Comparison of Soil and Vegetation Properties Using Salt Extractor and Conventional Soil Amendments From Irrigation With Coal Bed Natural Gas Product Water

by

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ABSTRACT

Coal bed natural gas (CBNG) production has become a significant contribution to the nation's energy supply. Large volumes of water are generated as a byproduct of CBNG extraction, of which this "product water" is relatively high in sodium. High sodicity reduces water quality and limits environmentally compliant disposal options for producers. Crop irrigation with CBNG product water complies with state and federal laws and is a disposal method that also provides a beneficial use to private landowners. However, this disposal method typically requires gypsum and sulfur soil amendments due to the high levels of sodium in the water, of which high levels of sodium can reduce soil infiltration and hydraulic conductivity. In this study, I tested a new product called Salt Extractor that was marketed to CBNG producers to ameliorate the negative effects of high sodicity. The experiment was conducted in the Powder River Basin of Wyoming. I used a random block design to compare the soil and vegetation properties of plots following application with CBNG product water and treatments of either Salt Extractor, gypsum and sulfur (conventional), or no treatment (control). Data was analyzed by comparing the amount of change between treatments after watering. Results demonstrated the known ability of gypsum and sulfur to lower the relative sodicity of the soil. Plots treated with Salt Extractor, however, did not improve relative levels of sodicity and exhibited no favorable benefits to vegetation.

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INTRODUCTION

Coal bed natural gas (CBNG) production has become a significant contribution to the nation's energy supply since the industry's inception just over two decades ago. According to the most recent report by the U.S. Energy Information Administration (EIA), CBNG wells produced nearly 10 percent of the nation's total natural gas in 2008. Of this, the state of Wyoming produced 29% of the national CBNG supply, which was equivalent to 551,396,801 million cubic feet (MCF) during 2008 (EIA, 2010; WOGCC, 2010)[1]. In Wyoming, CBNG has been actively produced and reported to the Wyoming Oil and Gas Conservation Commission (WOGCC) by CBNG producers since 1987, of which the Powder River Basin (PRB) supplies the largest amount. In 2008 approximately 536,200,024 MCF was produced from the PRB alone, which represented 97% of the total CBNG in the state.

With the extraction of CBNG, a byproduct of water is generated (i.e., "product water"). During 2008, 1,859,796 barrels of water per day were co-produced with extraction of CBNG in the state of Wyoming (WOGCC, 2010). Because product water is high in sodium, salinity, and occasionally other impurities, disposal is regulated and treatment is required by permitting agencies if disposed in surface waterways or groundwater. High sodicity and salinity of product water originates

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[1] Athough metric units are used throughout this document, English units are used in this section to correspond with industry terminology and reporting.

from interaction with the coal seam, carbonate dissolution from oxygenated recharge waters, and methanation processes (USGS, 2000; Freeze and Cherry, 1979).

Product water may be disposed of via injection wells, infiltration/evaporation reservoirs, or through more beneficial uses, such as crop irrigation (ALL, 2004). Disposal options depend on well proximity to treatment facilities, groundwater aquifer receiving potential, surface water regulations, capital and operating costs, and permit approval among others (Rice, 2000, personal observation). Due to the high costs associated with product water disposal, the U.S. Department of Energy (USDOE) expressed concerns that CBNG would not remain an economically viable energy resource. As a result, the USDOE conducted studies to determine costs associated with the various disposal options. Results showed that surface discharge was significantly less costly than all other disposal alternatives because expensive facilities and equipment are not required (ARI, 2002). Although not examined as a part of the aforementioned study, crop irrigation using CBNG product water is a method of surface discharge often referred to in the industry as “land application.” Land application is preferred by CBNG producers because the method is inexpensive due to less essential infrastructure (such as elaborate underground piping) and lack of regulatory jurisdiction requiring treatment and/or sampling (ALL, 2004). Crop irrigation may also provide a beneficial use of product water to landowners (personal observation) as long as the salinity and sodicity problems are ameliorated via soil amendments.

CBNG water is considered sodic due to high concentrations of sodium ion (Na^+), and is saline due to high concentration of bicarbonates (HCO_3^-) and chlorides (Cl^-). Sodicity negatively affects plant water availability at the root zone by causing soil crusting, clay dispersion, and platelet aggregation, all of which reduce water infiltration and hydraulic conductivity (Ayers and Westcot, 1985; Agassi et al., 1981; Yaron, 1968; Rhoades and Ingvalson, 1969; Quirk and Schofield, 1955; Frankel et al., 1978). Salinity reduces the ability of non salt-adapted plants to take up water due to a reduction in osmotic potential in the plant roots, and specific ions associated with the salt can be toxic to plants either from direct contact or by affecting the uptake or metabolism of essential nutrients (USSL, 1954).

While salinity can be managed through leaching with a higher rate of watering, soil amendments such as gypsum and sulfur are commonly used in the CBNG industry to ameliorate the negative effects of soil sodicity on plant growth (Ayers and Westcot, 1985; Johnston et al., 2008). Gypsum ($CaSO_4 \cdot 2H_2O$) contains calcium, which is nearly absent from CBNG product water due to cation exchange with sodic shales (Wheaton and Metesh, 2002; Voast, 2003). When sodic irrigation water contacts the gypsum, dissolution of the calcium (Ca^{+2}) ions occurs and Na^+ is replaced by Ca^{+2} on the negatively charged soil clay particle. Sodium is replaced due to the greater charge and higher concentration of calcium as part of the gypsum application calculation (Shainberg and Letey, 1984; Mitchell, 1964; Harvey and Brown, 2005). Soil amendments of elemental sulfur

(S), on the other hand, furnishes calcium if lime is present in the soil. The sulfur is acted upon by soil bacteria and oxidized to form sulphurous and sulphuric acid, which then reacts with lime to release calcium (Ayers and Westcot, 1994).

Finding a successful crop irrigation alternative without the expense of seasonal soil amendments or negative effects on crop growth is a driving factor within the industry. Becausee of this, several products have been explored to reduce sodium and salt concentrations in saline-sodic CBNG product waters. One of these products on the market is called "Salt Extractor" (SE), which has been developed by the company, Petrogenesis. Although untested in the CBNG industry, Petrogenesis claims that SE improves the permeability of soils irrigated with CBNG product water and will also "enrich" soil quality and contribute to increased crop production. According to Petrogenesis, SE is effective in remediating soils from the impacts of sodium salts in the crude oil industry and anticipates similar success in the CBNG industry. According to the Material Safety Data Sheet, SE is composed of water, enzymes, phosphoric acid, urea, 70 trace minerals, biopolymers, growth regulators, potassium hydroxide, fulvic acid, and Leonardite extract. Additionally, SE is 8% humic acid and 2% fulvic acid, both of which are collectively known as humic substances. The primary factor contributing to the effectiveness of SE according to the product developers is the presence of these humic substances.

To test these claims, I compared the effects of SE and conventional soil amendments (gypsum and sulfur) on soil properties and plant growth after irrigation with CBNG product water. I expected that soils treated with SE would exhibit lower salinity and sodium ratios than soils receiving no treatment (control) or those treated with gypsum and sulfur (conventional). Additionally, I expected that plots treated with SE would be well suited for plant growth. Specifically, I expected that plots treated with SE would have higher above-ground standing plant biomass, and that these plants would have greater forage quality (contain more nitrogen and crude protein) than plants in controls or conventionally treated plots. For explanatory purposes, I also measured a suite of soil properties related to soil quality, including magnesium and calcium concentration, cation exchange capacity (CEC), and pH.

Background

Coal bed natural gas is a gaseous hydrocarbon that occurs in coal seams and formed as a result of biogenic and thermogenic processes (Schenk et al., 2003). Over 50 million years ago, swamps and bogs covered much of the continental United States (U.S.) (Flores et al., 1999). During this time, the Rocky Mountains, including the Big Horn Mountains that surround the PRB, began to uplift, causing floods of debris to deposit on the peat in adjacent basins (Munn, 2001). As a result of the heat and pressure from burial, temperature increased and coal began to form from the decaying plant matter. Bacteria began to produce biogenic methane during coalification as a by-product of anaerobic respiration (USGS, 2003). After the coal was formed and temperatures exceeded 50 degrees Celsius due to the excessive sediment burial, thermogenic processes began to generate additional methane. The methane in the PRB is believed to be mostly derived from biogenic processes due to the absence of sulfate (Rice and Claypool, 1981; Rightmare, 1984; ALL, 2002).

Coal bed natural gas is liberated by drilling wells into coal seams that contain methane that is trapped by the pressure of groundwater. Releasing the hydrostatic pressure of groundwater by drilling into the coal seams frees the methane that is present (ALL, 2002). As the coal is de-watered by the well bore, methane is released and desorbed, transported up the well shaft with the water, and the gas is separated from the water at the surface (USGS, 2003). Methane is transported to a compression facility for sale, and product water is transported to a disposal site (USGS, 2000; Personal Observation).

Becausee CBNG is one of the purest forms of natural gas, once gases are extracted, processing is not required prior for use by consumers. Other conventional forms of natural gas extraction may require oil separation processes, such as glycol dehydration; liquid gas separation of ethane, propane, butane, and pentanes; and “acid gas” removal of sulfur, carbon dioxide and nitrogen. Processing natural gas from these other conventional methods involves large contributions of greenhouse gases such as methane, carbon dioxide, and nitrous oxide due to internal combustion engines, fugitive gas release, and venting and flaring among others. Because CBNG is pure methane, it only requires compression in order to inject the gas into a distribution line for use by consumers (WRAP, 2009).

Despite the beneficial effects of clean air quality, the production of CBNG is controversial due to the co-generation and subsequent disposal of high volumes of sodic and/or saline product water. The extent of sodicity in soil or water is often expressed using the sodium absorption ratio (SAR) index, which is the ratio of sodium ions to calcium and magnesium ions in the soil solution $[(Na/Ca+Mg)^{1/2}]$ (Quirk and Schofield, 1955). Exchangeable sodium percentage (ESP) is also used to evaluate sodicity, and is expressed as the ratio of exchangeable sodium ions to all other exchangeable ions [(100 x exchangeable Na)/(exchangeable Ca + Mg + Na + K + Al)] (Sumner 1993). Although the United States Salinity Laboratory (USSL) considers soils to be sodic and thus adversely affected when the ESP is greater than 15%, other studies have found that soils exhibit negative sodic effects with ESPs as low as 2-3% and depend on the soil texture, particularly clay (USSL, 1954; Agassi et al., 1981; Kazman et al., 1983; Greene et al., 1978). Exchangeable sodium percentages in the Powder River Basin are not available at a broad scale, but ESP in the Powder River Basin can be estimated as SAR = 0.8 x ESP (Bauder et al., 1997). Product water in the Powder River Basin typically has SAR values ranging from 5 to 7; therefore, ESP values range from 6.25% to 8.75 % (Rice et al., 2002; Bauder et al., 1997). These ESP values may not be considered sodic to USSL, but because the PRB generally consists of soils high in clay content, negative effects from sodicity are likely (USSL, 1954; Rice et al., 2002; Bauder et al., 1997).

Salinity is often measured as total dissolved solids (TDS) and/or electrical conductivity (EC) (Grattan, 2002). Typically, PRB CBNG product water TDS ranges between 270 and 2,720 mg/L, while later studies suggest that the TDS of CBNG product water varies between 200 mg/L and 170,000 mg/L (USGS, 2003). According to Ayers and Westcot (1994), severe effects to crop water availability occur with a TDS greater than 2,000 mg/L.

METHODS

Site Description

I tested the effects of SE on soil and plant properties in a pasture on private land approximately five miles northeast of Sheridan, in Sheridan County, Wyoming (latitude 44.949682, longitude -106.822434). The site is in the northwest quarter of the northwest quadrant of Section 1, Township 57 North, Range 83 West. This site was chosen based on landowner cooperation, CBNG product water access, and relatively minimal land use.

The site occurs within the Tongue River drainage, which is part of the larger Powder River Basin draining north into Montana. The perennial Prairie Dog Creek is about one mile to the east and the intermittent Coutant Creek is approximately one half mile to the west and south. Terrain within the general area is rolling and the site is 1,111 m above mean sea level. The Badger Hills are nearly four miles east, and the more precipitous Big Horn Mountains are about 20 miles west. Within the immediate site boundaries, the land slopes at approximately 4% to the northeast. The site is centered among a landscape patchwork of CBNG infrastructure including wells, reservoirs, and access roads, in addition to agricultural crops irrigated with CBNG product water. The nearest CBNG wells and reservoirs are greater than 300 m from the site boundaries. Annual average rainfall at this site over the last thirty years is 30.6 cm. May and June receive the highest amounts of rainfall, averaging approximately 5 cm for each of these two months. Rainfall is lowest between December and February, averaging less than 1.3 cm per month (WRCC, 2010).

Current and historical land use within the boundaries of the project site is horse grazing. Vegetation cover in the project area is short grass prairie with big sagebrush (*Artemisia tridentata* var. *wyomingensis)*. Grass species are predominantly western wheatgrass (*Pascopyrum smithii*), interspersed with Idaho fescue (*Festuca idahoensis*) and non-native Japanese brome (*Bromus japonicus)*. Soils are of the Worfka-Shingle-Samday complex, which consists primarily of shallow, well-drained, loams and clay loams. Specifically, the Worfka series is clayey, smectitic, mesic, shallow Ustic Haplargids; the Shingle series is loamy, mixed, superactive, calcareous, mesic, shallow Ustic Torriorthents; and the Samday series is clayey, smectitic, calcareous, mesic, shallow Ustic Torriorthents (NRCS USDA, 2010).

Experimental Design

In mid-July to mid-September 2006, product water from CBNG wells was piped above ground to an agricultural-sized sprinkler to irrigate 18 experimental plots containing short-grass prairie vegetation with some sage-brush shrubs. These 18 plots comprised six treatments assigned randomly, with three blocks of each treatment to control for the effects of slope, aspect, and variations in sprinkler watering pattern. Three of these treatments were not applicable to this study; thus, I will be reporting on the results from the remaining three treatments, including a control (CBNG product water applied with no soil amendments); conventional (CBNG product water applied with both gypsum and sulfur) and SE (CBNG product water applied with Salt Extractor).

Each plot was 4.5m x 4.5m, comprising a total experimental area of 27.4m x 16.8m (Figure 1). A 1.5m trench was constructed between the three blocks in order to prevent water running onto adjacent plots. Each of the blocks was marked for the duration of the experiment using stakes and string at each corner. Fencing was installed around the perimeter of the project site to deter horses from disrupting the experiment.

The source CBNG product water utilized for this experiment had a pH of 8.4, an EC of 2.6 mmhos/cm, and SAR of 62.4. Based on these water qualities, gypsum and elemental sulfur (sulfur) amendments were spread by hand at the rate prescribed by Ayers and Westcot (1994) (6 tons/acre and 1200 lbs/acre respectively). Salt Extractor was applied at a rate prescribed in the product manual, which consisted of an initial treatment prior to watering, and a monthly treatment (113.6 liters/acre initial, 7.6 liters/acre monthly). Salt Extractor was spread with a backpack sprayer after the first pass of the sprinkler to simulate injection into a sprinkler line as recommended in the product manual.

Watering

Product water was applied with a Big Gun sprinkler with a radius of approximately 42.7 m. In order to achieve uniform watering and adequate overlap, the sprinkler was consistently rotated between five locations prior to each watering event. The locations are numbered 1 through 5, running parallel and west of Block A (Figure 1). Sprinkler watering stations were positioned by calculating the spray distance verses experimental unit size to achieve consistent overlap for each plot to the extent possible. Thus, sprinkler watering stations were 9.1 m apart and 1.5 meters above the Block A plots.

Watering was conducted three days per week (Monday, Wednesday, and Friday) beginning in mid-July and ending in mid-September, 2006. Watering duration was four hours. Watering was not conducted on scheduled watering days if rain occurred. Rain gauges were placed in the center of each plot and oil was kept in each rain gauge to eliminate evaporation. Rain gauge data from the last watering session was collected before each new watering event (20 days total).

Soil Samples

Soil samples were collected before watering began, and after the 2006 watering season (mid-July and mid-September, respectively), in order to measure the change in soil properties following treatment. Three soil samples were collected at three soil depths per plot (0-15, 15-30, and 30-60 cm) to capture the movement of ions through the soil column throughout the watering season. Samples were obtained using an Oakfield hand probe with a ¾” core, drilled to the full depth of that level. Samples were placed in a resealable plastic bag and transported directly to the laboratory. Within 24 hours, soil samples were air dried and passed through a 2 mm sieve, then analyzed for EC (mmhos/cm); pH; calcium, magnesium, and sodium concentrations (meq/L); and CEC (meq/100g). The exchangeable Sodium Percentage (ESP) and sodium absorption ratio (SAR) were calculated after ion concentrations were obtained.

Electrical conductivity was measured according to Method 10-3.3 of Weaver and Mickelson (1994). Soil samples were dried and sieved, and followed by the addition of de-ionized water that was mixed until saturated. The saturated paste was transferred to a funnel and vacuumed, and then measured with a conductivity meter (Ayers and Westcot, 1994; USSL 1954). The pH was measured according to Method 10-3.2 of Weaver and Mickelson (1994), using the saturated paste mixture obtained from the conductivity analysis then measuring with a pH meter.

Calcium, magnesium, and sodium concentrations were analyzed according to Environmental Protection Agency (EPA) Method 6010-B (EPA 2007) in which the same saturated pastes as mentioned previously were brought to a solution and measured with an inductively coupled plasma-atomic emission spectrometer (ICP-AES). Reagents for these elements included suspending or dissolving $CaCO_3$, MgO, and NaCl, respectively and diluting in (1:1) HNO_3.

Cation exchange capacity was measured according to the protocol outlined in the Agriculture Handbook 60 (USSL, 1954). Soil samples were centrifuged and decanted through several iterations and then treated with reagents of sodium acetate, ethanol, and ammonium acetate. Following these treatments, the sample was treated again with centrifuging, decanting, evaporation, and reagents of ammonium acetate, nitric acid, hydrochloric acid, and acetic acid. From this, a saturated paste was prepared as described in the previous measurement of conductivity. Finally, soluble cation concentration was obtained using flame photometry.

Lastly, ESP was calculated by dividing the exchangeable sodium (meq/100 g soil) by the cation exchange capacity (meq/100 g soil), and multiplying by 100 (USDA 1993). The SAR was also calculated from the concentrations of sodium, calcium, and magnesium in the saturation extract, and determined by the equation: $SAR = (Na/Ca+Mg)^{1/2}$.

Vegetation Data

Natural vegetation properties were measured in response to experimental treatments to assess an indication of adverse soil affects from sodicity. The response in plant properties was measured as the relative change in biomass, total aboveground crude protein concentration, and total digestible nutrients (TDN) between the beginning (mid-July) and end of the watering season (mid-September) 2006. Crude protein and TDN are common forage potential analyses in the livestock industry. Crude protein is the amount of protein based on nitrogen present in plant matter, and TDN is a measurement of energy supplied by feed based on amounts required per day. Additionally, Ca^{+2}, Na^{+}, and Mg^{+2} concentrations were obtained in order to detect ion uptake by plants.

Branches, deciduous tree leaves, and other non-herbaceous materials were avoided systematically when a shrub occurred within one of the randomly located subsamples. All herbaceous plant matter was clipped at ground level and collected within three randomly located quadrats (0.6 m x 0.6 m) per plot. The left half of the quadrat was clipped prior to the watering season (mid-July) and the right half was clipped at the end of the watering season (mid-September). Quadrat corners were flagged and marked for relocation purposes. Clippings per quadrat were placed in brown paper bags and labeled according to subsample and plot number. Samples were transported to the laboratory and oven dried at 10 degrees Celsius within 24 hours.

Once dry, the samples were ground in a Wiley mill, followed by passing the ground sample through a 2 mm screen. The sample was mixed and then ground with an Udy Mill, followed by passing the ground sample through a 0.5 mm screen. Biomass was then obtained by weighing. Crude protein concentration was analyzed by combustion using a nitrogen analyzer, as prescribed by Cuniff (1995) in the Official Methods of Analysis of AOAC International, Method 968.06.

Total digestible nutrients were measured according to techniques established by Huang et al. (2004). The oven dried samples were placed in vessels after being powdered, and then diluted with concentrated HNO_3. After sitting overnight, the samples were then heated for 10 minutes at 75° C, heated at 109° C for 15 minutes, cooled for 15 minutes, diluted with 1 mL of H_2O_2 , and heated again at 109° C for 15 minutes. Samples were then diluted with triple-deionized water to 20 mL and analyzed with an ICP-AES spectrometer.

Sodium, calcium, and magnesium concentration of plant tissue were quantified using methods prescribed by Cunniff (1995), Method 985.01 in the Official Methods of Analysis of AOAC International. Samples were ashed and then digested in acid. Following this treatment, an Aerosol Collector Pyrolyser (ACP) spectrometer was used to analyze the solution for minerals. Each element was quantified by comparison based on a standard curve for each mineral.

Statistical Analyses

Statistics were performed using WinStat Version 2009.1. A one-way Analysis of Variance (ANOVA) was conducted on the amount of water applied to each plot in order to determine whether water application confounded treatment comparisons (9 treatments). To determine whether there was a significant difference between the initial soil and vegetation samples (collected mid-July) and the final soil and vegetation samples (collected at the end of the watering season after treatments were applied in mid-September), the amount of change was quantified by averaging each of the three subsamples per plot according to treatment. Then, the initial results were subtracted from the final results for all soil properties based on treatment type (N=3). This calculation was followed with two-way ANOVA tests with treatment and block as fixed factors. Finally, multiple comparison tests using a t-distribution were conducted following a Bonferroni correction for all treatment types (and at the three different depth levels for soil analyses). Assumptions of homogeneity and normal distribution were tested using the Bartlett test and the Kolmogorov-Smirnov test, respectively, and skew, and kurtosis were also verified using the Jarque–Bera test.

RESULTS

Watering Data

Plots were watered with CBNG product water for 20 days over a period of approximately two months. An average of 3 cm of water was applied to each plot per day, although the amount of water per day actually varied between 0 inches and 10.2 cm depending on the day and the location of the plot. The variations were due to wind and constraints associated with watering assistance. Despite the variations, there was no significant difference in applied water between plots over the experimental period according to a one-way ANOVA with plot as the fixed factor ($N = 9$, $DF = 8$, $f = 0.692$, $p = 0.698$). Applied water averages and the associated standard errors are illustrated in Figure 3.

Soil Properties

Soil properties varied by treatment but not by block. For all soil variables measured, there were no significant differences between blocks (two–way ANOVA, treatment and block as fixed factors, $df = 2$, $p \leq 0.05$). Thus, averages of three subsamples per plot according to treatment, both before and after the experimental treatment, were used in subsequent analyses (Table 1) (all variables were normally distributed). Average values of soil variables at the end of the experiment were subtracted from those average values at the beginning of the experiment and subjected to a one-way ANOVA (treatment type as fixed factor), using a Bonferroni correction, followed by post-hoc multiple comparison tests (Table 2).

Plots treated with SE exhibited no significant improvements compared with control and conventional treatments ($p \leq 0.008$). Conventional treatments of gypsum and sulfur, on the other hand, were successful in significantly lowering the SAR ($p \leq 0.008$) to nearly half of the values than plots with other treatment types at depths between 0 and 15 cm. There were no significant differences between treatments of SAR at other depths, however, and there were no significant differences between any other treatments.

Vegetation Data

For all plant results, there were no significant differences between blocks (two–way ANOVA, treatment and block as fixed factors, $DF = 2$, $p \leq 0.05$). Also, all data were normally distributed. Thus, averages of the three subsamples per plot according to treatment, both before and after the experimental treatment, were used in subsequent analyses (Table 3). Average values of plant variables (biomass, crude protein, and TDN) at the end of the experiment were subtracted from initial values at the beginning of the experiment, and exhibited no significant differences between the control and treatments (Table 2).

Analysis of chemical composition in vegetation in plots treated with gypsum and sulfur exhibited an increase of several magnitudes in percent calcium compared to other treatment types ($p \leq 0.006$). During the calcium analysis, the ANOVA significance tests failed the Bartlett test, indicating a significant difference in the variances. For this reason, the Kruskal-Wallis analysis was used since it is not dependent on homogeneous variances. The Kruskal-Wallis analysis indicated that calcium was significantly different between treatments ($p < 0.006$). There were no other significant differences.

DISCUSSION

Results from both the soil and vegetation results indicate that SE does not remediate the effects of sodicity and salinity associated with land application of CBNG product water.

Soils

Salt Extractor does not ameliorate the negative effects to soil from sodicity or salinity following land application of CBNG product water. Conventional treatments, on the other hand, successfully lowered the SAR in the first 15 cm, resulting in less sodic soils. There were no significant differences between treatments of SAR at other depths, which is probably due to the large size of the gypsum pieces tending to remain on the surface, and a longer watering period may be necessary.

Impacts to soils treated with gypsum and sulfur are expected to be less due to the lower SAR values. Essentially, the reduction in SAR indicates that there is relatively less sodium than other exchangeable cations, which in this case is likely derived from the calcium associated with the gypsum treatment. Due to the greater number of calcium ions from the gypsum treatment, the calcium ions will adsorb to the clay particle more readily rather than the sodium ion. Calcium ions adsorb to the clay particle in order of preference determined by size of the particle, Coloumb’s Law and Le Chatelier’s principle. Coloumb’s Law establishes that the force of attraction of two charged particles is equal to the product of its charges; Le Chatelier's Principle affirms that the larger concentration of ions takes precedence despite charge or particle size. Likewise, the order of cation exchange preference is according to the lyotropic series: $Al^{+3} > Ca^{+2} > Mg^{+2} > K^{+} > Na^{+} > Li^{+}$ (Mitchell, 1964). Therefore, unless sodium ions compose more than about 15% of the exchangeable ions in the soil column, calcium as a product of gypsum treatment is more likely to bond to the clay particle (Harvey and Brown, 2005).

Calcium ions are larger than sodium ions, covering less surface area on the soil clay particle, and resulting in a surface with less charge. Likewise, clay particles do not repel each other contributing to the deleterious effects of seal formation, dispersion, clay platelet aggregation, and swelling (Quirk and Schofield, 1955, Frankel et al., 1978). Dispersion and platelet aggregation cause a decrease in infiltration, which reduces hydraulic conductivity, and causes surface crusting (Ayers and Westcot, 1985, Agassi et al., 1981, Yaron, 1968; Rhoades and Ingvalson, 1969).

Effects to soil can be assessed according to Ayers and Westcot's salinity/sodicity model illustrated in Figure 5. Using the conductivity and SAR levels in Table 1, it follows that plots treated with gypsum and sulfur result in no effect to the rate of infiltration. In control plots, however, soils would exhibit slight to moderate reductions in rate of infiltration. Most notable, however, in plots treated with SE the low salinity and high SAR contributes to a severe reduction in the rate of infiltration.

I expected an increase in calcium in conventionally treated plots due to the addition of gypsum, which contains calcium, and because other studies have shown an increase in exchangeable calcium following gypsum treatments (Faverette, 2008; Farina et al., 2000b; Toma et al.,1999; Syed-Oinar and Sumner, 1991; Shainberget al., 1989). However, calcium concentrations were not significantly different than other treatment types. The lack of calcium in the soil may have been due to the effects of leaching, although this should have been captured in lower soil depth results. The most probable reason for the lack of calcium in the soil was the demonstrated uptake of calcium in plants, as discussed in the next section.

Vegetation

Salt Extractor did not contribute to greater plant biomass, crude protein, or total digestible nutrients compared with conventional treatments and control plots. In fact, neither conventional or control treatments contributed to an increase in these variables. When average resultant biomass data from all experimental units were compared with baseline average biomass data from all experimental units via an independent t-test, though, biomass was significantly higher in the former, indicating plant growth (N=9, p=0.004). Plant growth is presumed to be a result of watering and seasonal growth; however, plant growth (i.e., biomass) was not measured in un-watered plots for comparison.

Due to the improved infiltration from the reduced SAR in plots treated with gypsum and sulfur, I expected associated plots to have significantly more biomass. My expectations were derived from a four-year study by Vance et al. (2008), which examined the affects of land application of saline-sodic CBNG product water irrigation on soils, native plants, and agricultural crops in the PRB. Studies showed that although biomass increased, species diversity decreased. My experiment was not in effect long enough to detect changes in species diversity, but the lack of increase in biomass, crude potential, and TDN may have been because the vegetation had a degree of sodium tolerance, so there would be no difference between control plots and gypsum and sulfur-treated plots. As a matter of fact, western wheatgrass, the dominant species within my plots, is known to have a low to moderate salinity tolerance according to various studies. For instance, Moxley et al. (1978) demonstrated that for three varieties of wheatgrass, the salt tolerance index ranged between 7 and 8.5 mmhos/cm, which correlates with a "low" to "medium" salt-tolerant plant according to USSL (1954). The USSL (1954) defines the salt tolerance index as the EC of the soil saturation extract at which yields are reduced 50% from the control. In another study by Aschenbach (2006), western wheatgrass exhibited relative growth rates exceeding those of a widely recognized halophyte, inland saltgrass (*Distichlis spicata*), in response to increasing levels of salinity; inland saltgrass has been studied and recognized as a halophyte by Tiku (1976); Parrondo et al. (1978); Kemp and Cunningham (1981); Wrona and Epstein (1982); Enberg and Wu (1995); and El-Haddad and Noaman (2001). In addition, western wheatgrass is known to have a high drought tolerance (Lauriault et al. 2005), so the higher sodium as indicated by the SAR values, inhibiting water penetration to the root zone, may not have affected this plant. I would expect that if salinity was higher than 7 to 8.5 mmhos/cm or SAR was considerably higher, there would be a significant difference between control and gypsum and sulfur plots.

Calcium uptake in vegetation was detected in plots treated with gypsum and sulfur. I expected an increase in biomass in conventionally treated plots because calcium is an important part of plant cell wall structure and facilitates transport and retention of other elements, neutralizes acids, and is related to increases in nitrogen content (Parker and Trugg, 1920). It should be noted, though, that too much calcium can be detrimental to plant production (Parker and Trugg, 1920). Increasing calcium may increase ammonia concentrations in soil solution by competition for soil exchange sites which can interfere with nutrient availability and plant growth (Favaretto, 2008).Therefore, although there was an increase in calcium in plant matter, calcium may have reduced biomass due to the effects to physiology and metabolic processes.

The lack of an increase in crude protein and TDN indicates that SE as well as gypsum and sulfur treatments are not direct contributors to improved plant forage potential. Crude protein is the amount of protein based on nitrogen present in plant matter, and TDN is a measurement of energy supplied by feed based on amounts required per day. Thus, none of the treatments that were part of this study were influential in increasing the amount of nitrogen and/or nutrients related to feed energy.

This study primarily focused on variables that were important to the cattle ranching industry, such as crude protein and forage potential, because that was the dominant land use prior to the arrival of CBNG development. However, there would be value in further studies measuring and analyzing reproductive output, root biomass, root:shoot ratios, and biomass per species.

Implications

Salt Extractor did not contribute to reducing the effects of sodicity. Although gypsum and sulfur reduced the SAR, and likely the negative effects of sodicity, sodium concentrations were not reduced. This study was similar to other studies in this aspect. Studies by Ganjegunte et al. (2005) involving land application with CBNG product water in the PRB indicated significant buildups of sodium in the root zones of irrigated sites. Complicating matters, poor soil drainage and high evapotranspiration rates typical of the PRB can contribute to build-up of sodium and soluble salts in soils. Because production of CBNG typically only lasts 7 to ten years, once ceased, amendments will no longer be applied and elevated sodium and salts will remain in the soil profile (Grisha et al., 2005; Vance, 2008). Vance (2008) concluded that land application with CBNG product water has the potential to accumulate sodium and increase soluble salts in the root zone, which can lead to a reduction in species diversity and species composition.

Further contributing to the issue of sodium build-up is the relatively low cost of land application with gypsum application. The cost for gypsum is approximately $40/ton at a typical application rate of 6 tons/acre for a total of $240/acre (UMES, 2004). In contrast, Peterogenesis (2006) quotes $900/acre initially with monthly applications costing $60/acre. However, SE has been proven to be ineffective as a CBNG soil amendment. Therefore, a better understanding of potential impacts to lands receiving CBNG water is essential, and cost-effective ways of improving CBNG water quality is the key to managing the enormous amount of poor quality CBNG water (Grisha et al., 2005; Grisha et al., 2006).

Preliminary studies indicate that clinoptilolite zeolite may be used to reduce sodium and salt concentrations in saline-sodic CBNG waters. Field trials are yet to be conducted, though. Zeolites are hydrated aluminosilicates of alkaline and alkaline-earth metals, and occur both naturally and commercially. Zeolite is advantageous due to local occurrence, low mining cost, and capacity to retain cations. Commercial zeolite deposits in the U.S. are associated with the alteration of volcanic tuffs in alkaline lake deposits and open hydrologic systems. Different zeolites exhibit distinctive CEC adsorption properties and cation selectivity. Clinoptilolite zeolite has a preference for larger cations, having a preference of sodium over calcium, which makes zeolites a better choice for removing Na^+ from CBNG waters. In fact, in soil column studies, zeolite materials removed significant amounts of Na^+ from CBNG waters. The study estimated that one ton of zeolite can be used to treat 750 barrels of CBNG product water to reduce SAR from 34 to 10. Zeolite technology is potentially an efficient, effective, and affordable water treatment alternative that could maximize the beneficial use of CBNG product water (Grisha et al., 2006).

TABLES AND FIGURES

Table 1. Descriptive statistics of soil properties following irrigation with CBNG product water and application of three treatment types (N=3 replicate plots per treatment).

Test	Depth (cm)	No Treatment		Gypsum & Sulfur		Salt Extractor	
		Mean	StError	Mean	StError	Mean	StError
SAR	0-15	23.57	0.42	12.18	2.89	25.77	1.47
	15-30	17.87	0.52	17.80	1.64	17.63	0.98
	30-60	11.41	1.98	16.30	4.03	9.40	3.06
Conductivity (mmhos/cm)	0-15	2.45	0.70	4.36	0.82	1.97	0.24
	15-30	2.14	0.80	2.67	0.62	1.61	0.36
	30-60	2.38	1.33	2.78	0.17	2.45	1.24
ESP (%)	0-15	15.67	0.33	7.90	2.58	19.00	1.00
	15-30	11.33	0.33	10.83	1.30	12.23	1.86
	30-60	7.43	1.17	7.60	0.53	5.70	1.91
CEC (meq/100g)	0-15	34.00	3.54	31.37	1.52	30.03	1.96
	15-30	33.10	6.76	33.03	0.78	28.90	1.05
	30-60	29.90	7.05	32.37	0.97	27.43	3.01
pH	0-15	7.93	0.12	7.53	0.12	8.03	0.09
	15-30	8.00	0.10	7.93	0.03	8.07	0.07
	30-60	7.90	0.15	7.97	0.09	7.90	0.06
Sodium as saturated paste (meq/L)	0-15	26.07	6.07	33.47	5.08	21.50	2.45
	15-30	20.83	6.74	24.53	5.48	16.23	3.37
	30-60	17.39	7.51	24.70	3.05	13.67	2.99
Magnesium as saturated paste (meq/L)	0-15	0.62	0.30	5.08	2.40	0.43	0.15
	15-30	1.03	0.78	1.41	0.81	0.92	0.63
	30-60	4.02	3.69	1.92	0.36	11.77	11.12
Calcium as saturated paste (meq/L)	0-15	2.14	1.04	17.05	7.26	0.97	0.09
	15-30	2.48	1.54	2.59	0.63	1.09	0.37
	30-60	9.02	8.24	3.33	1.03	8.64	7.49

Table 2. Difference in soil properties results following irrigation with CBNG product water and application of three treatment types (i.e., initial mean minus final mean; N=3, DF=2). Significant differences following a one-way ANOVA and subsequent multiple comparison tests are indicated by asterisks which are described in the caption below (alpha = 0.006).

Test	Depth (cm)	No Treatment		Gypsum & Sulfur		Salt Extractor		F	P
		Mean	StError	Mean	StError	Mean	StError		
SAR	0-15	6.07	0.60	-6.02*	3.42	8.97	1.51	13.22	0.006
	15-30	5.66	2.01	4.90	2.80	6.31	1.26	0.111	0.897
	30-60	4.32	0.52	9.46	4.38	4.84	1.94	1.033	0.412
Conductivity (mmhos/cm)	0-15	0.83	0.70	2.93	0.77	0.50	0.22	4.624	0.061
	15-30	-0.16	0.12	0.89	0.81	0.19	0.37	1.064	0.402
	30-60	-0.04	0.40	1.26	0.30	-0.01	0.35	4.366	0.068
ESP (%)	0-15	0.67	1.45	-8.77	3.26	5.67	0.67	12.199	0.008
	15-30	1.03	1.16	-0.50	1.80	2.90	1.10	1.501	0.296
	30-60	1.13	0.33	1.07	0.44	1.27	1.24	0.017	0.983
CEC (meq/100g)	0-15	7.80	1.76	5.77	1.89	3.10	1.63	1.793	0.245
	15-30	5.97	1.59	7.23	1.50	2.07	1.12	3.610	0.094
	30-60	4.27	1.28	6.57	1.05	3.13	1.94	1.413	0.314
pH	0-15	-0.23	0.19	-0.60	0.10	-0.13	0.18	2.397	0.172
	15-30	-0.13	0.03	-0.37	0.07	-0.17	0.09	3.583	0.095
	30-60	-0.17	0.03	-0.17	0.12	-0.13	0.03	0.067	0.936
Sodium as saturated paste (meq/L)	0-15	9.63	6.47	18.43	4.92	6.53	2.46	1.585	0.280
	15-30	2.93	3.93	9.07	6.38	3.97	4.07	0.445	0.661
	30-60	3.95	5.92	14.03	3.33	2.98	2.36	2.170	0.195
Magnesium as saturated paste (meq/L)	0-15	0.26	0.29	4.71	2.31	-0.09	0.03	3.957	0.080
	15-30	-1.11	0.89	0.34	0.96	0.00	0.34	0.934	0.443
	30-60	-2.49	1.76	-0.27	0.56	-0.18	1.60	0.858	0.470
Calcium as saturated paste (meq/L)	0-15	0.73	1.00	16.05	7.21	-0.11	0.10	4.683	0.060
	15-30	-3.70	2.97	0.30	1.58	-0.58	0.06	1.174	0.371
	30-60	-1.44	0.27	0.19	1.57	-0.26	2.84	0.199	0.824

*Gypsum and sulfur treatment is significantly different than all other treatments.

Table 3. Mean vegetation results per plot following irrigation with CBNG product water and application of three treatment types (N=3).

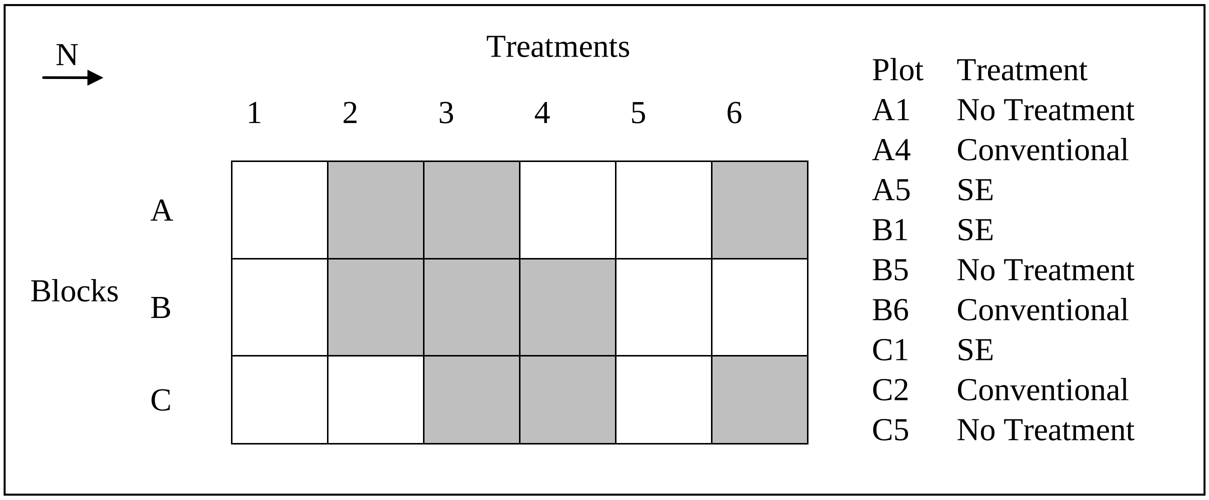
Test	No Treatment		Gypsum & Sulfur		Salt Extractor	
	Value	StError	Value	StError	Value	StError
Biomass (g)	26.1	2.6	20.3	3. 5	25.00	6.5
Na (%)	0.4	0.04	0.3	0.05	0.5	0.04
Mg (%)	0.09	0.02	0.09	0.02	0.07	0.02
Ca (%)	0.6	0.08	3.0	0.66	0.5	0.03
Crude Protein (%)	8.7	0.49	9.0	0.31	9.2	0.25
TDN (%)	52.7	1.07	56.5	1.66	54.3	0.80

Table 4. Calculated change in vegetation biomass and chemistry following irrigation with CBNG product water and application of three treatment types. Change was measured as the difference between initial and final vegetation results (i.e., initial mean minus final mean (N=3, DF=2). Significant differences following a one-way ANOVA and subsequent multiple comparison tests are indicated by asterisks which are described in the caption below (alpha = 0.008).

Test	No Treatment		Gypsum & Sulfur		Salt Extractor		F	P
	Value	StError	Value	StError	Value	StError		
Biomass (g)	16.6	8.06	27.7	9.62	15.0	1.78	0.899	0.455
Na (%)	0.24	0.06	0.20	0.08	0.23	0.09	0.064	0.938
Mg (%)	0.09	0.02	0.09	0.02	0.07	0.02	0.553	0.583
Ca (%)	0.24	0.08	2.59*	0.65	0.18	0.04	13.377	0.000
Crude Protein (%)	2.75	0.27	3.24	0.59	3.85	0.40	1.577	0.227
TDN (%)	0.97	1.38	2.12	1.90	2.75	0.80	0.394	0.678

*Significant difference between gypsum and sulfur and all other treatments.

Figure 1. Experimental design. Each plot was randomly assigned a treatment. Grayed boxes represent experimental plots that are not part of this experiment.



Plot	Treatment
A1	No Treatment
A4	Conventional
A5	SE
B1	SE
B5	No Treatment
B6	Conventional
C1	SE
C2	Conventional
C5	No Treatment

Figure 2. Sprinkler rotation locations (indicated with circles and numbers 1 through 5). Letters with numbers represent plots with assigned treatments as listed in Figure 2.

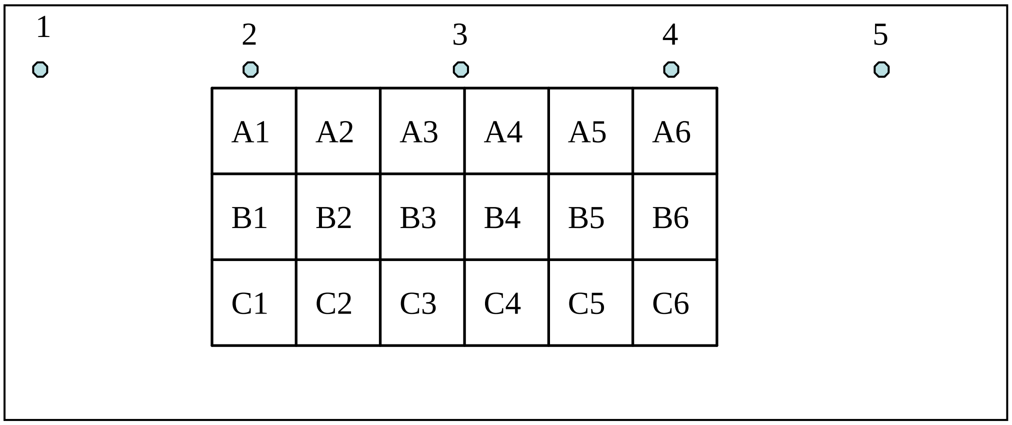


Figure 3. Average rates of water application (cm/day). Water was applied at this rate for a period of two months. Columns represent means and bars represent standard errors.

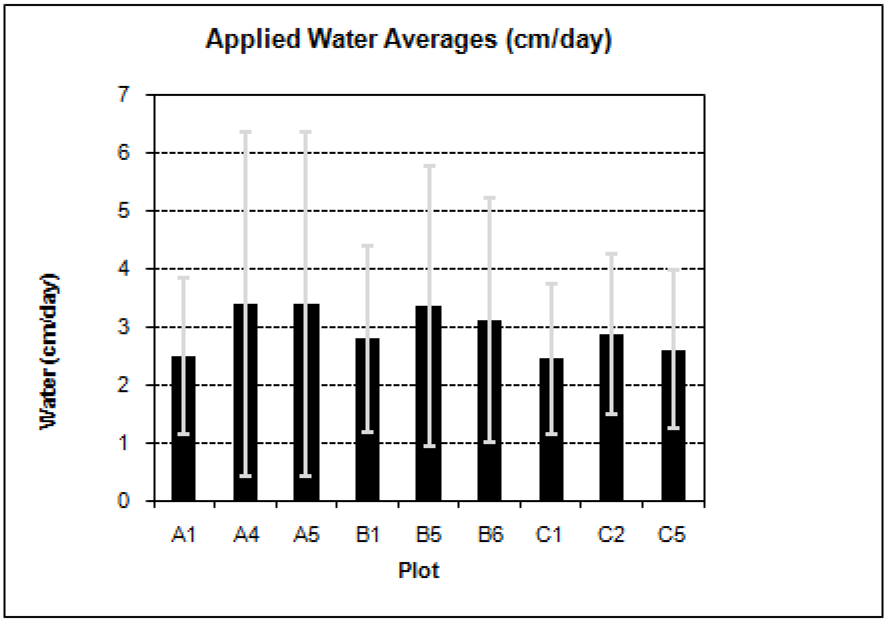


Figure 4. Calculated change in soil property results following irrigation with CBNG product water and application of three treatment types. Change was measured as the difference between initial and final soil results (i.e., initial mean minus final mean; N=3, DF=2).

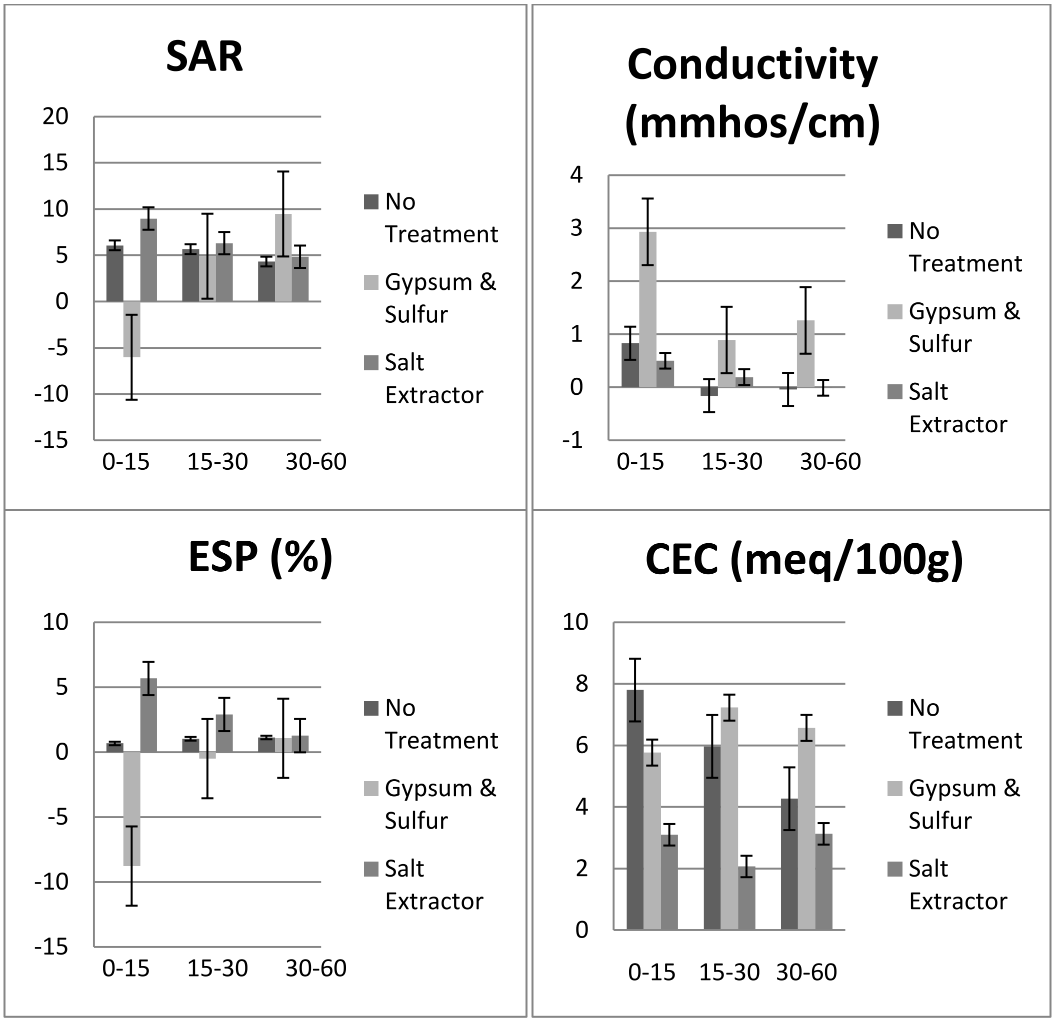


Figure 4 (Continued). Calculated change in soil property results following irrigation with CBNG product water and application of three treatment types. Change was measured as the difference between initial and final soil results (i.e., initial mean minus final mean; N=3, DF=2)

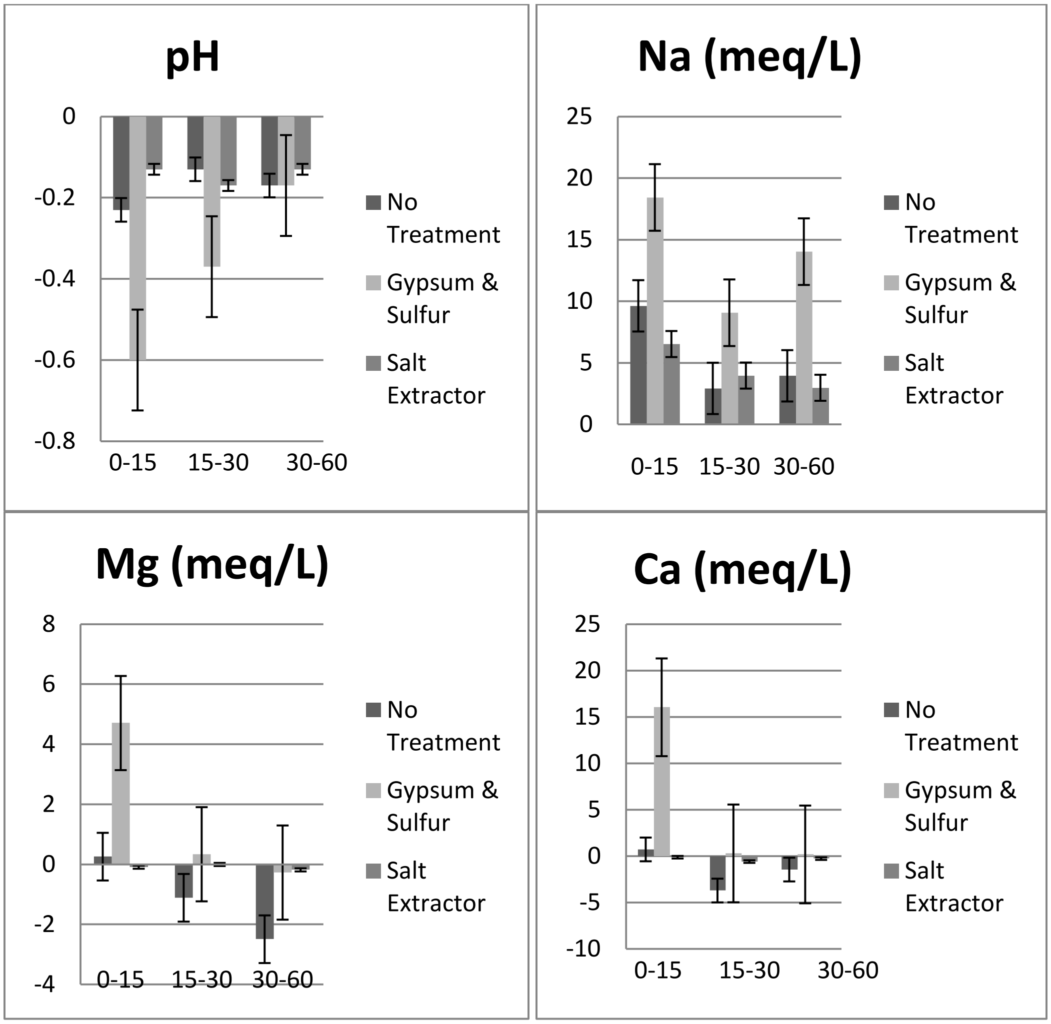
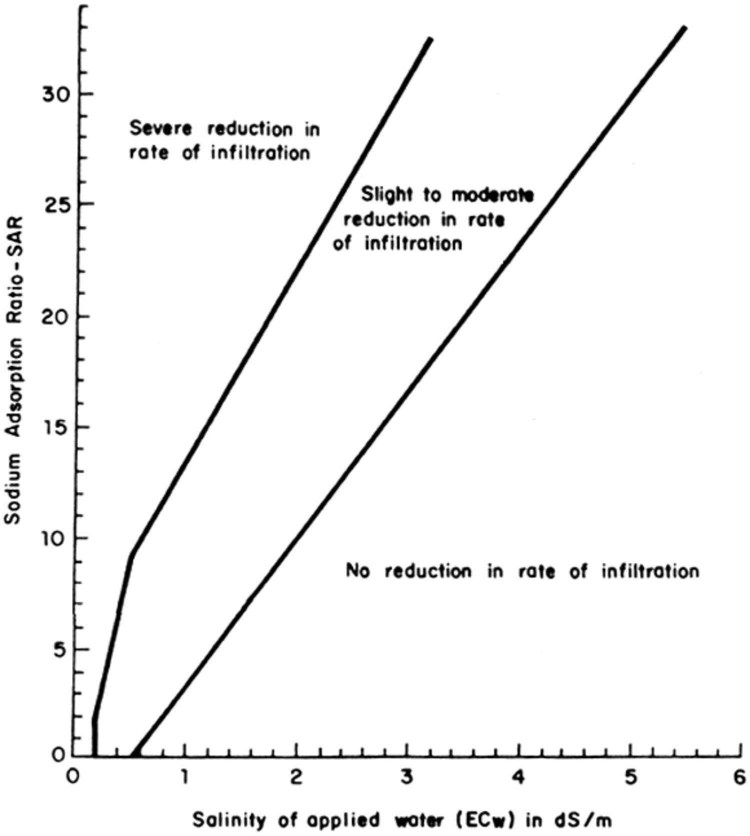


Figure 5. Relative rate of water infiltration as affected by salinity and SAR (Ayers and Westcot, 1994).



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