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Do Precision Chemical Amendment Applications Impact Sodium Movement in Dryland Semiarid Saline Sodic Soils?

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ABSTRACT

Expanding sodicity and salinity problems have placed many northern Great Plains (NGP) soils at the sustainability tipping point. This study assessed the impact of chemical restoration on water and salt transport in undisturbed soil columns collected from three hillslope model landscape positions. The backslope (Redfield), footslope (White Lake), and toeslope (Pierpont) soils had moderate (3.27 ± 0.59), high (7.3 ± 3.34), and very high (13.29 ± 3.2) sodium adsorption ratio (SAR_e) values, respectively. The soils were treated with KBr and one of four soil amendments (none, H_2SO_4, $CaSO_4$, and $CaCl_2$). The rapid movement of Br^- through the columns suggested that bypass water flow occurred. In addition, a comparison with widely used salinity models (final EC = 0.8 × initial EC/pore volume [PV]) underestimated the leaching requirements by 69, 79, and 41% in the backslope, footslope, and toeslope soils. In the footslope soils with high SAR values, H_2SO_4 was more effective at promoting Na^+ leaching than gypsum or $CaCl_2$. However, in back slope and toeslope soils with moderate and very high SAR values, the chemical amendments were not, and were equally effective at facilitating Na^+ leaching, respectively. These findings suggest that chemical amendments should target treatments to problem areas, and that bypass flow can influence their effectiveness. The LOESS regression model suggested that the electrical conductivity (EC_e)/SAR_e ratio was useful for assessing Na^+ risks, and that to maintain a water flow rate of 1 mm h^{-1} in a soil with a SAR_e value of 1, an EC_e value of ≥2 was required.

Core Ideas

- Worldwide, salinity and sodicity problems in the dryland systems are increasing.
- Standard restoration methods created for irrigated systems may not be appropriate in dryland systems.
- Bypass water flow that occurs in northern Great Plains saline/sodic soils may impact restoration success.
- New approach EC/SAR ratio to assess saline and sodic soil behavior.

Worldwide over 800 million ha of land are impacted by the combined impacts of salinity and sodicity (Rengasamy, 2006; FAO, 2017; Butcher et al., 2016). However, due to the wide range of factors responsible for this growing problem, a one-size-fits all solution is not appropriate. For example, in the North American NGP, salinity and sodicity problems are the result of rising water tables resulting from increased spring rainfall (Schrag, 2011; Melillo et al., 2014; Carlson et al., 2016), whereas in irrigated systems, the problem may be the result of declining amounts of irrigation water containing low concentrations of salts and increasing amounts of irrigation water containing high concentrations of salts. Regardless of the cause, salinity and sodicity reduce crop productivity and soil health.

The traditional approach to remediate US saline/sodic soils was developed in the arid, irrigated regions of the southwestern United States and is based on the measurement of the sodium adsorption ratio (SAR) or exchangeable sodium percentage (ESP), electrical conductivity (EC), and pH. Soil EC and SAR have been historically determined using a saturated paste extract methodology, which are reported as EC_e and SAR_e, respectively. The SAR and ESP values provide an index to the amount of Na^+ on the soil cation exchange sites. At ESP values less than 25 to 30, there is a close correlation between these values. The ESP threshold value for sodic soils is 15%, although some authors have suggested that problems can occur at values as low as 6% (Rengasamy, 2006). A major problem associated with sodium is clay dispersion, which progressively becomes more severe with decreases in the EC_e. Soils with an EC_e > 4 dS m^{-1} are classified as saline and soils with SAR_e values >13 are classified as sodic. Saline-sodic soils have EC_e values that are >4 dS m^{-1} and SAR_e values > 13.

Restoration of saline-sodic soils generally includes (i) improving soil drainage, which often involves installing tile drainage; (ii) adding a source of Ca^{2+} (gypsum, lime); and (iii) applying water in excess of the plants requirement to leach Na^+ out of the profile. These guidelines, or slight modifications, are used worldwide (Li et al., 2011; Mao et al., 2016). Chemical restoration

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Abbreviations: ANCOVA, analysis of covariance; CEC, cation exchange capacity; EC_e, electrical conductivity determined using saturated paste extract; ESP, exchangeable sodium percentage; KBr, potassium bromide; LCC, land capability class; LOESS, locally weighted polynomial regression; NGP, northern Great Plains; PV, pore volume; SAR_e, sodium adsorption ratio determined using saturated paste extract.

of saline-sodic soils is based on the exchange of Ca^{2+} for Na^+, followed by the subsequent transport of sodium out of the surface soil with percolating water. For example, water infiltration was increased from 0.6 mm h^{-1} to over 10 mm h^{-1}, and wheat (*Triticum aestivum* L.) biomass yields were increased from 4060 to 7710 kg ha^{-1} for sodic soils, when gypsum was applied and subsequently irrigated (Rasouli et al., 2013). In this example, it was likely that the combined impact of Ca^{2+} and EC helped maintain the soil structure (Sanders, 1988; He et al., 2013). However, if the EC of the percolating water is low, drainage of soluble salts can contribute to soil swelling and the formation of an impermeable soil layer (Pons et al., 2000; He et al., 2015).

In the structured soils found in the glaciated NGP, bypass water flow is common and soil EC is often higher in footslope than backslope positions (Clay et al., 2001, 2004). In these soils, water can flow down earthworm channels or fertilizer slots that are connected to the soil surface or between sub-angular blocky or prismatic subsoil structures (Munyankusi et al., 1994; Clay et al., 1994, 1995; Liu et al., 1995). What is unknown in these soils is how sodium-mediated degradation of surface soils impacts the effectiveness of the commonly followed restoration strategy and if the chemical amendments should be applied uniformly to both problem areas and closely adjacent non-problem areas.

Previous research did not designed to answer these questions, because they did not consider spatial variability, nor did they consider how interactions between SAR, EC, and water flow impacts restoration success (Rasouli et al., 2013; He et al., 2015). These knowledge gaps may be partially linked to the use of disturbed soil (Jury et al., 1979; He et al., 2015). For example, McIntyre (1979) used air-dried ground soil and reported that there was a relationship between hydraulic conductivity and ESP. In a second example, Jury et al. (1979) assessed changes in ESP as water percolated through large columns (122 cm diameter × 150 cm deep) filled with disturbed surface soil. Extending findings from these studies to salt-effected structured soils is difficult because previous research has shown that disturbance influences the physical, chemical, and biological properties of the soil (Shaykewich, 1970). The objective of this study was to determine the impact of chemical restoration on water and salt transport in undisturbed soil columns collected from three representative (hereafter called 'model') landscape positions.

MATERIALS AND METHODS

Characteristics of Study Sites

The three model landscape positions, White Lake (43°40′32″ N and 98°45′50″ W), Redfield (44°58′10″N and 98°27′45″W), and Pierpont (45°30′35″ N, 97°53′47″W), located in the southeast, east central, and northeast regions of South Dakota were used for this study. These soils were selected to serve as hillslope model landscape positions in a glaciated watershed. The Redfield site represented well-drained backslope soils with a linear surface feature and moderate EC_e and SAR_e values. The White Lake site represented moderately poorly drained concave footslope soils with relatively high EC_e and SAR_e values. The Pierpont site represented poorly drained concave toeslope soils with very high EC_e and SAR_e values. Saturated hydraulic conductivity, using a single ring infiltrometer, was measured at 10 or more locations in each model landscape position in 2014 and 2015. Physical and chemical characteristics of the sites are provided in Table 1.

Model Backslope Position

The soil mapping unit at Redfield was a Harmony (55%) (fine, smectitic, frigid, Pachic Argiudolls)–Aberdeen (35%) (fine, smectitic, frigid Glossic Natrudolls). Soils in this mapping unit were moderately well drained with little risk of flooding. The depth of the water table for this mapping unit was generally >1 m. The Harmony soil series contains Ap (0–20 cm), A (20–38 cm), and Bt1 soil horizons. The soil structure in the Ap horizon has a weak medium and fine granular structure, whereas the A horizon has a weak medium subangular blocky soil structure. The 25-yr average growing season precipitation and temperature at this site were 69 mm and 16°C, respectively.

Model Footslope Position

The soil mapping unit at White Lake was a Houdek (fine-loamy, mixed, superactive, mesic Typic Argiustolls)–Ethan (fine-loamy, mixed, superactive, mesic Typic Calciustolls) (Soil Survey Staff, 2017). These soils are characterized as being well drained. The Houdek soil contains a Bt1 soil horizon from 15–25 cm depth with a moderate medium prismatic soil structure. The Ethan soil has a land capability class (LCC) value of 3e (Soil Survey Staff, 2017) and contains a Bk1 horizon that has a weak medium subangular blocky soil structure. The 25-yr average growing season precipitation and temperature at the White Lake site were 69 mm and 16°C, respectively.

Model Toeslope Position

The soil mapping unit at Pierpont was a Nahon (fine, smectitic frigid Calcic Natrudolls)–Aberdeen–Exline (fine, smectitic, frigid Glossic Natrudolls and fine, smectitic, frigid Leptic Natrudolls). These soils have slow water permeability and varying depths to the natric horizon. The Nahon series classically contains Ap (0–15 cm), E (15–23 cm), and Btn1 (15–35.6 cm) soil horizons. In these soils, permeability is slow and slopes range from 0 to 2%. In the Ap horizon, the soil structure is weak fine granular, whereas the E horizon contains a weak medium platy soil structure (Soil Survey Staff, 2014). At Pierpont the 25-yr average rainfall and temperature were 66 mm and 16°C, respectively.

All sites used no-tillage and had been seeded to annual crops, such as sorghum (*Sorghum bicolor* L.), corn (*Zea mays* L.), soybean (*Glycine max* L.), and wheat. At Redfield (backslope) and White Lake (footslope), drainage tile had been installed 1 and 3 yr, respectively, prior to sample collection. Sampling sites were between tile lines, where disturbance had not occurred.

Collection of Soil Columns

Between 2011 and 2012, 18 undisturbed 15-cm diameter soil columns were collected from each site. The soil column lengths from White Lake, Redfield, and Pierpont were 30, 23, and 23 cm, respectively. Slightly different soil depths were collected to ensure that (i) Na^+ impacted surface soil was contained in the soil column, and (ii) the remediation treatments were primarily targeted to the Na^+ impacted surface soil. Undisturbed columns were collected by (i) pushing the plastic columns into the soil, (ii) digging around the columns, and (iii) using a

Table 1. Chemical properties for the surface soil (0–15 cm) from Redfield (model backslope position), White Lake (model footslope position), and Pierpont (model toe slope position), SD. The chemical analysis for pH_e, EC_e, SAR_e, Na^+, Ca^{+2}, and Mg^{+2} was determined on a saturated paste. Total N and C were determined by combustion. The 95% confidence interval is provided.

	Saturated paste						
Site	pH_e	EC_e	SAR_e	Na^+	Ca^{2+}	Mg^{2+}	Sulfate
		dS m^{-1}		mg L^{-1}	mg L^{-1}	mg L^{-1}	mg kg^{-1}
Redfield	8–8.8	6.0 ± 1.0	3.27 ± 0.59	405 ± 94	216–508	157–1046	271–400
White Lake	8–8.04	12.2 ± 1.6	7.79 ± 3.34	1300 ± 630	369–694	538–1628	320–3146
Pierpont	7.5–8.4	14.0 ± 3.72	13.27 ± 3.20	2710 ± 752	259–1902	68 -2590	1181–3017
Sites	Total N	Total C	Inorganic carbon	Gypsum	1 pore volume/ CEC	Avg. sat. hydraul con.	Median.sat hydraul. con.
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	Cm	mm h^{-1}	mm h^{-1}
Redfield	2.3	24.8	2	0.5 ± 0.48	11.3(2.05L)/25	215 ± 89	81.5
White Lake	2.3	23.5	1.7	0.2 ± 0.22	14.7 (2.67L)/25	107 ± 78	57
Pierpont	1.6	18	0.3	0.5 ± 0.08	11.3 (2.05L)/25	134 ± 135	0

winch attached to a tripod to extract the columns from the soil. Acid washed sand (10% HCl) was placed at the base of each soil column and columns were held upright using a pre-constructed brace. Columns were transported to the laboratory, where studies were conducted at 25°C.

Soil samples (0–15 cm) collected adjacent to the columns were air-dried (40°C) and ground to pass through a 2-mm sieve. For chemical analysis of these samples, approximately 150 mL of Type I (high purity deionized nanopure) water was added to 250 g of ground samples to make saturated pastes. Soil pH_e and EC_e of the saturated paste extracts were measured (accumet Excell XL60, Fisher Scientific, Hampton, NH), whereas Na^+, Ca^{2+} and Mg^{2+} were measured using an atomic absorption spectrometer, (model 200A, Buck Scientific, East Norwalk, CT). Based on these values, SAR_e $\left[Na \Big/ \sqrt{0.5 \times \left(Ca^{2+} + Mg^{2+} \right)} \right]$ was calculated (U. S. Salinity Laboratory Staff, 1954).

The surface soil cation exchange capacity (CEC) was estimated to be 25 $cmol_c\ kg^{-1}$ (Soil Survey Staff, 2017), and the inorganic C was determined in a two-step process where organic matter was removed following Combs and Nathan (1988), followed by combustion at 1000°C to determine total remaining C. Gypsum content was determined following precipitation with acetone (U. S. Salinity Laboratory Staff, 1954), and sulfate-sulfur (SO_4-S) content was determined following Combs et al. (1998). This chemical information by location and model landscape position is summarized in Table 1.

Chemical Restoration

The experiment contained four chemical restoration treatments (none, $CaSO_4$, $CaCl_2$, and H_2SO_4). All treatments were replicated four times. For the Redfield (backslope) soil, the gypsum, calcium chloride, and H_2SO_4 treatments were 12 g of reagent grade $CaSO_4{\cdot}2H_2O$ (6.8 Mg ha^{-1}), 7.74 g of $CaCl_2$ (4.4 Mg ha^{-1}), or 3.79 mL of concentrated H_2SO_4 (18 M) added to the individual columns (Carlson et al., 2016). Given that the SAR_e value for this soil was relatively low (3.27), the chemical amendments were used to assess if they could be used as a preventative treatment. The chemical amendments for the White Lake (footslope) and Pierpont soil (toeslope) columns were 36.0 g of reagent grade $CaSO_4{\cdot}2H_2O$ (20.4 Mg ha^{-1}), 23.3 g $CaCl_2$ (13.2 Mg ha^{-1}), and 11.4 mL of concentrated H_2SO_4. Except for Redfield, these rates were selected to simulate a broadcast application of the chemical amendments to soils having an ESP of 15, a CEC of 25 $cmol_c\ kg^{-1}$, a bulk density of 1.3 Mg m^{-3}, and a target ESP value of 3. In these soils, the $CaCl_2$ and H_2SO_4 were included as alternative treatments because these soils naturally contained gypsum and calcium carbonate. To track the movement of surface applied water, 0.874 g of potassium bromide (KBr) was applied to the soil surface in each column (Clay et al., 2004).

Preventing Edge Flow and Assessing Water Movement

The approach discussed in Clay et al. (2004) was used to prevent edge flow and prepare the columns for the experiment. The process of eliminating edge flow involved creating a surface and subsurface soil seal between the undisturbed soil and plastic column. This process involved a visual inspection and insuring that the surface interphase between the soil and plastic was completely and fully packed with soil. The subsurface interphase was sealed during preconditioning when one PV of water was applied to the columns. The water applied to the column swelled the clays which sealed the interphase (He et al., 2013, 2015). Following the experiment, the effectiveness of this approach was evaluated by visual inspection of the columns for evidence of sidewall movement, excavation of the columns at the completion of the study, and inspection of the Br^- breakthrough curves for evidence that sidewall movement occurred.

Different water transport processes and experimental approaches have different tracer movement signatures. For example, when the tracer, such as Br^-, is applied directly to the soil surface, the water moving through the granular surface soil structure picks up the negatively charged label and transports it to the subsurface (Clay et al., 2004), where it can travel between the subsurface soil structures to the drain. If the water travels down the sidewall and does not travel through the surface soil, the label will remain in the soil. Under these conditions, water traveling through gaps on the edge of the column, or earthworm or root channels connected to the soil surface will have a low concentration of the label. A more complete discussion of water flow in structured soils is available in Beven and Germann (1982) and Gerke (2006).

When the tracer (Br^-) is contained in the water, the water does not need to move through the soil to pick up the label (Seyfried and Rao, 1987). In this situation, the label can be rapidly transported down root and earthworm channels, fertilizer slots, and along the edge of column if the macropore is open at the soil surface (Liu et al., 1995; Clay et al., 1994, 1995).

Type I water (EC < 0.004 dS m^{-1} with total organic carbon <20 µg L^{-1}) was used to mimic rainwater, which can have EC values that approach zero (Sanders, 1988). In the White Lake soil columns, 14.7 cm (1 PV) of Type I water was applied, whereas in the Redfield and Pierpont columns, 11.3 cm of (1 PV) of Type I water was applied to prepare them for the experiment. Twenty-four hours after preconditioning, 50 mL of solution containing KBr and the soil amendments (none, $CaSO_4$, $CaCl_2$, or H_2SO_4) were applied uniformly to the soil surface of the appropriate soil column. Following the surface treatments, the soil was covered with multiple layers of filter paper and four PVs of Type 1 water in increments of two PVs each were added to all columns. Leachate was separated into 120 mL increments (0.66 cm of water) and the length of time to collect each sample was noted. Each sample was analyzed for pH, Br^-, EC, and Na^+ (Warncke and Brown, 1988; Clay et al., 2004). After the water had percolated through the soil, the soil was separated to 0- to 5-, 5- to 10-, 10- to 15-, and 15- to 23- or 30-cm depths increments. Soil samples were dried, ground, and saturated pastes prepared. The pH, EC, Br^-, Na^+, Ca^{2+}, and Mg^{2+}concentrations in the saturated paste extracts were determined.

Data/Statistical Analysis

Based on the collected data, water infiltration at different time intervals, the amount of water that percolated through the soil at the peak Br^- concentration (Peak Br^-), the time to Peak Br^-, the amount of Br^- remaining in the surface 15-cm of soil after 44.5 cm of water had percolated through the columns (3.07 PVs in White Lake columns and 4 PVs in Redfield and Pierpont soil columns), the total amount of Br^- contained in 0.5 L (2.7cm), 1 L (5.5 cm), and 2 L (11 cm) of leachate, the amount of Na^+ that was removed from the columns, and changes in the saturated paste extract for EC_e, Na^+, and Ca^{2+} were calculated and statistically analyzed. For each site (model landscape position), separate analysis of covariance (ANCOVA) was performed to test the treatment effect on the displaced Na^+ by using the initial SAR_e value as a covariate. ANCOVA was used to determine Na^+ removal with 0.5 PV, 2 PV, and 4 PV of water, using the R-statistical program (R Core Team, 2015). Correlations between the different measurements were used to compare the treatments and the 95% confidence intervals are provided for many of the measurements.

Developing and Using the LOESS Model

Locally weighted polynomial regression (LOESS; Cleveland and Devlin, 1988) was used to explore the relationship between the saturated water infiltration and the EC_e to SAR_e ratio. LOESS is a non-parametric approach that requires no prior knowledge on the relationship between independent and dependent variables (Cohen, 1999). This approach is suitable when the dataset contains outliers and/or robust curve fitting is required. Theoretical background of locally weighted regression is available in Atkeson et al. (1997) and Cohen (1999). Lal et al. (2006) used locally weighted polynomial regression to forecast changes in the amount of water contained in Great Salt Lake, and they showed that LOESS can be used for nonlinear systems.

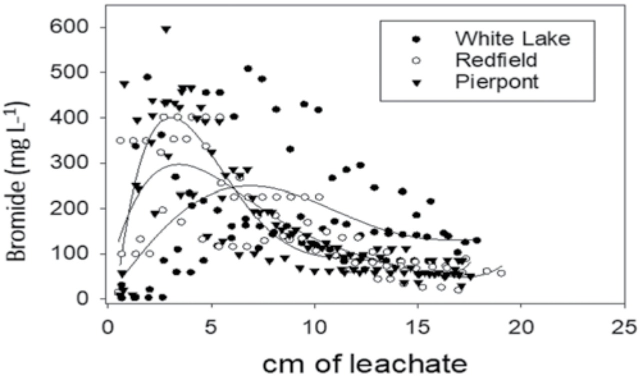

Fig. 1. Bromide leaching vs. cm of leachate collected in the untreated soil columns from Redfield (model backslope, 1 pore volume (PV) = 11.3 cm), White Lake (model footslope, 1PV = 14.7 cm), and Pierpont (model toeslope, 1 PV = 11.3 cm), SD.

Building the model involved multiple steps that included (i) calculating the saturated water infiltration rates (permeability) for the baseline EC_e/SAR_e ratios; (ii) using the equations,

$$Y=\frac{permeability}{SAR_e};\ Y=\frac{1mm/hr}{SAR_e};\text{and}\ \ SAR_e=\frac{1mm/hr}{Y}$$

to set the critical saturated water infiltration to 1 mm h^{-1}; (iii) inserting the new SAR_e value into the dataset and finding the corresponding EC_e value using the equations,

$X=\frac{EC_e}{SAR_e};EC_e=X\times SAR_e$; and 4(iv) defining the EC_e and SAR_e values required to maintain saturated water flow at the desired rate. The process was repeated to identify the EC_e and SAR_e values required to maintain a water flow at 2 mm h^{-1}. LOESS estimation was performed at five different PVs (PV0.5, PV1, PV1.5, PV2, and PV2.5) and standard errors of estimation (permeability/SAR_e) were 0.58, 0.59, 0.61, 0.57, and 0.68, respectively. In the LOESS model, the root mean square errors for the EC_e/SAR_e values of PV0.5, PV1, PV1.5, PV2, and PV2.5 were 0.005, 0.15, 0.19, 0.19, and 0.28, respectively, and the model had a $P < 0.01$.

RESULTS AND DISCUSSION

Evidence for Bypass Flow

In the untreated soil columns, peak Br^- concentrations occurred after 2.61, 5.57, and 2.44 cm of water had percolated through the Redfield (backslope), White Lake (footslope), and Pierpont (toeslope) soil columns, respectively. These values were less than one PV for all soils (White Lake [1 PV = 14.7 cm], and Redfield and Pierpont [1 PV = 11.3 cm]) (Fig. 1). The rapid movement of Br^- through the soils indicated that bypass flow occurred. Using a similar experimental approach, Clay et al. (2004) had similar results when the label was applied to the soil. In addition, the observed Br^- breakthrough curves were very similar to the breakthrough curves of labeled water as reported by Seyfried and Rao (1987) and Munyankusi et al. (1994).

When all three soils were considered simultaneously, the SAR_e and EC_e values were not correlated to the leachate volume at the peak Br^- concentration or to the amount of Br^- contained in 0.5 (2.7 cm or 0.18 PVs in the White Lake and 0.24 PVs in Redfield and Pierpont), 1 (5.5 cm), 2 (11 cm),

Table 2. The correlation coefficients (*r*) between the soil and water flow data in the untreated soil columns combined from all three sites; Redfield (model backslope position); White Lake (model footslope position), and Pierpont (model toeslope position). The data in this analysis include the initial soil sodium adsorption ratio ($\mathrm{SAR_e}$) for the surface 15-cm, soil electrical conductivity ($\mathrm{EC_e}$), the amount of water that percolated through the soil at the peak $\mathrm{Br^-}$ concentration (Peak $\mathrm{Br^-}$), the time to peak bromide, the amount of $\mathrm{Br^-}$ remaining in the surface 15-cm of soil after 45.2 cm of water had percolated through the columns, and the total amount of $\mathrm{Br^-}$ contained in 0.5 L (2.7cm), 1 L (5.5 cm), and 2L (11 cm) of leachate.

Soil and water flow parameter	$\mathrm{SAR_e}$	$\mathrm{EC_e}$	$\mathrm{EC_e/SAR_e}$	Leachate at peak $\mathrm{Br^-}$	Time to peak $\mathrm{Br^-}$	$\mathrm{Br^-}$ remaining in soil	Leachate 0.5 L (2.7cm)	Leachate 1L (5.5cm)	Leachate 2L (11 cm)
$\mathrm{EC_e}$	0.930	1.000							
$\mathrm{EC_e/SAR_e}$	-0.729	-0.461	1.000						
Leachate at peak $\mathrm{Br^-}$	0.439	0.263	-0.557	1.000					
Time to peak $\mathrm{Br^-}$	0.431	0.307	-0.407	0.731	1.000				
$\mathrm{Br^-}$ remaining in soil	-0.536	-0.390	0.771	-0.334	-0.156	1.000			
$\mathrm{Br^-}$ in 0.5 L leachate	-0.333	-0.257	0.318	-0.905	-0.775	0.161	1.000		
$\mathrm{Br^-}$ in 1L leachate	-0.271	-0.281	0.049	-0.651	-0.826	-0.102	0.850	1.000	
$\mathrm{Br^-}$ in 2 L leachate	-0.226	-0.288	-0.058	-0.178	-0.738	-0.134	0.340	0.701	1.000
$\mathrm{Br^-}$ in 3 L leachate	-0.047	-0.133	-0.202	0.125	-0.512	-0.238	0.008	0.381	0.908
Sig. r value at $P = 0.05$	0.553								
Sig. r value at $P < 0.01$	0.684								

and 3 L (16.5 cm) of leachate (Table 2). Different results were observed for $\mathrm{EC_e/SAR_e}$ values, which were negatively correlated to the leachate volume at peak $\mathrm{Br^-}$ ($r = -0.557, P < 0.05$) and positively correlated to the amount of $\mathrm{Br^-}$ remaining in the surface 15-cm of soil after 45.2 cm of water had percolated through the soil (3.07 PVs in White Lake and 4 PVs in Redfield and Pierpont columns) ($r = 0.771, P < 0.01$). Because $\mathrm{Br^-}$ was applied to the surface soil, it is logical to assume that the time to peak $\mathrm{Br^-}$ would decrease as bypass flow increased. The negative correlation between $\mathrm{EC_e/SAR_e}$ and leachate volume at peak $\mathrm{Br^-}$ when combined with the negative correlation between $\mathrm{EC_e/SAR_e}$ and time to peak $\mathrm{Br^-}$ ($r = -0.407$) suggests that the $\mathrm{EC_e}$ to $\mathrm{SAR_e}$ ratio could be used to assess the clay dispersion risk, whereas the positive correlation between $\mathrm{EC_e/SAR_e}$ and amount of $\mathrm{Br^-}$ remaining in the soil at the completion of the experiment supports the hypothesis that bypass flow occurred.

The identification of the water flow mechanism is important because it may impact the effectiveness of the chemical restoration practice (Shaykewich, 1970; Beven and Germann, 1982). If piston flow is the dominant water flow mechanism, then little $\mathrm{Br^-}$ should remain in the columns at the end of the experiment, whereas if bypass flow was the dominant mechanism, then more $\mathrm{Br^-}$ should remain in the soil at the completion of the study. These results are attributed to several factors including (i) $\mathrm{Br^-}$ is not sorbed to soil exchange sites (Clay et al., 2004) and (ii) that bypass flow reduces $\mathrm{Br^-}$ transport. Therefore, the rapid movement of $\mathrm{Br^-}$ through these soil columns when combined with the negative relationship between $\mathrm{EC_e/SAR_e}$ and time to peak $\mathrm{Br^-}$ and the positive correlation between $\mathrm{EC_e/SAR_e}$ and $\mathrm{Br^-}$ remaining in the column at the completion of the study suggests that bypass flow may reduce the remediation effectiveness in the field environment.

These results are important because, $\mathrm{EC_e}$ and $\mathrm{SAR_e}$ are the classical approaches to characterize saline and sodic soils, and the relative amount of $\mathrm{Na^+}$ contained in a soil is often correlated with water flow (McIntyre, 1979). Under controlled conditions, others have noted the importance of considering $\mathrm{EC_e}$ and $\mathrm{SAR_e}$ simultaneously (He et al., 2013).

Chemical Restoration

The ability of the soil to retain its soil structure and transmit water are the ultimate tests for saline–sodic soil management (Gardner et al., 1959; Quirk and Schofield, 1955; Shainberg and Caiserman, 1971). In this experiment, chemical restoration did not influence water movement. For example, the average infiltration rates (±95% confidence interval) for the first 10 cm of percolating water for the $\mathrm{CaCl_2}$, gypsum, $\mathrm{H_2SO_4}$, and control treatments were 6.67 ± 7.06, 5.70 ± 3.10, 5.32 ± 4.05, and 4.60 ± 3.15 mm $\mathrm{h^{-1}}$, respectively. The large range in values is attributed to the natural variation of the soil physical properties (Table 1).

The lack of treatment differences was attributed to the importance of bypass flow. Keren and Shainberg (1981) had similar infiltration rates for untreated soil, however, they also reported that gypsum increased water infiltration. In this experiment, the results were attributed to water flowing through the surface soil where the $\mathrm{Br^-}$ was applied. The $\mathrm{Br^-}$ and other soil nutrients contained in the percolating water were then transported through the remaining soil column. In the transport process, these data suggest that much of the soil was bypassed.

In the footslope soils from White Lake, $\mathrm{H_2SO_4}$ was more effective at promoting $\mathrm{Na^+}$ leaching than $\mathrm{CaSO_4}$ or $\mathrm{CaCl_2}$ (Table 3). However, in the backslope soils from Redfield, the chemical amendments did not facilitate $\mathrm{Na^+}$ movement. These findings suggest that in well-drained soil with a moderate SAR (3.27) value, the chemical amendments had little value as a preventative treatment.

In the model toeslope soils from Pierpont, the three chemical amendments were equally effective at promoting $\mathrm{Na^+}$ leaching. These findings indicate that in poorly drained soils with very high SAR values, the chemical amendments may facilitate $\mathrm{Na^+}$ movement.

The amount of $\mathrm{Na^+}$ remaining in the surface 15 cm at the completion of the study was not impacted by chemical remediation, however it was decreased by 69% in the White Lake (footslope) columns, 62% in the Redfield (backslope) columns, and 86% in the Pierpont (toeslope) soil columns during the study. Others have reported that chemical amendments have a mixed impact on $\mathrm{Na^+}$ transport (Prather et al., 1978; Jury et al., 1979). Similar to White Lake (footslope), Prather et al. (1978)

Table 3. The influence of the three sites, cm of leachate, and chemical amendment on the mg of Na^+ leached from soils collected from Redfield (model backslope), White Lake (model footslope position), and Pierpont (model toeslope position), SD. The leachate volumes represent 0.5, 2, and 4 pore volumes.

		Leachate		
Redfield	Backslope	5.65	22.6	44.8
		mg Na^+		
Gypsum		807	1391	2432
$CaCl_2$		441	1025	2057
H_2SO_4		761	1345	2440
Control		768	1353	2376
P value		0.06	0.12	0.11
LSD	0.10	226		
		Leachate		
White Lake	Footslope	7.35	29.4	58.8
		mg Na^+		
Gypsum		2736	3767	5111
$CaCl_2$		4015	5045	6191
H_2SO_4		5157	6186	6910
Control		2630	3660	4903
P value		< 0.01	< 0.01	< 0.01
LSD	0.10	876	931	729
		Leachate		
Pierpont	Toeslope	5.65	22.6	44.8
		mg Na^+		
Gypsum		3077	4794	6654
$CaCl_2$		3271	4988	6962
H_2SO_4		3642	5358	7056
Control		1862	3579	5153
P value		< 0.01	< 0.01	< 0.01
LSD	0.10	695	731	717

found that more Na^+ was removed by H_2SO_4 when compared with gypsum. Yahia et al. (1975) had similar results and reported that water penetration was greater in soil columns treated with H_2SO_4 than gypsum. The impact of H_2SO_4 on Na^+ transport was attributed to the acid increasing the solubility of $CaCO_3$.

The chemical amendments did not influence the final soil pH_e in the surface 15 cm at the completion of the study. However, slight changes in pH_e were observed during the study. In the Redfield (backslope) control treatment, soil pH_e was 8.4 ± 0.25 prior to the experiment and 8.36 ± 0.05 after the experiment, whereas in the White Lake (footslope) control treatment, soil pH_e in the surface 15 cm was 8.25 ± 0.14 prior to the experiment and 8.45 ± 0.38 after the experiment. In the Pierpont (toeslope) control treatment, soil pH_e was 8.04 ± 0.21 prior to the experiment and 7.48 ± 0.19 at the completion of the experiment.

In the soil columns, the EC_e of the Redfield (backslope) surface soil (0–15 cm) decreased from 6.03 to 2.62 dS m^{-1}. At White Lake (footslope) and Pierpont (toeslope) similar findings were observed and EC_e decreased from 12.2 to 3.55 dS $m{-}^1$ and from 15.1 to 3.4 dS m^{-1}, respectively. The decrease in EC_e during the study was attributed to the transport of cations and anions with the percolating water in all columns.

A variety of models have been used to assess leaching requirements in saline soils (Jury et al., 1979; Cardon et al., 2007; Bauder et al., 2014). A model described by Jury et al. (1979) [final salts = 0.8 × (initial salts/PVs)] overestimated the leaching of salts by 79% in the White Lake columns (footslope), 69% in the Redfield (backslope) columns, and 41% in the Pierpont (toeslope) soil columns. Differences between the predicted and measured results were attributed to bypass water flow. The estimation of accurate leaching requirements is further complicated by different models producing different results (Letey and Feng, 2007), and the possibility that water flow models based on the Richards equation may not adequately describe water movement in structured soils (Gerke, 2006).

Critical EC_e to SAR_e ratio for Water Infiltration

The LOESS modeling was used to assess the relationship between the EC_e/SAR_e ratio and water infiltration. This analysis showed that to maintain a water infiltration rate of 1 mm h^{-1} for a soil with a SAR_e value of 1, an EC_e/SAR_e ratio of 2 or greater was required (Fig. 2). This ratio decreased to 1, 0.8, and 0.6 as SAR_e increased to 5, 10, and 20, respectively (Fig. 2). Similarly, to maintain a column water flow rate of 2 mm h^{-1} in a soil with SAR_e value of 1, an EC_e/SAR_e ratio of 2.7 was required. For soils with SAR_e values of 5, 10, and 20, the EC_e/SAR_e ratios required to maintain a flow rate of 2 mm h^{-1}were calculated to be 1.4, 1.0 and 0.8, respectively.

The LOESS modeling findings were consistent with McNeal (1968), Walworth (2006), and He et al. (2013). For example, the critical EC_e/SAR_e ratios required to prevent soil dispersion in findings reported by Walworth (2006) ranged from 0.7 to 1.0, whereas He et al. (2013) showed that for montmorillonite, dispersion occurred in solutions with SAR_e values of 5 when the EC_e/SAR_e ratio decreased to values lower than 0.36.

Summary

The majority of the prior research on salinity and sodicity has concentrated on improving the understanding of salinity and sodicity remediation in irrigated systems. However, because this research was often conducted using disturbed soil, it is difficult to extend these findings to the structured soils found in NGP. Our work showed that bypass flow was the major mechanism for water flow in salt-affected NGP structured soils. Comparisons between the observed findings with those from classical leaching models, showed that models substantially underestimated leaching amounts needed to reestablish even modest increases in water infiltration rates for NGP structured soils. Differences between the model predications and observed findings were attributed to bypass flow.

The chemical remediation approach had a mixed impact on Na^+ leaching. In the backslope soils from Redfield, the chemical amendments were not effective, whereas in the footslope soils from White Lake, sulfuric acid was more effective at promoting Na^+ leaching than gypsum or $CaCl_2$. In the toeslope soils from Pierpont, the three chemical amendments were equally effective at promoting Na^+ leaching. The lack of treatment differences in the backslope soils with moderate SAR values (3.27) indicate that preventative treatments had minimal impacts on facilitating Na^+ transport. In the untreated control columns, the initial EC_e/SAR_e ratio was correlated ($P < 0.01$) to Br^- remaining in the column after 45.2 cm of water leaching and to the amount of leachate at peak Br^- ($P < 0.05$). The EC_e or SAR_e values were not correlated to Br^- transport and water infiltration.

The LOESS model indicated that the EC_e/SAR_e ratio may be useful to identify soils at risk of dispersion or swelling.

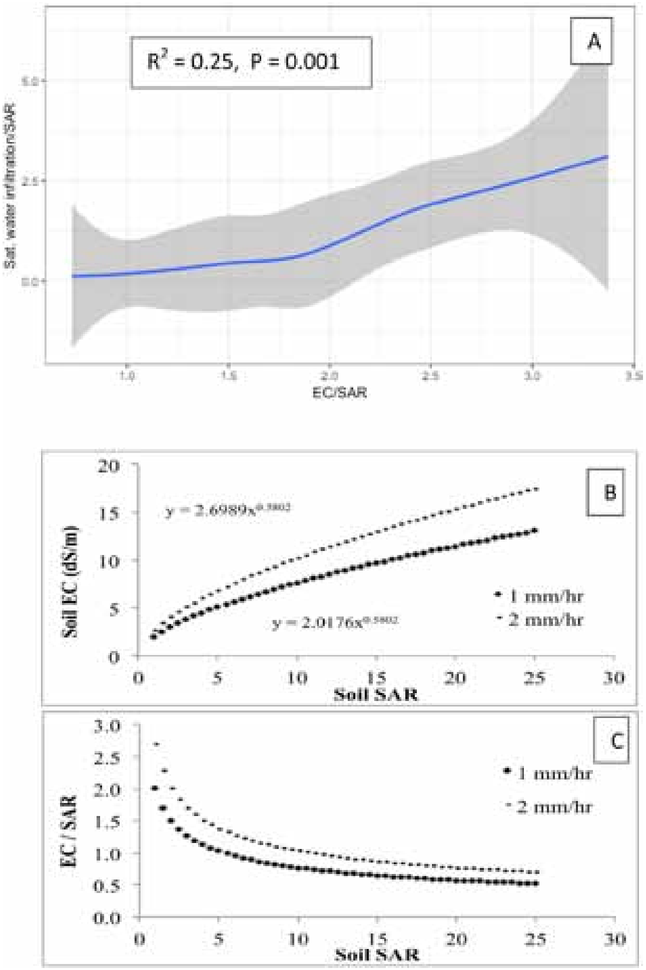

Fig. 2. The locally weighted polynomial (LOESS) model prediction with standard error of predicted value (A), the relationship between LOESS based calculated (see *Method* section for calculation) sodium adsorption ratio (SAR) and electrical conductivity (EC) (B), and the relationship between calculated SAR and the EC/SAR ratio that will maintain saturated water infiltration rates of 1 and 2 mm h^{-1} (C).

For the soils tested in this study, the analysis showed that to maintain a column water flow rate of 1 mm h^{-1} for a soil with a SAR_e value of 1, an EC_e to SAR_e ratio of 2 or greater was required. This ratio decreased to 1, 0.8 and 0.6 with SAR_e values of 5, 10, and 20, respectively. To maintain a higher water flow rate, a higher ratio was needed. Different ratios are likely for soils with different chemical characteristics, organic C levels, and clay minerals.

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