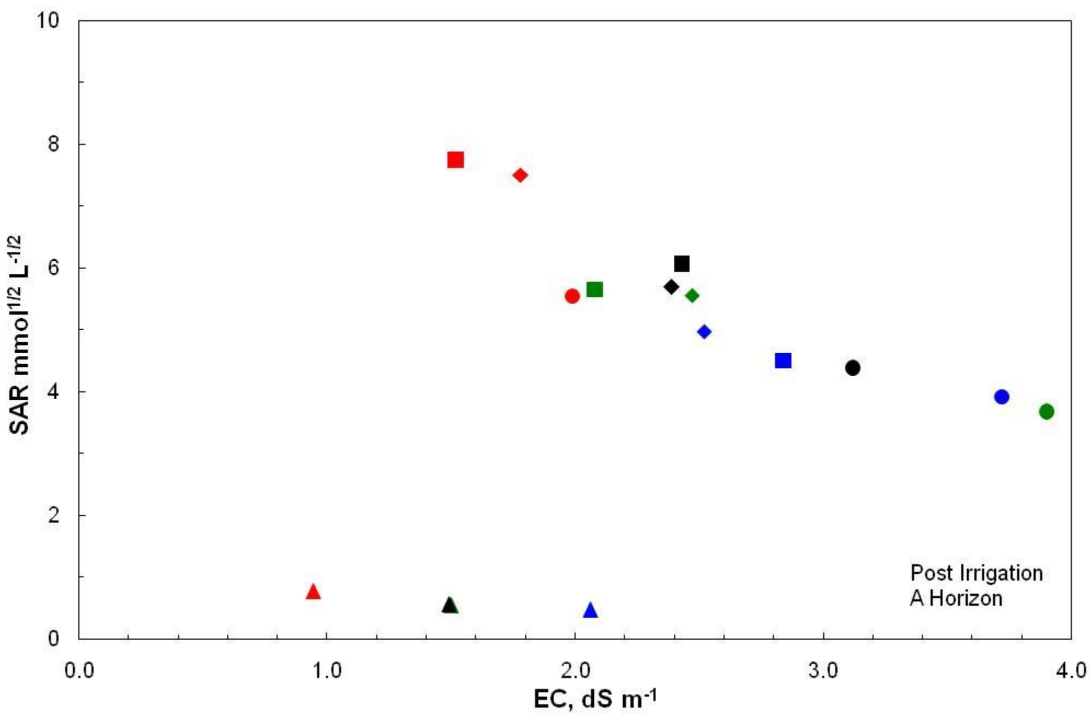
BOLD indicates significant differences between means of post irrigation and spring 2006 samples for each soil amendment and water treatment combination at the same depth ($P \leq 0.05$). Capital letters indicate a significant difference among soil amendment means of spring 2006 samples for each water type at the same depth ($P \leq 0.05$). lower case letters indicate a significant difference among soil horizon means of spring 2006 samples for each soil amendment and water treatment combination ($P \leq 0.05$).

Increases in SAR in the Bt_1 horizon occurred in most water treatment and soil amendment combinations indicating the movement of Na^+ out of the A horizon and into the Bt_1 horizon. In addition, when comparing A and Bt_1 horizons, SAR values were significantly higher in the Bt_1 horizon in all water treatment and soil amendment combinations except for CBNG+NT. The CBNG+NT treatment was expected to result in less Na^+ leaching due to lack of amendments. The lowest Bt_1 SAR for CBNG irrigated sites was observed with the CBNG-GSB+GS treatment ($1.93\ mmol^{1/2}L^{-1/2}$).

The Bt_2 horizon follows a similar trend as the Bt_1 horizon with all water treatment and soil amendment combinations resulting in an increase in SAR. This increase indicates further movement of Na^+ though the profile into the Bt_2 horizon. SAR values in the Bt_1 and Bt_2 horizons of the CBNG-GSB treatment are similar across soil amendments. This does not hold true for CBNG and CBNG-G water treatments with SAR values lower in the Bt_2 horizon, indicating irrespective of soil amendment, CBNG-GSB water treatment results in faster leaching of Na^+ through the soil profile. A slight difference was observed among soil amendments in the CBNG-GSB water treatment. The CBNG-GSB+GS treatment had the lowest SAR (2.34 $mmol^{1/2}L^{-1/2}$) among soil amendments in Bt2 horizon, which was significantly lower than no soil amendment, but similar to G and S soil amendments. Interestingly, SAR values were consistently lower in the CBNG-GSB+GS treatment in each horizon indicating that perhaps much of the Na^+ had been leached below the Bt_2 horizon. Comparisons among soil amendments in both the CBNG and CBNG-G water treatments indicate no significant differences in the Bt_2 horizon.

The EC and SAR concentrations for post irrigation and spring 2006 data were plotted against each other by soil horizon (Fig. 2-4). The relationship between EC and SAR in irrigation water presented by Ayers and Westcot (1985) and Hanson et al. (1999) and the approximate boundaries between no reduction in infiltration, slight to moderate reduction in infiltration and severe reduction in infiltration were used to compare treatment combinations for the A horizon (Fig. 2). The Ayers and Westcot (1985) and Hanson et al. (1999) relationship is generally used for irrigation water EC and SAR values and not soil paste extract solutions; however, for general comparison purposes it was used for soil paste extract solutions in this study. The Post irrigation EC and SAR comparisons indicated there should be no reduction in infiltration rate in the A horizon for any of the treatment combinations except for CBNG+NT. The CBNG+NT treatment with an EC of 1.54 dS/m and an SAR of 7.74 $mmol^{1/2}L^{-1/2}$ fell into the slight to moderate reduction in infiltration range, thus confirming the need for amendment application for CBNG water land application. For the spring 2006 data, both the NT and G soil amendments fall into the slight to moderate reduction in infiltration rate for the A horizon, while S and GS soil amendments maintain no reduction in infiltration rate in the A horizon (Fig. 2). This is in part due to the increased rate of leaching of the water treatments, resulting in the soil amendment dissolution rate controlling EC concentrations. Again, the slower oxidation of S resulted in higher residual EC concentrations in the A horizon for the S and GS soil amended plots, which met the TEC requirements. It is important to note that these comparisons are general and there may be few direct correlations between the Ayers and Westcot (1985) and Hanson et al. (1999) EC and SAR relationships and the post irrigation and spring 2006 EC and SAR relationship due to differences in solution used, soil texture, clay content and clay mineralogy.

Comparisons between EC and SAR in the Bt_1 horizon for post irrigation and spring 2006 show a trend of increased SAR and decreased EC concentrations (Fig. 3). The CBNG-GSB water treatment in the post irrigation Bt_1 horizon generally resulted in the highest EC concentrations. Increased EC concentrations in the Bt_1 horizon are most desirable due to the increased interactions with cation exchange sites on clay surfaces in those horizons. When compared to the spring 2006 data, however, EC concentrations are very similar to results of the A horizon.



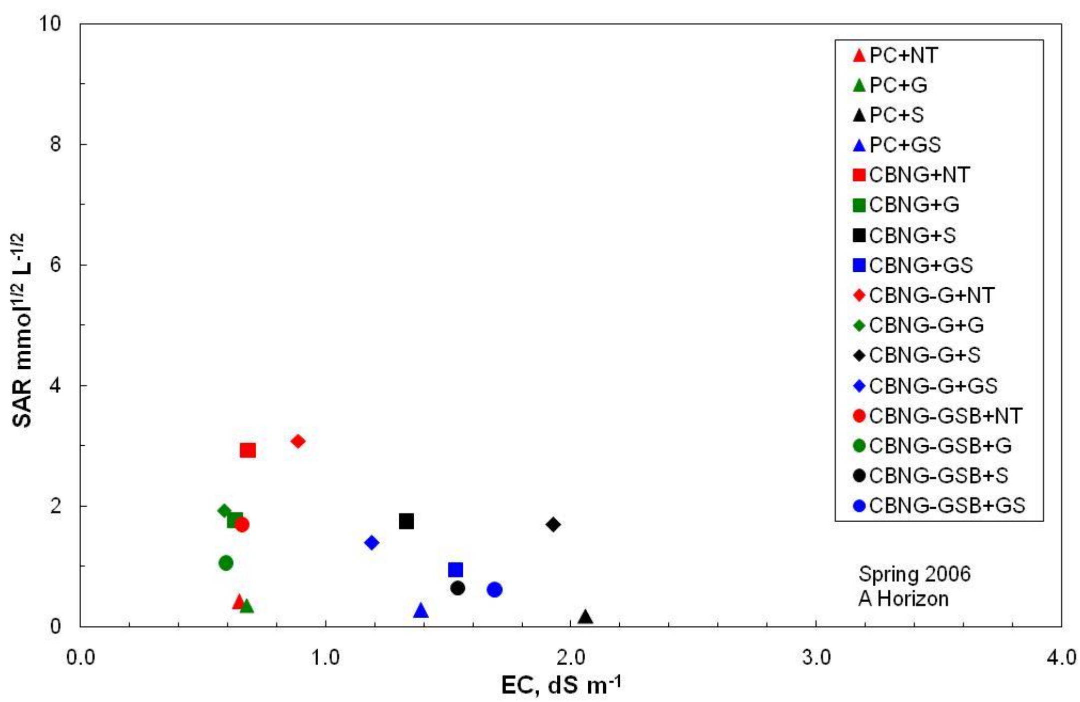
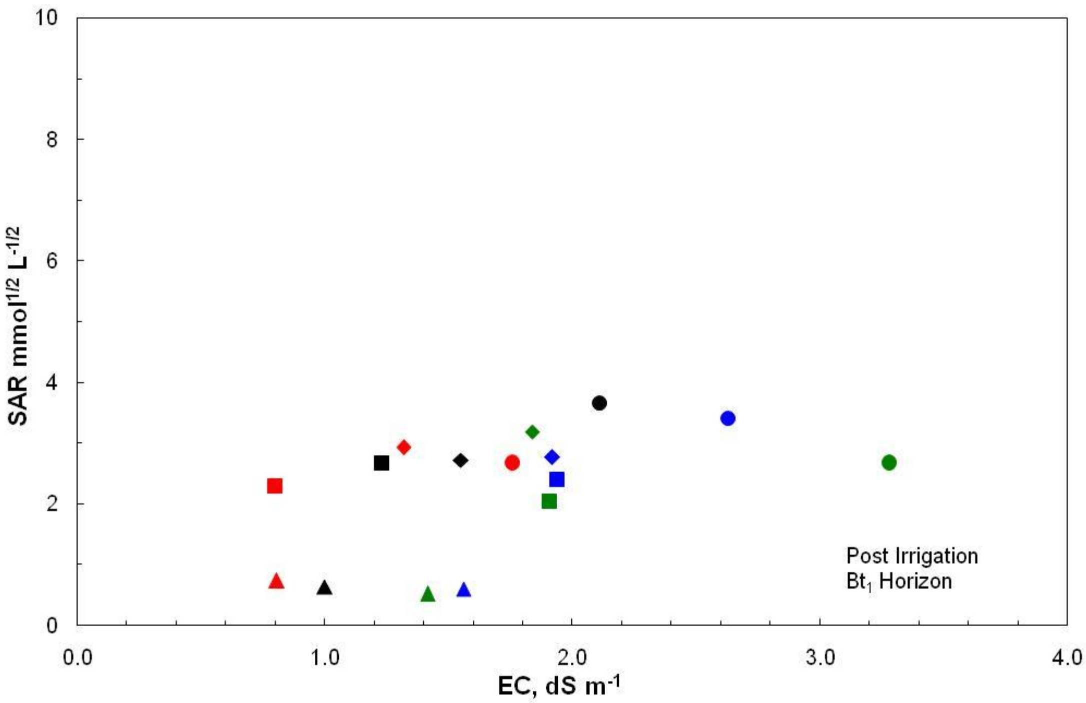


Figure 2. EC/SAR comparisons for post irrigation and spring 2006 A horizon samples.



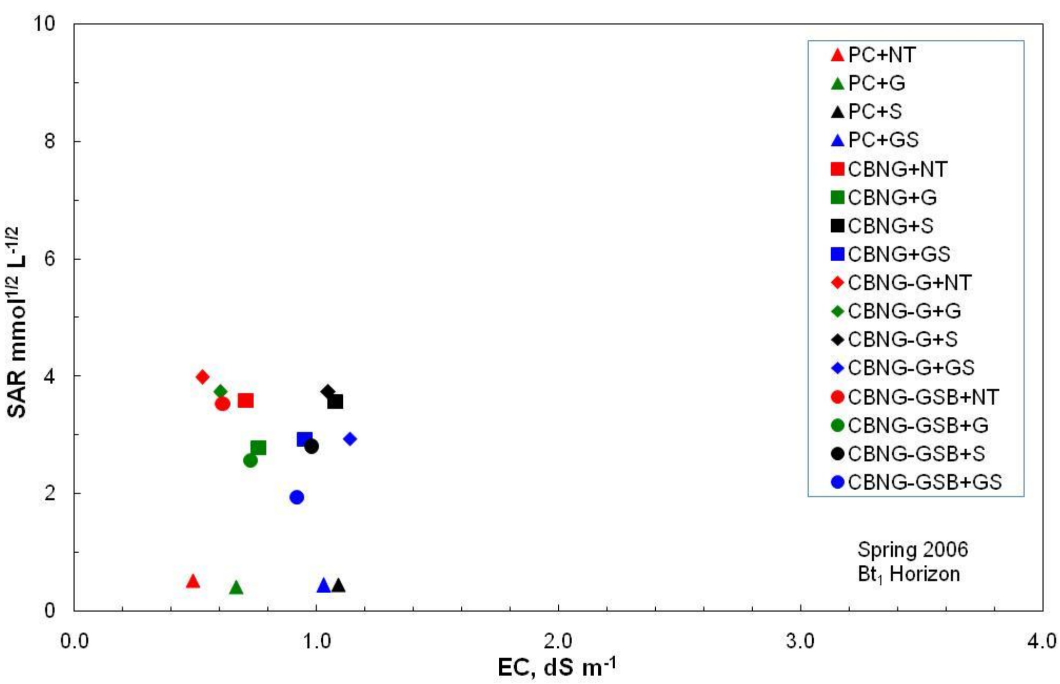
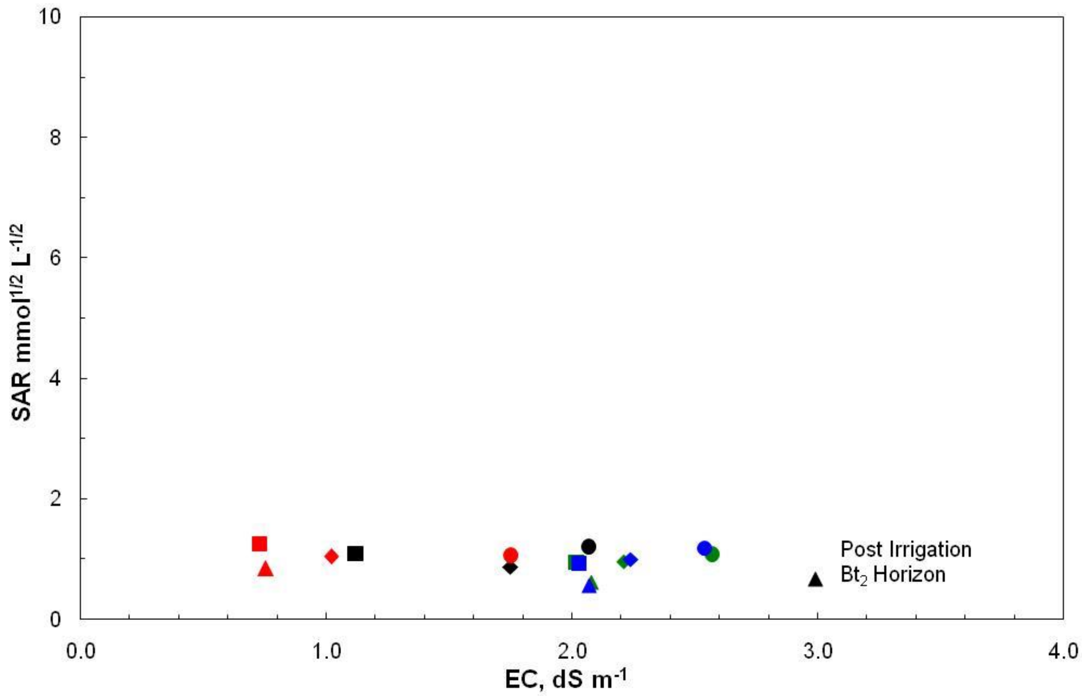


Figure 3. EC/SAR comparisons for post irrigation and spring 2006 Bt_1 horizon samples.



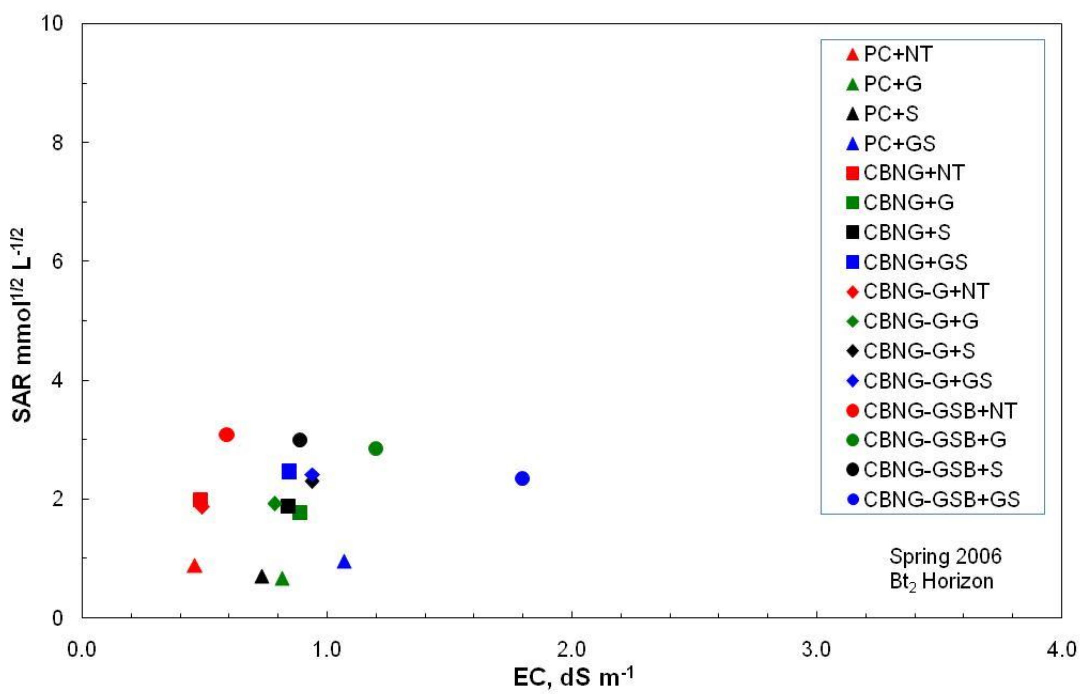


Figure 4. EC/SAR comparisons for post irrigation and spring 2006 Bt_2 horizon samples.

Increased rate of leaching of water treatments result in soil amendment dissolution rates controlling EC concentrations. Similar trends are seen in the Bt_2 horizon (Fig. 4). Lower EC concentrations in the both Bt horizons would suggest that additional amendments need to be applied subsequent to CBNG water application.

Infiltration Study

Infiltration results are shown in Table 7. Infiltration studies indicate the use of CBNG water with no soil amendments or water treatments results in a significant decrease in infiltration rate from 25.3 cm hr^{-1} for PC+NT to 12.2 cm hr^{-1} for CBNG+NT. In addition, G soil amendment also resulted in a significant decrease in infiltration rate from 27.1 cm hr^{-1} for PC+G to 13.5 cm hr^{-1} for CBNG+G indicating that G as a soil amendment may not be effective in maintaining soil solution concentrations of Ca^{2+} and subsequently soil structure. In addition, S and GS soil amendments appear to lower infiltration rates; however, they are not significantly different.

Table 7. Infiltration rates (cm hr^{-1}) for Piney Creek and CBNG irrigation treatment sites receiving water and soil amendments. LSD = 12.95.

Water	Soil Amendment			
Treatment	NT	G	S	GS
PC	25.3^{a}	27.1^{a}	25.0	24.6^{ab}
CBNG	12.2^{b}	13.5^{b}	17.7	17.7^{b}
CBNG-G	13.2^{ab}	22.1^{ab}	21.5	23.8^{ab}
CBNG-GSB	18.2^{Bab}	25.8^{ABab}	27.0^{AB}	33.5^{Aa}

Capital letters indicate a significant difference among soil amendment means ($P \leq 0.05$).

Lower case letters indicate a significant difference among water treatment means ($P \leq 0.05$).

All soil amendments generally had higher infiltration rates when compared to NT treatments, although, there were no significant differences between soil amendments for PC, CBNG, and CBNG-G water treatments. Differences were determined, however, for the CBNG-GSB water treatment, with the GS soil amendment resulting in the highest infiltration rate (33.5 cm/hr); an increase of 8.2 cm hr^{-1} from the baseline value of 25.3 cm hr^{-1} for PC+NT. The higher infiltration rate of the CBNG-GSB+GS treatment may be attributed to the dissolution of $CaCO_3$ in the soil and the higher overall amount of amendment used. The CBNG-GSB water treatment appears to be the most effective at maintaining infiltration rates at pre CBNG irrigation levels irrespective of soil amendment.

Irrigated Land Suitability

Irrigated cropland was selected for this study because of the benefits associated with managed irrigation. There are currently about 92,000 ha of irrigated land in the Power and Tongue River watersheds ranging in size from <1 ha to 7,000 ha. Irrigated areas are located primarily along drainage channels in Sheridan, Johnson, and Campbell counties.

There were a total of 33 soil series (Table 8) at the 1:100,000 scale, including 11 in Sheridan County, 11 in Johnson County, and 11 in Campbell County. Of the 33 soil series, ten had textures with >35 % clay. In addition, these 10 soils series contained smectitic clays. Smectitic clays are 2:1 type clays that are known for swelling upon hydration. Swelling of the soil in the presence of increased Na^{+} could have negative affects on soil structure. These ten soils were classified as not suitable for CBNG water irrigation.

Table 8. Soil series on irrigated land in the Powder River Basin, WY. Predominate soil series located in SH – Sheridan, JC – Johnson, and CM – Campbell Counties.

SMU	Soils Series Description
SH01	Ustic Haplargids, fine-loamy, mixed, frigid
SH02	Ustic Torrifluvents, fine-loamy, mixed, frigid
SH03	Ustic Paleargids, fine, smectitic, frigid
SH04	Ustic Torriorthents, clayey, smectitic, (calc), frigid
SH05	Lithic Ustic Torriorthents, loamy, mixed, frigid, non acid
SH06	Ustic Torriorthents, clayey, smectitic, (calc), frigid, shallow
SH07	Ustic Torriorthents, loamy, mixed, (calc), frigid, shallow
SH11	Ustic Torriorthents, loamy-skeletal, mixed, (calc), frigid
SH12	Typic Dystrocryepts, loamy-skeletal, mixed
SH16	Typic Haplocryalfs, fine, smectitic
SH17	Typic Cryorthents, loamy-skeletal, mixed
JC01	Ustic Haplargids, fine-loamy, mixed, mesic
JC02	Ustic Torrifluvents, fine-loamy, mixed, mesic
JC03	Ustic Paleargids, fine, smectitic, mesic
JC04	Ustic Torriorthents, clayey, smectitic, (calc), mesic, shallow
JC05	Lithic Ustic Torriorthents, loamy, mixed, non acid, mesic
JC06	Ustic Torriorthents, clayey, smectitic, (calc), shallow, mesic
JC07	Ustic Torriorthents, loamy, mixed, (calc), shallow, mesic
JC08	Ustic Torrifluvents, fine-loamy, mixed, (calc), frigid
JC09	Torriorthentic Haplustolls, fine-loamy, mixed, frigid.
JC10	Ustic Torriorthents, loamy-skeletal, mixed, (calc), frigid, shallow
JC11	Ustic Torriorthents, loamy-skeletal, mixed, (calc), frigid
CM03	Ustic Haplargids, fine-loamy, mixed, mesic
CM04	Ustic Torrifluvents, fine-loamy, mixed, (calc), mesic
CM05	Ustic Torrifluvents, coarse-loamy, mixed, (calc), mesic
CM06	Ustic Haplargids, fine-loamy, mixed, mesic
CM07	Ustic Torriorthents, clayey, smectitic, acid, mesic, shallow
CM09	Ustic Torriorthents, loamy-skeletal over fragmental, mixed, (calc), mesic- Wibaux RO
CM11	Ustic Torriorthents, clayey, smectitic, non acid, mesic, shallow
CM12	Ustic Haplargids, fine-loamy, mixed, mesic
CM13	Ustic Torriorthents, fine-loamy, mixed, (calc), mesic
CM14	Ustic Haplargids, fine, smectitic, mesic
CM15	Ustic Haplargids, fine-loamy, mixed, mesic

Of the remaining 23 soils, ten contained a calcic horizon. The presence of a calcareous horizon indicates the potential for mineral dissolution which would increase Ca^{2+} levels and decrease the SAR helping maintain soil structure. Nine of these ten soils were classified as likely suitable. The tenth soil also contained smectitic clay, but because of the coarser texture (coarse-loamy) and lower clay content (0-17%), it was classified as possibly suitable instead of not suitable. The remaining 13 soils with <35% clay and no calcic horizon present were classified as possible suitable. Results are shown in Table 9.

The location of irrigation lands in the Power and Tongue River watersheds and their suitability for managed irrigation is shown in Fig. 5. Of the approximate 92,000 ha available for managed irrigation, about 15,500 ha (17%) are considered likely suitable, about 17,500 ha (19%) are considered possibly suitable, and about 59,000 ha (64%) are considered unsuitable. Potentially suitable lands (likely + possibly) make up 36% of total irrigated cropland available for CBNG managed irrigation.

Table 9. Soil Suitability for CBNG irrigation with amendments.

SMU	Texture	% Clay	Calcareous	Smectitic	Suitability
SH07	loamy	<35	X		likely suitable
SH11	loamy-skeletal	<35	X		likely suitable
JC07	loamy	<35	X		likely suitable
JC08	fine-loamy	18-35	X		likely suitable
JC10	loamy-skeletal	<35	X		likely suitable
JC11	loamy-skeletal	<35	X		likely suitable
CM04	fine-loamy	18-35	X		likely suitable
CM09	loamy-skeletal	<35	X		likely suitable
CM13	fine-loamy	18-35	X		likely suitable
SH01	fine-loamy	18-35			possibly suitable
SH02	fine-loamy	18-35			possibly suitable
SH05	loamy	<35			possibly suitable
SH12	loamy-skeletal	<35			possibly suitable
SH17	loamy-skeletal	<35			possibly suitable
JC01	fine-loamy	18-35			possibly suitable
JC02	fine-loamy	18-35			possibly suitable
JC05	loamy	<35			possibly suitable
JC09	fine-loamy	18-35			possibly suitable
CM03	fine-loamy	18-35			possibly suitable
CM05	coarse-loamy	0-17	X	X	possibly suitable
CM06	fine-loamy	18-35			possibly suitable
CM12	fine-loamy	18-35			possibly suitable
CM15	fine-loamy	18-35			possibly suitable
SH03	fine	<60		X	not suitable
SH04	clayey	>35	X	X	not suitable
SH06	clayey	>35	X	X	not suitable
SH16	fine	<60		X	not suitable
JC03	fine	<60		X	not suitable
JC04	clayey	>35	X	X	not suitable
JC06	clayey	>35	X	X	not suitable
CM07	clayey	>35		X	not suitable
CM11	clayey	>35		X	not suitable
CM14	fine	<60		X	not suitable

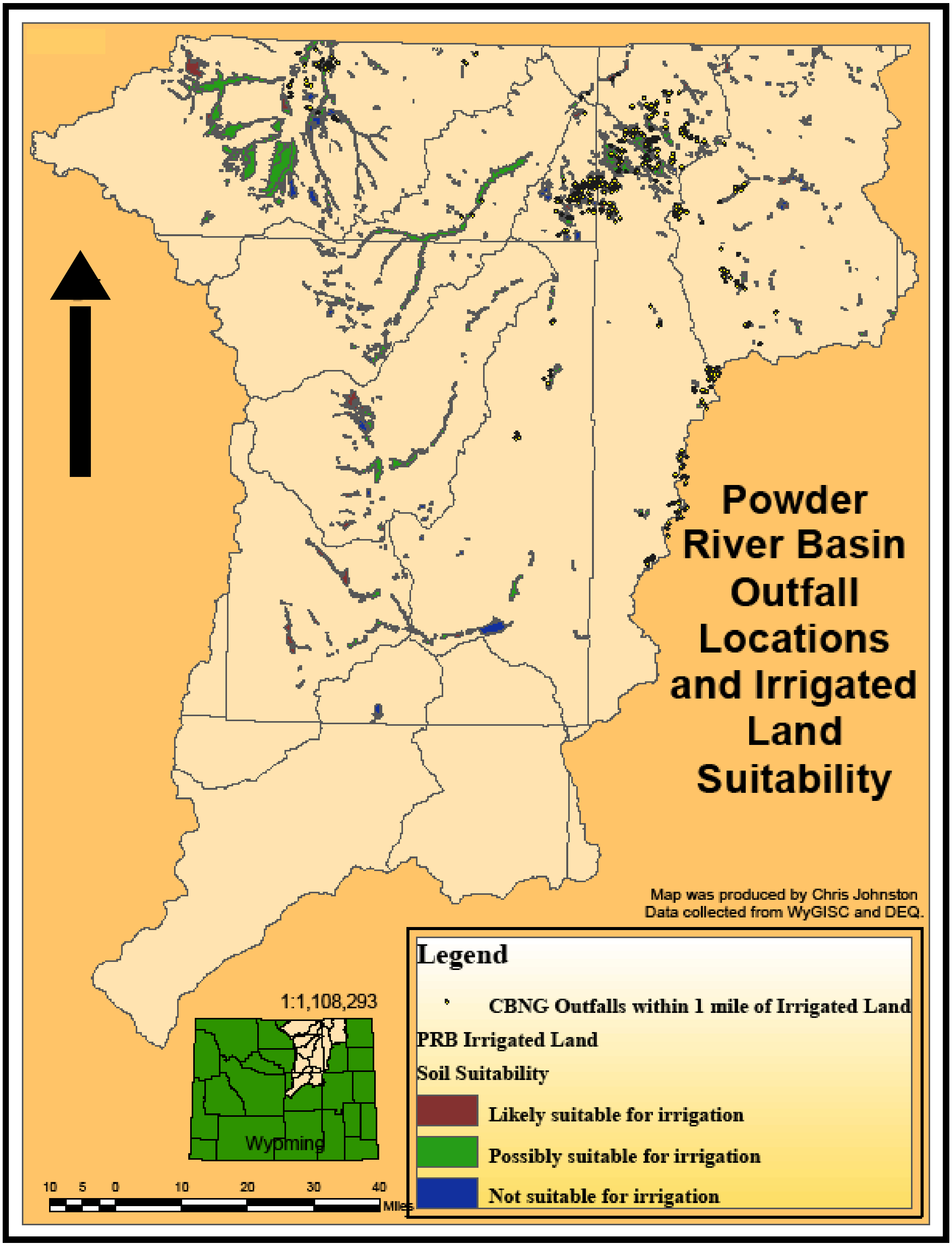


Figure 5. PRB outfall locations and irrigated land suitability.

Conclusions

Soil saturation paste extracts from samples taken two years after irrigation with CBNG water indicted decreases in EC concentrations for almost all horizons and depths excluding PC+S plots. Higher EC values in general were seen for S and GS amended plots. These higher values are attributed to the delayed microbial conversion of S to SO_4^{2-} that produces acidity and enhances the dissolution of $CaCO_3$ resulting in the release of Ca^{2+} into the soil solution. Comparisons to pre irrigation data show higher EC values for S and GS soil amendments and similar EC values for NT and G soil amendments among all water types. Few differences were observed in pH between soil amendments. The CBNG and CBNG-GSB water treatments both result in lower pH values for GS soil treatments in the A horizon. This is again attributed to the slower conversion of elemental S via microbial processes and continued acidity produced during the oxidation of S to SO_4^{2-}.

Spring 2006 soil paste extracts indicate significant changes in SAR in all horizons when comparing post irrigation and spring 2006 data. Decreases in SAR were observed in the A horizons for all water treatment and soil amendment combinations, indicating the movement of Na^+ from the surface horizon deeper into the profile. Soil amendments of G, S, and GS result in lower SAR values than NT with the lowest SAR observed in the CBNG-GSB+GS treatment (0.608 $mmol^{1/2}L^{-1/2}$). Movement of Na^+ out of the surface horizon into lower horizons is an important finding because of the A horizons susceptibility to increased Na^+ concentrations with lower EC levels in irrigation and precipitation water, mechanical forces resulting from raindrop impact, the flow of water at the surface due to flooding, or the use of farm equipment that can cause dispersion at the soil surface.

Increases in SAR in the Bt_1 and Bt_2 horizons occurred in most water treatment and soil amendment combinations indicating the movement of Na^+ out of the A horizon and into the Bt horizons. SAR values in the Bt_1 horizon were significantly higher than SAR values in the A horizon in all water treatment and soil amendment combinations except for CBNG+NT. The lowest SAR was observed in the CBNG-GSB+GS treatment (1.93 $mmol^{1/2}L^{-1/2}$). SAR values in the Bt_1 and Bt_2 horizons of the CBNG-GSB treatment are similar across soil amendments. This is not true for the CBNG and CBNG-G water treatments indicating that CBNG-GSB water treatment, irrespective of soil amendment, results in faster leaching of Na^+ through the soil profile. SAR values were consistently lower in the CBNG-GSB+GS treatment for all horizons suggesting much of the Na^+ had been leached below the Bt_2 horizon. Comparisons among soil amendments in both the CBNG and CBNG-G water treatments indicate no significant differences, again, indicating that CBNG-GSB water treatment results in faster leaching of Na^+ through the soil profile.

Infiltration data indicates that CBNG water application without amendments and/or treatments results in a significant decrease in infiltration rate. In addition, there does not seem to be a difference between soil amendments for CBNG and CBNG-G water treatments. The only differences seen between soil amendments occurred in the CBGN-GSB treatment with the GS soil amendment resulting in an increased infiltration rate.

Drought conditions in the PRB are making it harder to find water for irrigation of croplands. Coalbed natural gas water has the potential to be used for cropland irrigation if managed properly. A total of 33,000 ha (36%) of irrigated land in the Powder and Tongue River watersheds are potentially suitable for managed irrigation with CBNG water. It is important to remember, however, that the soils data used for this analysis is at the 1:100,000 scale and site specific soil and water analysis should always be completed to verify soil suitability for land application of CBNG waters. In addition, crop suitability, topology, and hydrology need to be investigated. The use of the information found in this study along with good scientific techniques and best management practices (BMP's) will lead to the beneficial use of CBNG water for managed irrigation in the PRB.

These are results from one irrigation site in the PRB receiving only 31 cm of CBNG water. There was no leaching fraction used at the end of the irrigation season, which could have possibly resulted in faster leaching of Na^+ though the profile in the presence of amendments. These results indicate managed irrigation can be successful; however, more studies are needed.

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