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Leaching and reclamation of a biochar and compost amended saline–sodic soil with moderate SAR reclaimed water

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ABSTRACT

Remediating saline–sodic soils with organic amendments is increasingly seen as a cheaper and sustainable alternative to inorganic materials. The reclamation potential of biochar, biosolids and greenwaste composts applied to a saline–sodic soil was evaluated in a laboratory leaching experiment using moderate SAR reclaimed water. Treatments included biochar, biosolids co-compost, greenwaste compost (all applied at a 75 t ha^{-1} rate), gypsum (50% soil gypsum requirement), biochar + gypsum, biosolids + gypsum, greenwaste + gypsum and a non-amended control. All treatments were subjected to a one month incubation after which, soils were filled in columns and leached using reclaimed water until 7 PV of water had passed. Cumulative leachate losses of Na^+, Ca^{2+}, and Mg^{2+} were evaluated in addition to soil properties after leaching. Results show that leaching with moderate SAR water was effective in reducing the soil salinity and sodicity of all soils, irrespective of amendment application. However, incorporating biochar and composts significantly enhanced this effect. Salt leaching was higher in soils treated with organic amendments. Cumulative leachate losses of cations were significantly higher from biochar and compost treated soils compared to gypsum and unamended controls. Improvements in soil aggregate stability and saturated hydraulic conductivity were prominent in compost treated soils. After leaching, soil analyses indicated that organic amendments lowered significantly more soil EC_e, ESP and SAR than that of the control soils and saturated the exchange complex with Ca^{2+}. Soil pH was significantly reduced and CEC was significantly increased in only compost treated soils. Although individual organic amendment applications proved to be significant enough to remediate a saline–sodic soil, combined applications of gypsum and organic amendments were more effective in improving soil properties directly related to sodium removal including sodium leaching, hydraulic conductivity, ESP, and SAR, and therefore could have a supplementary benefit of accelerating the reclamation process.

1. Introduction

Soil salinization is defined as an excessive accumulation of salts within the soil profile to the extent that it decreases plant growth. It has been one of the major environmental problems threatening agricultural productivity since ancient times (Rengasamy, 2006). Salt-affected soils are in general classified as; saline, sodic or saline–sodic, based on their respective electrical conductivity (EC_e) and sodium adsorption ratio (SAR) of the saturated paste extracts or the sodium on the exchange sites (exchangeable sodium percentage, ESP) (Richards, 1954). Saline soils are characterized by having high EC_e values (>4 dS m^{-1}) while saline–sodic soils have both high EC_e (>4 dS m^{-1}) and SAR (>13) of the saturation extract and an ESP > 15. Sodic soils are those which have low EC_e (<4 dS m^{-1}) but have high SAR's (>13) or ESP > 15 (Richards, 1954). Saline–sodic soils can be considered to be highly degraded and least productive due to their simultaneous effect of salinity and sodicity on soil physical, chemical and biological properties. High salinity retards plant growth by creating osmotic imbalances and specific ion toxicities. On the other hand, sodicity deteriorates soil physical structure by clay swelling and dispersion due to high concentrations of Na^+ in the soil solution or at the exchange phase, forming dispersed soils (Rengasamy and Olsson, 1991). Dispersed saline–sodic soils are compacted and have reduced water infiltration and hydraulic conductivity, which play a major role in water, air, and solute movement through the soil profile (Shainberg and Lety, 1984; Suarez et al., 2006). In addition to physical effects, chemical, biological and biochemical property deteriorations have been well reported in literature for saline and sodic soils (García and Hernández, 1996; Ghollarata and Raiesi, 2007; McClung and Frankenberger, 1985;

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Pathak and Rao, 1998; Rietz and Haynes, 2003; Setia et al., 2012; Wong et al., 2008).

Reclamation of a saline–sodic soil requires the removal of sodium from the soil exchange sites into soil solution by divalent cations (Ca^{2+} preferably) to promote soil flocculation. Subsequently, salts are leached from the soil profile (Abrol et al., 1988). Extensive research has been conducted over decades with respect to use of chemical amendments to provide Ca^{2+} to replace Na^{+} on the exchange sites (Brinck and Frost, 2009; Qadir et al., 2002). Gypsum ($CaSO_4{\cdot}2H_20$) is the most commonly used chemical amendment and its efficiency as a supplier of Ca^{2+} to offset Na^{+} on exchange sites has been long studied and is an established technology to remediate saline–sodic soils (Ghafoor et al., 2001; Mace and Amrhein, 2001; Oster et al., 1999). Other chemical amendments such as sulfur and sulfuric acid have also been used to remediate saline–sodic soils by facilitating native calcite dissolution to release required calcium into soil solution (Amezketa et al., 2005; Sadiq et al., 2007; Zia et al., 2007). Alternatively, phyto-remediation technique has gained attention as a less expensive alternative to chemical amendments. This technique works on the same principle of native calcite dissolution to supply soluble calcium by facilitating changes in root zone partial pressure of CO_2 by plants and thus helping to remediate calcareous saline–sodic soils (Qadir et al., 2007; Qadir and Oster, 2004).

Organic amendments including composts have long been studied for their effectiveness in improving soil properties such as soil structure, aggregate stability, hydraulic conductivity and other chemical and biological properties (Giusquiani et al., 1995; Haynes and Naidu, 1998; Ros et al., 2003; Tejada et al., 2009) when applied on degraded lands. Several studies have also reported the benefits of using organic materials to remediate salt-affected soils by improving their physical, chemical and biological properties (Lax et al., 1994; Liang et al., 2005; Tejada et al., 2006; Wahid et al., 1998; Walker and Bernal, 2008). Composts differ in their physiochemical properties based on the feedstocks from which they are made and could influence soil properties differently when used for reclamation (Lakhdar et al., 2009). The effects of two different composts, i.e., biosolids and greenwaste composts were evaluated in this study to reclaim a saline–sodic soil. Moreover, the benefits of combined applications of these composts and gypsum during the process of saline–sodic soil remediation and their effects on specific soil properties such as hydraulic conductivity and aggregate stability have been seldom studied. Besides, the effect of extremely stable organic materials, such as biochar, on the reclamation of saline–sodic soils has not been investigated.

Biochar, a carbonaceous organic material, is produced by slow pyrolysis of biomass under zero or limited oxygen conditions, in a closed furnace at temperatures $\leq$700 °C (Lehmann and Joseph, 2009). Interest in biochars is more recent with its use mainly focused to combat global climate change by sequestering atmospheric CO_2 into soil C (Chan et al., 2008). In addition to the C sequestration value, beneficial aspects of improved soil quality, nutrient enhancement and plant growth have also been reported when biochar is used as an organic soil conditioner (Glaser et al., 2002; Lehmann et al., 2006). However, the use of biochar as a potential soil amendment for salt-affected soils, in particular saline–sodic soils, has never been evaluated. Biochar was shown to improve soil physical properties such as bulk density, porosity, aggregate stability, and saturated hydraulic conductivity (Herath et al., 2013; Laird et al., 2010). Moreover, recent studies have reported that biochars can be rich in nutrients like Ca^{2+} and Mg^{2+} (Tsai et al., 2012) and may enhance their availability in soil when added as amendments (Laird et al., 2010; Rajkovich et al., 2012). Therefore, addition of biochar to a saline–sodic soil could aid in its remediation by adding Ca^{2+} and Mg^{2+}, improve aggregate stability, hydraulic conductivity, and potentially might enhance Na^{+} leaching.

Degraded water, defined as “water which has suffered chemical, physical or microbiological degeneration in quality”, (O’Connor et al., 2008) such as agricultural drainage water, municipal treated waste water, water from animal and feed operations, are increasingly seen as alternative sources of irrigation water due to an augmented demand for high quality potable water in urban areas (Corwin and Bradford, 2008). In California and much of the Western United States, agricultural drainage and municipal treated waste water, termed as ‘reclaimed water’, are used mainly for agricultural irrigation to supplement the scarcity of fresh canal water and as an alternative for their disposal (Mandal et al., 2008; Wu et al., 2009). The chemical characteristics that determine the suitability of these marginal quality waters for irrigation are same as those of fresh waters given by Ayers and Westcot (1985). Important issues that constrain the use of these low quality waters for irrigation are salinity, sodicity, and specific-ion toxicities. Salinity (EC_{iw}) and sodicity (SAR) of the irrigation water are the principal water quality properties that determine the extent of soil degradation. Many studies have evaluated the effects of irrigation water salinity and sodicity on soil structure deterioration by clay dispersion and subsequent reduction in hydraulic conductivity (Frenkel et al., 1978; Grattan and Rhoades, 1990; Mace and Amrhein, 2001; McNeal and Coleman, 1966; McNeal et al., 1968; Quirk and Schofield, 1955). Reclaimed water from municipal treatment plants may contain higher EC and SAR values (Wu et al., 2009) than other fresh water resources. While the effects of water with high SAR’s (>15) on soil properties have been well studied (Grattan and Oster, 2003; Jalali et al., 2008; Murtaza et al., 2006), the use of moderate SAR waters ($SAR < 8$) (Mace and Amrhein, 2001), especially to leach a saline–sodic soil treated with organic amendments for reclamation, is questionable and warrants study.

The main objective of this study was to compare and evaluate the effects of organic amendments (biochar and composts) and gypsum as individual and conjunctive applications on the reclamation potential of a saline–sodic soil, when leached with marginal quality reclaimed water. Our hypothesis is that the combined applications of gypsum and organic amendments and subsequent leaching with reclaimed water will accelerate the reclamation process beyond what is achieved when they are used separately. Moreover, the negative chemical effects of reclaimed water use on soil structure degradation will be negated due to the structural stability enhancements offered by organic matter additions.

2. Materials and methods

2.1. Soil sampling

Bulk saline–sodic soil samples (0–20 cm) were collected from an agricultural farm located on the west side of San Joaquin valley, California (36°22′57.2″N, 120°13′50.8″W). These soils had a history of being previously irrigated with saline–sodic drainage water as part of integrated on farm drainage management (IFDM), and were abandoned without any crop cultivation for more than a year due to poor soil performance. The soil has a clay loam texture and belongs to the Ciervo soil series (Fine, smectitic, thermic VerticHaplocambids). Bulk soils were air-dried and crushed to pass through a 2 mm sieve and were homogenized by thorough mixing. Sub samples were randomly collected from the bulk soil to analyze for their physical and chemical properties. Soil particle size analysis was conducted using the hydrometer method (Gavlak et al., 2003). Soil EC_e and pH measurements were made on saturated paste extracts following the method given by Richards (1954) using Oakton CON 6 conductivity meter (Oakton Instruments, IL) and Thermo Scientific Orion 3 star bench top pH meter (Thermo Scientific, Inc. MA). Soluble cations (Na^{+}, Ca^{2+}, and Mg^{2+}) were analyzed

Table 1
Soil physical and chemical characteristics.

Soil characteristic	Value
Sand (%)	43
Silt (%)	18
Clay (%)	39
Texture	Clay Loam
Bulk density (g cm^{-3})	1.23
Organic matter (%)	0.6
CEC (cmol$_c$ kg^{-1})	27.8
pH	8.26
EC$_e$ (dS m^{-1})	23.3
Soluble Na$^+$ (mmol$_c$ l^{-1})	177.6
Soluble Ca^{2+} (mmol$_c$ l^{-1})	47.3
Soluble Mg^{2+} (mmol$_c$ l^{-1})	15.3
Exchangeable Na$^+$ (cmol$_c$ kg^{-1})	6.88
Exchangeable Ca^{2+} (cmol$_c$ kg^{-1})	18.4
Exchangeable Mg^{2+} (cmol$_c$ kg^{-1})	4.8
SAR (mmol l^{-1})$^{0.5}$	31.8
ESP (%)	24.7
CCE (%)	3.85

on the same saturated paste extracts by inductively coupled plasma optical emission spectrophotometry (ICP-OES) using a PerkinElmer optima 7300DV spectrophotometer (PerkinElmer, Inc., MA). Soil cation exchange capacity (CEC) was estimated by following the Bower method of Na$^+$ saturation using 1 M sodium acetate solution (pH 8.2), followed by ethanol rinsing and replacing adsorbed Na$^+$ by NH$_4$$^+$ using 1 M ammonium acetate (pH 7.0) solution. Extractable cations (Na$^+$, Ca^{2+}, and Mg^{2+}) were measured by rinsing soils with excess of 1 M ammonium acetate solution buffered at pH 8.5 for ~10 min (Normandin et al., 1998). Exchangeable cations were then determined by subtracting soluble cations from total extractable cations. Calcium carbonate equivalent (CCE) was calculated following the calcimeter method, which measures the pressure developed by soil reaction with concentrated hydrochloric acid (Loeppert and Saurez, 1996). Important soil physical and chemical characteristics are presented in Table 1.

2.2. Amendments and irrigation water

Woodchip biochar, greenwaste compost, and biosolids co-compost were used as organic amendments. In addition to these, 98% pure laboratory grade gypsum was used as an inorganic amendment. Greenwaste and biosolids composts were collected from local STA (seal of testing assurance) affiliated compost producers. Greenwaste compost was produced using turned windrows, while biosolids co- compost was produced in aerated static piles. Greenwaste composts consisted of mostly roadside landscaping green material and biosolids compost was made as a co-compost with municipal biosolids and horse stable beddings. Woodchip biochar was procured from a local biochar producer (Western Environmental Inc., Mecca, CA). The feed stock was charred at 500 °C for about an hour under oxygen free conditions in an industrial furnace. Compost materials had passed through a 0.25 inch (<6.35 mm) sieve while biochar had passed through a 2 mm sieve. Composts were analyzed for their properties using methods outlined in TMECC (TMECC, 2001), while biochar was analyzed following the methods outlined in International Biochar initiative (IBI, 2013). Some important properties of the organic materials used are presented in Table 2. Irrigation/leaching water used was the reclaimed water collected from a local farm with its primary source from Eastern Municipal Water District (EMWD), Southern California. Chemical properties of the reclaimed water are given in Table 3. This water can be classified as “moderate SAR” water, given its SAR less than 8 (Mace and Amrhein, 2001).

Table 2
Physical and chemical characteristics of composts and woodchip biochar.

Characteristic	Woodchip Biochar	Biosolids compost	Greenwaste compost
Total C (%)	63	24.4	23
Total N (%)	0.74	3.8	0.99
Org. C (%)	53.1	7.82	7.60
C:N ratio	85.1	6.42	23.2
Organic matter (%)	–	61.4	56
pH[a]	8.55	7.38	6.36
EC[a] (dS m^{-1})	0.56	12.8	2.75
Stability indicator (mg CO$_2$-C OM g^{-1} day^{-1})	–	2.3	0.66
Total elements (%)			
Ca	1.68	2.84	1.47
Mg	0.41	0.48	0.37
Na	0.46	0.16	0.09
K	0.53	0.55	0.73

[a] pH and EC of composts were measured on 1:5 water extracts (TMECC, 2001), and that of biochar were measured on 1:20 water extracts (IBI, 2013).

Table 3
Chemical composition of reclaimed water.

Characteristic	Value
EC$_w$ (dS m^{-1})	0.96
pH	7.2
Na$^+$ (mmol$_c$ l^{-1})	5.21
Ca^{2+} (mmol$_c$ l^{-1})	2.09
Mg^{2+} (mmol$_c$ l^{-1})	1.12
SAR (mmol l^{-1})$^{0.5}$	4.11
Cl$^-$ (mmol$_c$ l^{-1})	5.4
SO$_4$$^{2-}$ (mmol$_c$ l^{-1})	1.8
HCO$_3$$^-$ + CO$_3$$^{2-}$ (mmol$_c$ l^{-1})	1.5

2.3. Soil treatments and incubation

Three hundred grams of air-dried base soil samples were treated with organic and gypsum treatments. Organic amendments were applied at a rate of 75 t ha^{-1} on a dry weight basis (~5% w/w) and gypsum was applied at 50% soil gypsum requirement (GR). The high organic amendment application rate was chosen to simulate a one-time application and long–term effects of addition of these amendments. Organic amendments are generally cheaper than inorganic materials but economic implications of applying such high rates of these amendments should also be considered. We however, believe that the long–term and multi-faceted benefits achieved through soil reclamation could outweigh the initial cost of ameliorating treatments, producing net gains over time. Reduced gypsum rate was to simulate reduced usage of an inorganic amendment and to test its effects when applied at half of its recommended dosage. A total of 8 treatments were used in this experiment: no amendment (Control), gypsum at 50% soil GR (G), greenwaste compost (GWC), biosolids compost (BSC), biochar (BC), biochar + gypsum (BCG), biosolids compost + gypsum (BSCG) and greenwaste compost + gypsum (GWCG). The combined treatments had the same ~5% application rate and 50% soil GR. All the amendments were thoroughly mixed into the soil and were incubated for a month in mason jars maintained at 60% water filled pore space (WFPS) and room temperature (25 ± 1 °C). WFPS was calculated using Eq. (1).

$$\mathrm{WFPS}(\%) = \frac{\theta_g \times \rho}{\left(1 - \frac{\rho}{2.65}\right)} \times 100 \qquad (1)$$

where θ_g is the gravimetric water content (g), ρ is the soil bulk density (g cm^{-3}) and 2.65 is the particle density. This incubation was done in order to stabilize the microbial activity and evaluate the wet aggregate stability improvements after the organic amendment additions. Also, soils maintained at 55–60% WFPS have been shown to have higher microbial activity (Doran et al., 1990). Increased microbial activity was shown to increase aggregate development and stability (Kandeler and Murer, 1993; Tisdall et al., 1978). After a month of incubation, treated soils were carefully emptied from the mason jars, were air-dried, and gently crushed to pass through a 2 mm sieve.

2.4. Leaching experiment

Leaching columns consisted of acrylic tubes with an internal diameter of 5 cm and a length of 20 cm. The acrylic columns were filled with acid washed #12 silica sand at the bottom (to a height of 1.5 cm) and incubated soils were added in batches with simultaneous tapping to achieve a uniform bulk density and avoid any air pockets. Soils were packed close to a field bulk density of 1.23 g cm^{-3}. Final mean bulk densities after packing into columns were calculated to be 1.24 g cm^{-3} for the control and G treatments, and 1.20 g cm^{-3} for all other organic amendment treated soils. Soil filled columns were initially subjected to wetting from the bottom in order to remove any air pockets developed during the packing process. After complete saturation from bottom, the direction of the flow was reversed by maintaining a 5 cm constant head on top of the soil using a Mariotte bottle setup. For every treatment, three replicates were used and were setup in a completely randomized experimental design.

The pore volume (*PV*) of each soil column was calculated using volume of the soil in the column (V_s) and its associated porosity (ϕ_s), and is given as ($PV = V_s \times \phi_s$) (Kirkham, 2004). Organic amendment treated soil columns had a mean pore volume of 148 cm^3 while the control and gypsum treated soils had a pore volume of 126 cm^3. All soil columns were leached with approximately seven pore volumes of moderate SAR reclaimed water. Leachate samples were collected for every one third pore volume in centrifuge tubes. Saturated hydraulic conductivity measurements were made after every one pore volume of leaching solution had passed through the column. Saturated hydraulic conductivity (K_s) was calculated using the standard Darcy's law as given in Eq. (2).

$$K_s(\text{cmhr}^{-1}) = \frac{V \times L}{[A \times t \times (H_2 - H_1)]} \qquad (2)$$

where L is the length of the soil in the column (cm), V is the volume of leachate (cm^3) collected within a time interval t (h), and A is the cross sectional area (cm^2) of the column. H_2 and H_1 are the respective pressure heads (cm) at the top and bottom of the soil column (Kirkham, 2005). Leachate was analyzed for Na^+, Ca^{2+}, and Mg^{2+} ions using ICP analysis. Cumulative amounts of cations leached were calculated using Eq. (3).

$$Q_L = \Sigma(C_1 - C_{1s})V_j \qquad (3)$$

where Q_L is the cumulative amount of a cation in the leachate (mmol), C_l and C_{ls} are the respective cation concentrations (mmol$_c$ l^{-1}) in the leachate and leaching solution and V_j is the volume of the leachate (L) collected in the jth interval of time (Jalali and Ranjbar, 2009). After the completion of leaching phase, all columns were allowed to drain freely. Soils from the columns were carefully removed, air-dried and crushed to pass through a 2 mm sieve. These air-dried soil samples were analyzed as post-leaching soil samples to determine their respective chemical properties including EC$_e$, SAR, CEC, soluble, and exchangeable cations. Wet aggregate stability measurements were also conducted on base (before amendment application) soils, soils after incubation and on post-leaching soils. Percent wet aggregate stability was measured on 1–2 mm soil aggregates using wet sieving apparatus following the method given by Nimmo and Perkins (2002).

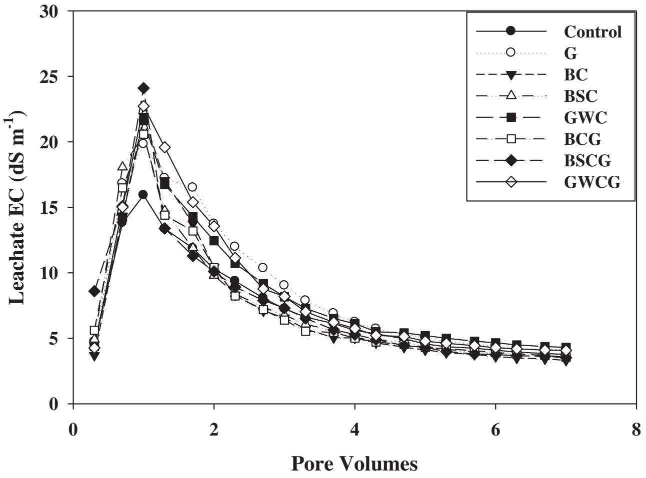

Fig. 1. Mean leachate electrical conductivity (EC) for different treatments.

2.5. Data analysis

A two-way factorial analysis of variance was conducted using SPSS V.20 software to test the effects of gypsum addition to the organic amendments. Where there was no effect of gypsum, data were analyzed using one-way ANOVA to separate the means. Significant differences between the treatment means were analyzed using Tukey's test in SPSS at 95% significance level ($P < 0.05$).

3. Results and discussion

3.1. Leachate EC

Breakthrough curves for mean leachate EC for various treatments during the leaching process are presented in Fig. 1. For all the treatments, EC initially increased reaching a maximum value after approximately 1 PV. EC values then decreased gradually with further leaching. This trend may be attributed to the movement of soluble salts to the upper part of the soil column along with the wetting front while the columns were initially saturated from the bottom. Therefore, the soil in the column was likely not uniform with respect to its salt concentrations along its profile, as opposed to leaching a dry soil with a uniform salt profile. Therefore, the first sample of leachate had a low salt concentration followed by increasing concentration due to the movement of the accumulated salts downward from the top of the soil profile. This was followed by a continuous decrease in EC due to additional leaching of salts, until equilibrium was reached between the ECs of the leaching and soil solutions. All treatments had significantly higher mean leachate EC's at about 1 PV compared to the control (Fig. 1) demonstrating that amendments increased the salt concentration of the leachate. BSCG had the highest leachate EC followed by other amendments. Addition of gypsum to organic amendments significantly ($P < 0.05$) increased leachate EC of the combined applications at 1 PV. This can be ascribed to added Na^+ from irrigation water and also its increased replacement from exchange sites into the soil solution by the combined applications. As the leaching progressed, gypsum alone treatment (G) continued to have a higher leachate EC followed by GWC and GWCG until about 4.7 PV of water had passed. An increase in leachate EC by organic amendments during the initial stages of leaching was also observed by Jalali and Ranjbar (2009) when sheep and poultry manure were applied to a degraded soil. The high initial leachate EC in the biosolids compost treated soils was also likely due to the high EC of the biosolids material compared to the green waste compost and biochar materials.

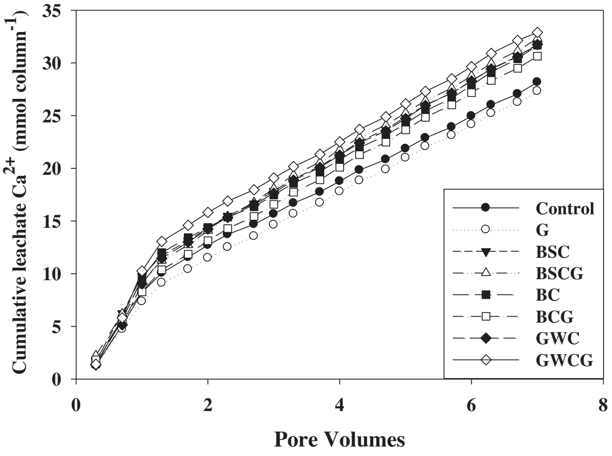

Fig. 2. Mean cumulative leachate losses of Ca^{2+} from soils of different treatments.

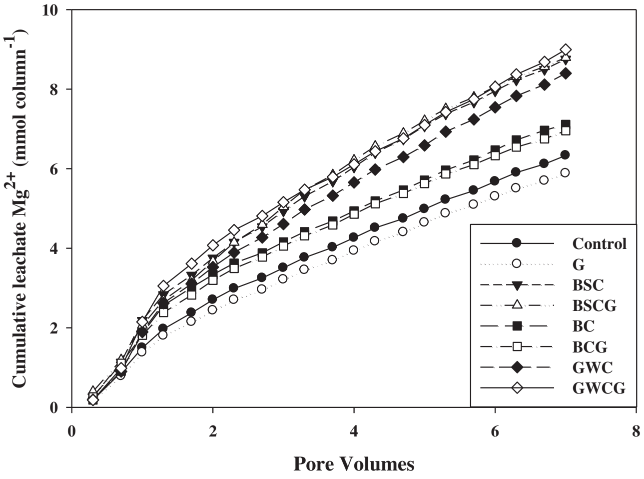

Fig. 3. Mean cumulative leachate losses of Mg^{2+} from soils of different treatments.

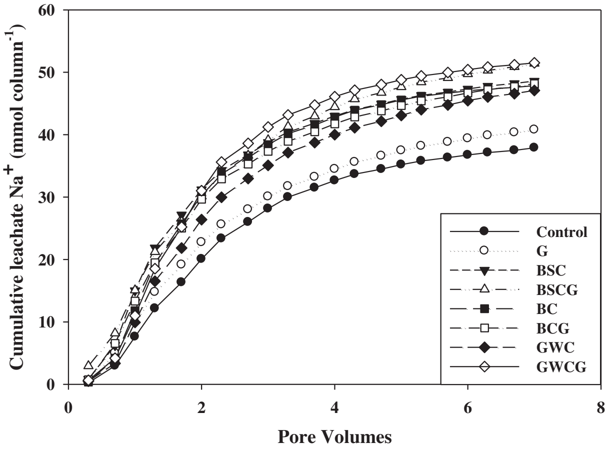

Fig. 4. Mean cumulative leachate losses of Na^{+} from soils of different treatments.

3.2. *Cumulative leachate losses of Ca^{2+}, Mg^{2+}, and Na^{+}*

3.2.1. *Cumulative Ca^{2+} and Mg^{2+}*

The breakthrough curves showing cumulative leachate losses of Ca^{2+} and Mg^{2+} from different treatments during different stages of leaching are presented in Figs. 2 and 3. Soils amended with organic amendments leached significantly ($P < 0.01$) greater amounts of both $Ca^{2+}$and Mg^{2+} than the G and control soils. Cumulative leachate losses of divalent cations were not significantly affected ($P > 0.05$) when gypsum was added to organic amendments. Both Ca^{2+} and Mg^{2+} were lost at a higher rate from compost treated soils than the soils that were amended with biochar. Average leachate losses of Ca^{2+} were 14, 18, and 10% higher from greenwaste, biosolids, and biochar treated soils respectively, relative to the control soils. Similarly, mean cumulative losses of Mg^{2+} were respectively 11, 39, and 37% more from soils treated with biochar, biosolids, and greenwaste composts relative to the unamended control soils. Mineralization of composts likely resulted in the release of excess amounts of fixed Ca^{2+} and Mg^{2+} into soil solution (Jalali and Ranjbar, 2009), given that these amendments were applied at a very high rate (75 t ha^{-1}). It can also be observed that relative to the controls, compost treatments increased the leaching of Mg^{2+} by 38% on average while Ca^{2+} losses were increased by only 16%. This difference can be attributed to the preferential exchange of Ca^{2+} over Mg^{2+} within the soil exchange complex (Udo, 1978). Nevertheless, these results indicate that organic amendments such as composts and biochar can significantly enhance soil Ca^{2+} and Mg^{2+} concentrations when added to ameliorate saline–sodic soils.

3.2.2. *Cumulative Na^{+}*

Mean cumulative leachate losses of Na^{+} for different treatments are shown in Fig. 4. All amended soils lost significantly higher ($P < 0.01$) amounts of Na^{+} compared to the unamended control. Gypsum addition had a significant effect ($P < 0.05$) in increasing the cumulative losses of Na^{+} from compost treated soils. BSCG and GWCG lost significantly more Na^{+} compared to BSC and GWC treatments. Differences between BC and BCG were not significant ($P > 0.05$), however. On average, combined applications leached 33% more total Na^{+} relative to the control, while the sole organic amendment applications leached 26% more cumulative Na^{+} from the soil. High Ca^{2+} releases from the organic amendments preferentially exchanged Na^{+} and facilitated its release into the soil solution, where it was subsequently leached. Additional Ca^{2+} availability from gypsum enhanced this exchange rate and thus released more Na^{+} into the solution when soils were treated with both gypsum and composts together. Na^{+} losses from soils treated with gypsum at 50% soil GR (G) were significantly higher than from the untreated control but less than that observed from the compost and biochar amended soils. These results suggest that application of organic amendments can facilitate efficient replacement of Na^{+} on the exchange sites by adding significant amounts of divalent cations and may further prevent the entry of Na^{+} onto the exchange phase, when low SAR water is used as a leaching solution. Similar results of enhanced Na^{+} leaching were observed in other studies when saline–sodic soils were treated with various amendments (Ahmad et al., 2006; Ghafoor et al., 2012; Gharaibeh et al., 2011; Jalali and Ranjbar, 2009). It should be noted that the cumulative amounts of cations given in $mmol_c$ $column^{-1}$ (Figs. 2–4) can be converted to a normalized unit of $mmol_c$ kg^{-1} by using a conversion factor of 3.33 for control and Gypsum treatments and 3.17 for all organic amended treatments.

3.3. *Soil aggregate stability*

Mean soil wet aggregate stability measurements at three different stages of the experiment are presented in Fig. 5. Before the amendment application, the mean wet aggregate stability of base soils ranged from a low of 33.1% to a high of 34.9%. After 30 day incubation, marked differences were observed between treatments. Soils treated with compost amendments exhibited significantly higher ($P < 0.01$) mean soil aggregate stability compared to G, biochar, and unamended control soils. Adding gypsum to

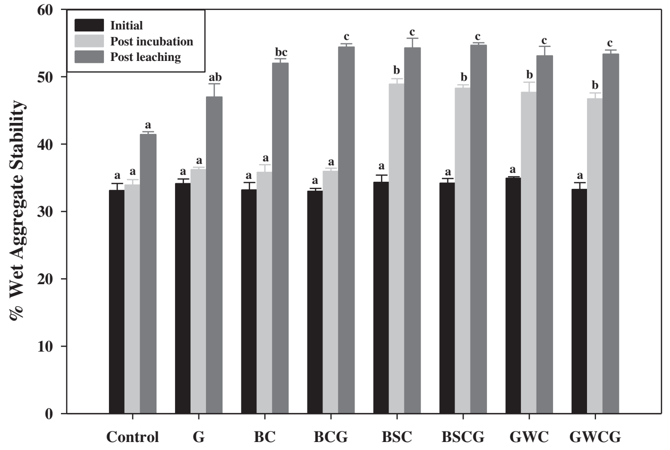

Fig. 5. Soil wet aggregate stability (%) (mean ± s.e.) for different treatments. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

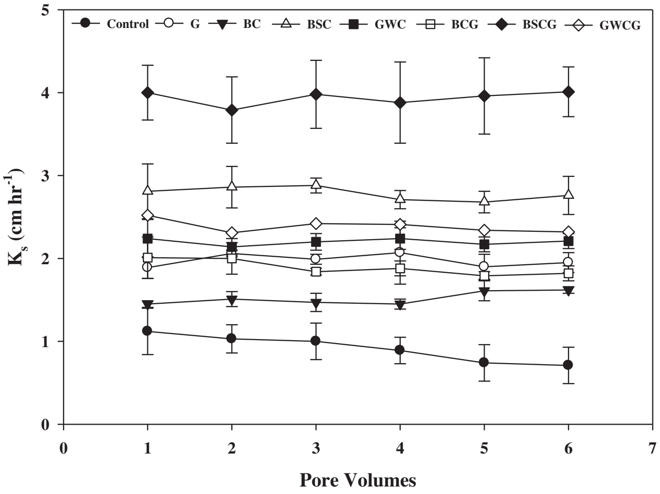

Fig. 6. Saturated hydraulic conductivity (K_s) (mean ± s.e.) for soils of different treatments during leaching.

either composts or biochar did not significantly affect ($P > 0.05$) the soil aggregate stability relative to their sole applications. On average, compost applications increased the soil wet aggregate stability by 41 and 32% relative to the control and G after incubation (Fig. 5). These results are consistent with Wahid et al. (1998), who reported increases in water stable soil aggregates when manure, clover hay, and wheat straw were applied at 3% to a highly saline soil in Pakistan. Furthermore, in a long term field study, Tejada et al. (2006) found significant increases in soil structural stability following the incorporation of cotton gin crushed compost and poultry manure into a semi-arid Mediterranean soil. They determined that humic fractions of organic matter and chelation of Ca^{2+} and Mg^{2+} by organic matter contributed to the structural stability of the soil. Many other studies have also reported similar increases in aggregate stability following compost applications (Aggelides and Londra, 2000; Annabi et al., 2007; Caravaca et al., 2001). In addition, increased biological activity and their release of soil agglutinants such as exo-polysaccharides, likely contributed to the increase of soil aggregate stability in our study (Roberson et al., 1995).

Soil aggregate stabilities of BC and BCG treatments were 5.5% and 6% higher than the control after 30 day incubation but the differences were not statistically significant ($P > 0.05$). Literature with respect to biochar effects on soil aggregate stability is rather limited and conclusions are mixed. Piccolo et al. (1996) demonstrated that highly stable humic substances from oxidized charcoal can significantly increase the aggregate stability of soils. More recently, Herath et al. (2013) reported increases in aggregate stability in two different soils when biocharred corn stover was applied. They explained that longer incubation of biochar treated soils facilitated the release of microbial exudates, which glued soil particles and lead to the formation of macro aggregates. This was confirmed with scanning electron microscope (SEM) images showing increased concentration of fungal hyphae and other microbial products within the pores of biochar (Herath et al., 2013). Contrastingly, in China, Peng et al. (2011) reported no significant increase in aggregate stability when biochar from rice straw was applied to an ultisol. It appears that the properties of a feedstock used to produce the biochar likely determine the ability of that biochar to affect the soil aggregate stability. Soil aggregate stability increased for all treatments, including the control, post leaching (Fig. 5). At 41.4%, the control had the lowest soil aggregate stability followed by G with 47% soil stability. Aggregate stability measurements ranged from 52% to 55% for soils treated with organic amendments. Combined applications of gypsum and organic amendments did not significantly differ from their individual applications in increasing the soil aggregate stability. Overall, biosolids compost, greenwaste compost and biochar increased the soil aggregate stability by an average of 58, 56, and 61%, respectively, compared to their respective initial measurements. Also, a 25% and 37% increase in soil aggregate stability was observed in the control and G soils compared to their respective initial stabilities. This was likely because of Na^+ leaching from all treatments, which helped the soils to flocculate. Stability increases were more pronounced and significant in soils that received organic amendments, which also had significantly higher Na^+ losses relative to G and the control soils.

3.4. Saturated hydraulic conductivity (K_s)

Mean saturated hydraulic conductivity (K_s) measurements are provided in Fig. 6. All organic amendments significantly increased ($P < 0.01$) the mean K_s of soils. Mean K_s of all the treatments stayed relatively constant throughout the leaching process, indicating that soils reached a steady state immediately after leaching started. Hydraulic conductivity of the control soils were the lowest and gradually decreased over time as leaching progressed (Fig. 6), which was likely due to some exchange of Na^+ taking place between the leaching solution and soil exchange sites. A decrease in soil K_s was also observed by Mace and Amrhein (2001) when moderate SAR water was used to leach a clay loam soil. They attributed this effect to increased swelling and dispersion by Na^+ exchange. Similar processes likely dominated in our system and reduced the K_s of the control soil over time. Factorial analysis revealed that combined applications of organic amendment and gypsum produced a significant effect on soil K_s. Gypsum addition to organic amendments significantly increased ($P < 0.05$) their soil K_s compared to those soils that received only organic materials (Fig. 6). Statistically, the order of soil K_s observed for various treatments during leaching was: BSCG > BSC > GWCG > GWC > G ≥ BCG > BC > control. High Na^+ leaching observed from soils with combined applications contributed to the increased K_s of these soils more than their individual applications. Also, addition of gypsum likely increased the electrolyte concentration of the leaching solution and therefore helped to increase the soil K_s (McNeal and Coleman, 1966; Quirk and Schofield, 1955). On average, combined applications of composts increased the soil K_s by 346% and 63% relative to the control and G treatments, respectively. Individual applications of both biosolids and greenwaste composts also significantly increased ($P < 0.01$) the soil K_s (Figs. 2 and 6). The mean soil K_s of BSC and GWC was 287% and 210% higher than the control and 42% and 14% higher than the

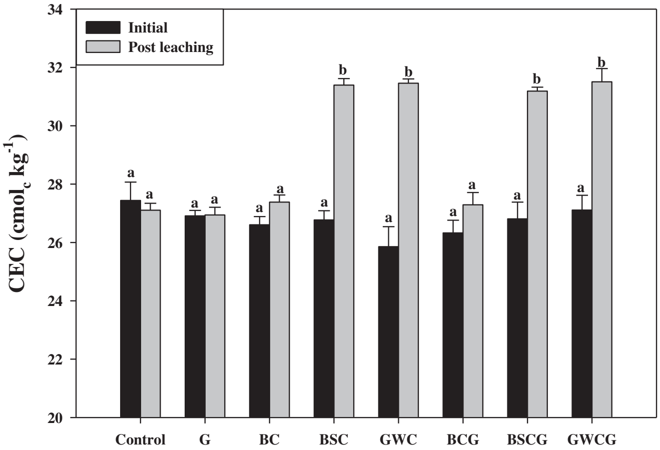

Fig. 7. Soil cation exchange capacity (mean ± s.e.) for different treatments before and after leaching. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

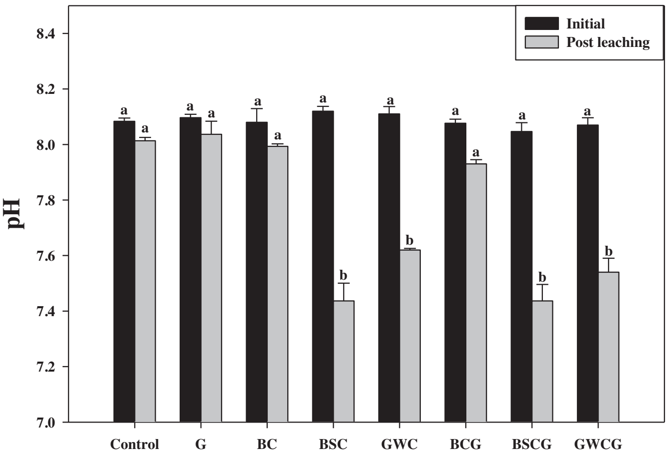

Fig. 8. Soil pH (mean ± s.e.) for different treatments before and after leaching. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

G treatment. This can be attributed to an increase in soil aggregate stability by organic amendments (Fig. 5), which directly helped to increase the porosity of the soil thereby enhancing soil permeability. Addition of organic amendments such as composts was shown to significantly increase the soil hydraulic conductivity in other studies (Aggelides and Londra, 2000; Felton and Ali, 1992). The biochar on the other hand, performed better than the control but was not efficient in increasing soil K_s when compared to G treatment (Fig. 6). Mean conductivities of BC and BCG treatments were 127% and 155% higher than the control but were 16% and 6.5% lower than that of the G treatment. Similar improvements in K_s of the top soil were observed by Asai et al. (2009) when biochar was applied to rice fields in northern Laos. Also, in a more recent study in New Zealand, Herath et al. (2013) reported a 50%–139% increase in soil K_s after corn stalk biochar was applied at 11 t ha^{-1} to silt loam soils and attributed this effect to increased soil aggregate stability and porosity. In this study, we observed significantly higher improvements in soil K_s with a biochar application rate of 75 t ha^{-1}.

3.5. Soil CEC

Cation exchange capacities of different treatments at the end of the experiment are presented in Fig. 7. Significant differences were observed between treatments at the end of the experiment. Addition of composts significantly increased ($P < 0.01$) soil CEC compared to the biochar, G, and the control soils (Fig. 7). Gypsum addition to composts did not have any significant effect ($P > 0.05$) in altering the soil CEC when compared to their individual applications. BSC and GWC treatments had soil CEC increased by an average of 15 and 16% relative to the control; by 16% and 17% relative to G and 14.5% and 15% compared to the biochar treatments, respectively. Percent changes compared to their initial values were also significantly higher for greenwaste and biosolids composts, relative to G and the control. BSC and GWC increased soil CEC by an average of 17% and 19% than their initial CEC. Previous studies have also reported similar increases in soil CEC after addition of organic amendments like composts (Aggelides and Londra, 2000; Ouédraogo et al., 2001). CEC of biochar–amended soils (both BC and BCG) on the other hand, did not significantly differ from G and the control soils at the end of the experiment. However, addition of biochar nominally increased the soil CEC by an average of 3.2% when compared to an initial mean soil CEC of 26.47 cmol$_c$ kg^{-1}. Laird et al. (2010) observed CEC increases ranging from 4% to 30% when hardwood biochar was incorporated at different rates after a 500 day incubation. In our study, woodchip biochar did not significantly increase the soil CEC after 30 day incubation. A longer incubation might be necessary to facilitate adequate abiotic or microbial oxidation of the biochar (Cheng et al., 2008; Liang et al., 2006).

3.6. Soil pH and EC$_e$

The initial and final soil pH values of different treatments are presented in Fig. 8. Post leaching soil analysis revealed that soil pH was significantly lower ($P < 0.01$) in compost treated soils compared to biochar, G and the control soils. Gypsum addition to organic amendments did not have any significant effect ($P > 0.05$) on post-leaching soil pH values. On the other hand, when compared to their respective initial values, soil pH was reduced in all treatments after leaching. However, this pH reduction was statistically significant ($P < 0.01$) in only compost treated soils compared to other treatments (Fig. 8). Mahdy (2011) also reported similar results of reduced soil pH, when a saline–sodic soil was leached after being amended with a compost made from animal and plant residues. However, in the same study, anthracite coal powder did not significantly alter the soil pH, which concurs with our results using the biochar. Reductions in soil pH were also reported by other researchers when organic amendments were applied to salt-affected soils (Makoi and Ndakidemi, 2007; Wong et al., 2009). In addition to leaching of sodium salts, it is possible that adding composts likely increased the partial pressure of CO_2 (P_{CO2}) due to increased microbial activity during incubation and/or leaching. This likely resulted in the formation of inorganic and organic acids, which caused greater soil pH reductions in compost treated soils (Nelson and Oades, 1998; Wong et al., 2009). The biochar on the other hand, either with or without gypsum, did not increase soil pH but in fact reduced soil pH (Fig. 8). This result contrasts with Chan et al. (2008) and Laird et al. (2010) who reported increases in soil pH upon biochar additions. It is likely that leaching of Na^+ salts from the biochar–amended soils merely contributed to reductions in soil pH relative to their initial pH. The same may be true in the case of G and control treatments.

Soil EC$_e$ differences among various treatments before and after leaching are shown in Fig. 9. Post leaching, G and GWC treatments significantly differed ($P < 0.01$) from the control in reducing the soil EC$_e$. Other treatments were not significantly different from either G or GWC treatments (Fig. 9). Nevertheless, all treatments achieved significant reductions in soil EC$_e$ compared to their respective initial values, a consequence of salt removal through leaching. Except for the control, all other treatments had their initial soil EC$_e$ lev-

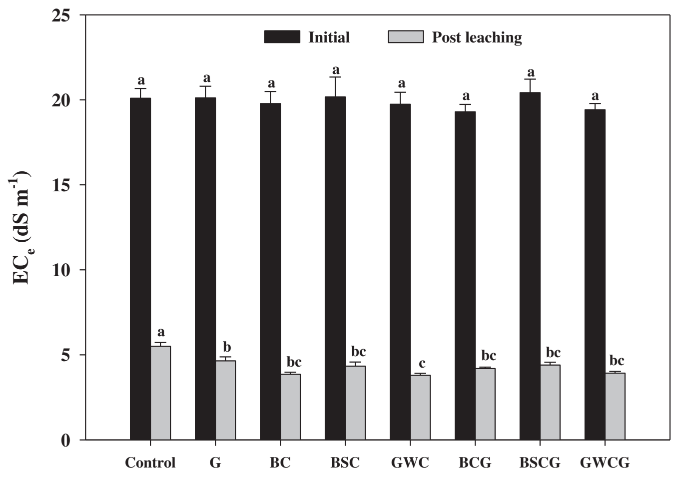

Fig. 9. Electrical conductivity (mean ± s.e.) of saturation paste extracts of soils before and after leaching for different treatments. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

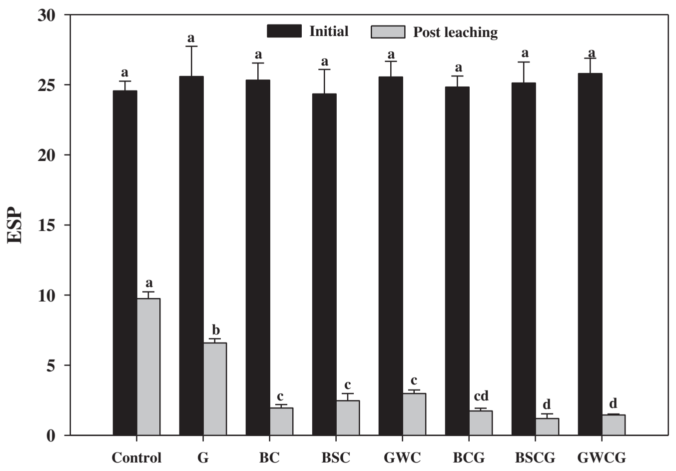

Fig. 11. Exchangeable sodium percentage of soils (mean ± s.e.) before and after leaching. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

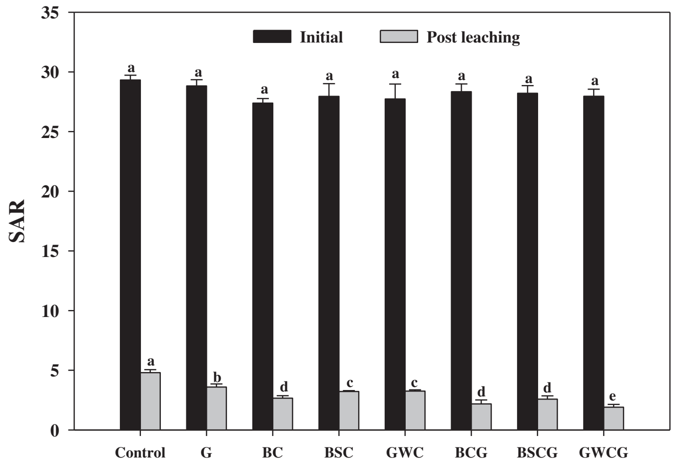

Fig. 10. Sodium adsorption ratio (mean ± s.e.) of soils before and after leaching for different treatments. Same letters in a column series indicate no significant differences among treatments ($P < 0.05$, Tukey's test).

els reduced close to the saline soil threshold of 4 dS m^{-1}. Gypsum addition to organic materials had no significant effect in decreasing soil EC_e when compared to their respective individual applications. Similar reductions in soil EC_e were reported by Ghafoor et al. (2001, 2012) and Tejada et al. (2006), when organic manures and composts were added to saline soils. Overall, addition of organic amendments decreased soil EC_e by an average of 79% while the soil EC_e of G and the control soils were reduced by 77% and 73%, respectively, when compared to their initial readings.

3.7. Soil SAR

The sodium adsorption ratio (SAR) is determined as the relative concentration of Na^+ over the square root of the mean of Ca^{2+} and Mg^{2+} concentrations in soil solution. Sodium adsorption ratios of different treatments before and after leaching are presented in Fig. 10. Post-leaching, reductions in soil SAR were observed in all treatments (Fig. 10) due to Na^+ removal facilitated by leaching. However, soils treated with G and organic amendments had more sodium leached (Fig. 4) and therefore had significantly lower ($P < 0.01$) SAR relative to the control soils. Factorial analysis revealed the significant effect ($P < 0.05$) of gypsum, with combined applications (BSCG and GWCG) reducing soil SAR significantly more than that of the individual compost applications (BSC and GWC). Conversely, SAR reductions between BCG and BC treatments were not significant. An increased release of Ca^{2+} and Mg^{2+} by organic amendments increased their concentrations in soil solution and helped to replace Na^+ on exchange sites into soil solution and enabled its loss through leaching, thus causing reductions in soil SAR. Also, additional Ca^{2+} availability from gypsum in combined applications (BSCG and GWCG) enhanced the Na^+ displacement from exchange sites into soil solution, and therefore promoted greater reductions of soil SAR in these treatments. It is evident that organic amendments can be a significant source of Ca^{2+} and Mg^{2+} and can significantly increase their concentration in soil solution. Percent SAR reductions for different treatments compared to their initial respective values ranged from a low of 83% in the control soils to a high of 93% in GWCG soils and followed the order: GWCG > BCG = BSCG = BC > BSC = GWC > G > control. These results concur with those observed by Shaaban et al. (2013) and Tazeh et al. (2013), who also reported significant reductions in SAR after leaching soils amended with gypsum and organic amendments.

3.8. Soil ESP

Soil exchangeable sodium percentages of different treatments are shown in Fig. 11. All treatments were effective in reducing the soil ESP to <15 after leaching with 7 pore volumes of reclaimed water including the control. Koo et al. (1990) and Gharaibeh et al. (2011) reported similar results with saline–sodic soil being reclaimed with irrigation water and attributed this effect to 'valence dilution' (Reeve and Doering, 1966), where adsorption of divalent cations is preferred at the expense of monovalent cations when soil solution is diluted by added water. ESP reductions were still significantly greater ($P < 0.01$) in soils amended with organic amendments than in the control soils (Fig. 11). Conjunctive applications of composts and gypsum (BSCG and GWCG) were highly effective ($P < 0.01$) in reducing soil ESP compared to their individual (BSC and GWC) applications (Fig. 11). BC and BCG were statistically equally effective in reducing the soil ESP, however. Gypsum (G) alone significantly reduced ($P < 0.05$) soil ESP relative to the control but had significantly higher ESP compared to both individual and combined organic amendment applications (Fig. 11). Greater ESP reductions seen in soils that received both gypsum and composts can be attributed to factors including 1) release of Ca^{2+} from the organic amendments (Table 2), 2) supplementary Ca^{2+} provided by gypsum, and 3) Ca^{2+} contributions from the dissolution

Table 4
Soil exchangeable Na^+, Ca^{2+}, and Mg^{2+} concentrations ($cmol_c\ kg^{-1}$) for different treatments, before and after leaching (mean ± s.e.).

Treatment	Na^+		Ca^{2+}		Mg^{2+}	
	Initial	Final	Initial	Final	Initial	Final
Control	6.73 ± 0.15 a[*]	2.46 ± 0.14 a	18.6 ± 0.58 a	17.9 ± 1.30 a	4.80 ± 0.33 a	3.69 ± 0.52 a
Gypsum	6.89 ± 0.63 a	1.68 ± 0.10 b	18.7 ± 0.49 a	21.4 ± 0.73 b	4.93 ± 0.38 a	3.92 ± 0.42 a
BC	6.54 ± 0.31 a	0.53 ± 0.07 cd	18.6 ± 1.08 a	21.1 ± 0.69 b	4.57 ± 0.26 a	2.79 ± 0.28 a
BSC	6.51 ± 0.44 a	0.78 ± 0.16 c	18.4 ± 0.67 a	22.7 ± 1.79 b	4.21 ± 0.23 a	3.76 ± 0.33 a
GWC	6.80 ± 0.28 a	0.92 ± 0.07 c	18.3 ± 1.16 a	21.8 ± 1.31 b	4.59 ± 0.23 a	3.60 ± 0.42 a
BCG	6.74 ± 0.32 a	0.47 ± 0.05 d	18.0 ± 0.39 a	21.9 ± 0.99 b	4.10 ± 0.24 a	3.05 ± 0.12 a
BSCG	6.61 ± 0.38 a	0.37 ± 0.11 d	18.8 ± 0.90 a	23.5 ± 0.84 b	4.34 ± 0.29 a	2.43 ± 0.17 a
GWCG	6.91 ± 0.19 a	0.46 ± 0.02 d	17.9 ± 0.96 a	22.2 ± 0.40 b	4.88 ± 0.18 a	3.10 ± 0.10 a

[*] Same letters within a column indicate no significant differences between treatments ($P < 0.05$, Tukey's test).

of native calcite by compost addition, which likely enhanced the Na^+–Ca^{2+} exchange rate between the soil solution and exchange phases. Reductions in soil ESP were also reported by previous studies with gypsum and other organic amendment applications (Gharaibeh et al., 2011; Jalali and Ranjbar, 2009; Qadir et al., 1996; Qadir et al., 2002; Tejada et al., 2006). Percent reductions of soil ESP compared to the respective initial ESP's were also higher in soils that received both gypsum and organic amendments. The ESP reclamation ranged between 93% to 95% for combined applications while that of individual applications ranged between 87% to 91%. G and control soils had a reclamation efficiency of 74% and 60%.

3.9. Exchangeable Na^+, Ca^{2+}, and Mg^{2+}

Exchangeable Ca^{2+}, Mg^{2+}, and Na^+ concentrations for soils before and after leaching are presented in Table 4. Post-leaching soil analysis revealed significant differences between various treatments with respect to their exchangeable Ca^{2+} concentrations. All amended soils had significantly higher ($P < 0.01$) exchangeable Ca^{2+} relative to the control. Gypsum (G) applied at 50% soil GR also had significantly higher ($P < 0.05$) soil exchangeable Ca^{2+} (19%) than the control but was not different from organic amendment treatments. On average, exchangeable Ca^{2+} concentrations were 20, 28, and 23% higher in the biochar, biosolids compost, and greenwaste compost treated soils respectively, relative to the control. When compared to their respective initial measurements, G and organic amendments augmented soil exchangeable Ca^{2+}. Average increases were 14, 17, 24, and 21% for soils treated with G, biochar, biosolids, and greenwaste composts, respectively. This increase in soil exchangeable Ca^{2+} levels by organic amendments likely increased the displacement of Na^+ from exchange sites and enhanced its leaching from the soil profile, thus helping the soils to be remediated at a much faster rate. Similar observations were made by Jalali and Ranjbar (2009), who reported increases in soil exchangeable Ca^{2+} after leaching a saline sodic soil treated with gypsum, sheep, and poultry manure. Also, Walker and Bernal (2008) reported increased sodium leaching due to the saturation of soil exchange sites with Ca^{2+} when olive mill waste compost was applied to a highly saline soil. Similarly, Laird et al. (2010) reported significant increases in soil extractable Ca^{2+} when soils were treated with different rates of oak biochar.

Significant differences between treatments were not observed with respect to soil exchangeable Mg^{2+} levels in post-leaching soils (Table 4). However, when compared to their respective initial measurements, all treatments had lower soil exchangeable Mg^{2+} concentrations, especially in the G, composts, and the biochar treated soils. This can be partly attributed to the increased Ca^{2+} concentrations in soil solution, which favored its adsorption onto the soil exchange sites compared to Mg^{2+} (Jalali and Ranjbar, 2009). Decreased Mg^{2+} levels are considered good with respect to the soil structure, as some studies have shown that elevated soluble or exchangeable Mg^{2+} could be deleterious in maintaining the soil permeability (Mahmoodabadi et al., 2013).

Initial and post-leaching soil exchangeable Na^+ concentrations are given in Table 4. Post-leaching soil analysis revealed significant differences among treatments with the control having significantly higher ($P < 0.01$) soil exchangeable Na^+ than soils that received amendments. Organic amendments by themselves significantly reduced ($P < 0.05$) soil exchangeable Na^+ compared to the control and G treatments (Table 4) and this result can be attributed to their release of Ca^{2+}, which displaced Na $^+$ from the exchange complex. However, when combined with gypsum, this effect was much more pronounced due to enhanced availability of Ca^{2+} and therefore exchangeable Na^+ concentrations of the BSCG and GWCG treatments were significantly lower ($P < 0.05$) than the BSC and GWC treatments (Table 4). Nevertheless, application of composts and the biochar helped to reduce high exchangeable Na^+ by saturating the exchange complex with Ca^{2+}. Overall, biochar, biosolids compost, and greenwaste compost amendments reduced soil exchangeable Na^+ by 80, 77, and 72%, respectively, relative to the control. Gypsum applied at 50% soil GR (G) reduced the same by only 32% relative to the control. When compared to their respective initial exchangeable Na^+ levels, the same trend was observed where decreases were more prominent in soils with combined and individual organic amendment applications than for the G and control treatments. Percent reductions relative to initial measurements were between 93% to 94% for the combined applications while the individual organic amendments had percent reductions ranging between 86% and 92%. On the other hand, G and the control had their initial soil exchangeable Na^+ reduced by 76% and 63% after leaching, respectively.

4. Conclusions

This study evaluated the reclamation potential of a woodchip biochar and two composts (biosolids and greenwaste), applied as individually or together with gypsum, to remediate a saline–sodic soil leached with moderate SAR water. The results demonstrated that reclaimed water can be used by itself to leach and reclaim a saline–sodic soil. However, in the presence of organic amendments such as composts and biochar, the reclamation effect was significantly enhanced. Soil structural improvements were elevated in compost treated soils. Both composts and the biochar were found to significantly contribute divalent cations (Ca^{2+} and Mg^{2+}) that facilitated the exchange of sodium from soil exchange sites. Soil saturated hydraulic conductivities were significantly increased by both composts and the biochar relative to the unamended soils. Use of composts or biochar reduced soil salinity and sodicity as much as or more than the traditional gypsum amendment and reductions were always greater than the control treatment. Use of gypsum together with organic amendments produced a significant synergistic effect in remediating soil sodicity but not salinity. Both composts significantly improved soil CEC and pH values but the biochar did not.

Overall, this laboratory study suggests that moderate SAR reclaimed water can be used together with organic amendments to leach and improve saline–sodic soils. Where available, reclaimed water use may provide a cost- effective alternative that conserves fresh water for other agricultural uses. Also, using organic amendments in lieu of inorganic amendments can produce input cost savings and therefore offer a cheaper and an efficient management method to reclaim salt-affected soils. As these observations were derived from a short-term laboratory experiment, further work, including long-term and field implementation studies are warranted.

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