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Field capacity water as influenced by Na and EC: Implications for subsurface drainage

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ABSTRACT

Subsurface-tile drainage is designed to remove gravitational water and soluble salts from the soil-root zone. However, soil swelling, as influenced by soil Na and electrical conductivity (EC), will reduce saturated hydraulic conductivity. The objective of the experiments reported in this paper was to determine the influence of Na and EC on the amount of water retained at field capacity (−33 kPa) in northern Great Plains Na-affected soils. Field capacity water (gravimetric water content) for all soils increased with increasing sodium adsorption ratio (SAR) and decreasing EC, respectively. For example, at an EC of 4 dS m^{-1}, the amount of water retained at field capacity increased from 0.23 to 0.31 g g^{-1} as SAR in the treatment solution increased from 7 to 28. For the Exline soil at 30–60 cm depth, field capacity water decreased from 0.31 to 0.18 g g^{-1} when EC increased from 0.5 to 15 dS m^{-1} at SAR 24. In general, across all SAR values, an EC greater than 4 dS m^{-1} was required to prevent swelling. However, for soils with high natural salinity, no significant difference was observed for field capacity water using the above methods; high salt content and the presence of calcite in these soils may have reduced the potential for water retention and may have lower field capacity. Therefore, to maintain drainage performance in sodium-affected soils one should regularly monitor Na and EC within the soil profile so that EC values do not fall below critical threshold values.

1. Introduction

Many sodium (Na)-affected soils, commonly referred to as sodic soils, have low to moderate plant production potentials, depending on the location of the sodium-rich horizon within the profile. In the northern Great Plains of the USA excessive annual precipitation resulting in wetter spring soils and higher groundwater levels, in combination with increased commodity prices (Hellerstein and Malcolm, 2011), have resulted in farmers increasing the installation of subsurface tile drainage. However, there are over 4.7 million acres (1.9 million ha) of Na-affected soils within this region (J. Brennan, personal communication, NRCS North Dakota, 2008) and since Na-affected soils are interspersed with high-productivity soils, these too are being tiled. The tile drainage of Na-affected soils can result in clay dispersion and or swelling and reduced water flow through soils as increased percolation will result in selective leaching of higher charge cations thus reducing soil electrical conductivity (EC) and decreasing soil hydraulic conductivity (Sumner and Naidu, 1998). Dispersion and swelling are both related with the thickness double layer of clay in soils, and the thickness of the diffuse double layer is inversely related with the valence charge and ionic strength of solution (Essington, 2004). Ionic strength of solution, associated with the concentration and valence of ions, is positively correlated with EC (Alva et al., 1991). Therefore, when EC is decreased through loss of salts in drainage, the thickness of diffuse double layer is increased, and adjacent diffuse double layers may overlap, resulting in repulsion. This repulsion is the basis for dispersion and swelling. Sodium induced swelling and dispersion are more severe in 2:1 swelling clays (i.e., montmorillonite) that are most common in the northern Great Plains, compared to 1:1 or 2:1 non-swelling clays (Curtin et al., 1994; He et al., 2013).

Swelling is associated with the hydration, and when the force of hydration is greater than electrostatic attractive forces, clay tactoids separate and the distance between them increases (Foster, 1954; Sumner and Naidu, 1998). The Na has a greater hydrated radius compared to other high charge cations and lower charge which results in a weak bridge between clay layers, so bigger quasicrystals (QC) of clay break into smaller clay quasicrystals (clay tactoids) with Na staying on external surface of (Foster, 1954; Grim, 1968; Pils et al., 2007). As more water enters the soil system the cation chemical potential in the clay interlayers and bulk solution become lower than that on the clay mineral surface. Therefore, cations have the potential to diffuse into

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the adjacent bulk solution in order to reduce the enthalpy of the system (Engel and Reid, 2014). When this process continues, clays are more separated and dispersed and finally a new equilibrium will be reached after attractive and repulsive forces equilibrate.

Swelling, associated with water in soils, is related to both Na and electrical conductivity (EC) (Essington, 2004). Swelling reduces soil pore size and therefore reduces saturated hydraulic conductivity (Ksat) (Ben-Hur et al., 2009; Cass and Sumner, 1982) and aeration (Sumner and Naidu, 1998). Considering results in Shabtai et al. (2014), the reduction in Ksat is mainly dominated by swelling and partially by dispersion, both related to Na concentration and EC. In their study when swelling increased from 36 to 97%, measured as the ratio of change in aggregate volume, the Ksat decreased from 400 to 0 mm h^{-1}. In addition, swelling increases gravimetric water retention at field capacity (−33 kPa) (Curtin et al., 1994), increases the soil plastic and liquid limits (Grim, 1968; Kyei-Baffour et al., 2004), decreases trafficability (Earl, 1997), and may increase energy requirements for soil tillage (Guarnieri et al., 2005).

For water retention, ions in soils are hydrated and at least one water molecule exists between the adsorbed ion and clay surface functional group (Essington, 2004). The H in the dipole water molecule in the interlayer space of clay minerals is coordinated to the surface of clay minerals by attraction between H and the surface oxygen layer of Si-tetrahedron in clay minerals (Grim, 1968). The layers of water molecules adsorbed to clays are dependent on the clay charge density, and the interlayer cations. When Na is the dominant cation, the small size of Na allows it to reside in the pseudohexagon of clay silicon tetrahedron sites (Grim, 1968; Velde and Meunier, 2008), and an increase in the thickness of the diffuse-double layer can occur which causes adjacent double layers to overlap which results in repulsion, and finally an increase in interlayer space resulting in more water to be retained (Essington, 2004; Grim, 1968). Initially water rapidly enters to its liquid limit (LL) and beyond, contributing to increased swelling (Grim, 1968; White and Pichler, 1959).

Given the relationship between water retention and swelling, the field capacity water is used as a proxy to indicate swelling. Although it is desirable to determine soil field capacity *in situ*, water retention of air-dried and ground soils in the laboratory (Cassel and Nielsen, 1986) can be more easily investigated compared to *in situ* situations (Bagarello et al., 2006). Although laboratory approaches may not yield a complete picture of sodicity effects in the field, reliance on chemical equilibrium and different time scales can be much better controlled.

In order to supply more food to an increasing population, many marginal lands such as steep sloped and salinized and sodic soils, will continue to be converted to cultivated cropland (Scherr and Yadav, 1996). One engineering approach to improve sodic and saline-sodic soils will be to install subsurface drainage. Improved knowledge of water retention and swelling in sodic soils is essential so that these sodic lands are not further degraded with selective leaching of higher charge cations, reduction in soil and soil hydraulic conductivity during drainage. The objective of this research was to determine the influence of Na and EC on the amount of water retained at field capacity (−33 kPa) in northern Great Plains Na-affected soils.

2. Materials and methods

2.1. Soil samples

Soil samples were obtained from four different soil series from eastern North Dakota (Table 1). The series were Exline (Fine, smectitic, frigid Leptic Natrudolls), Stirum (Coarse-loamy, mixed, superactive, frigid Typic Natraquolls), Ryan (Fine, smectitic, frigid Typic Natraquerts), and Bearden-saline phase (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls). All samples were collected from the 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm depths. After collection, the soils were air-dried, ground, and sieved (<2 mm). Particle size distribution was determined using the hydrometer method (ASTM 152-H Soil Hydrometer, H-B Instrument Co.) following the procedure of Gee and Bauder (1986). Saturated paste extracts for soil were prepared following the standard method described by U.S. Salinity Laboratory Staff (1954). From saturated paste extracts, pH, ECe and SARe were determined using a pH meter (13-636-AB15B, Fisher Scientific), EC meter (Sension 378; Hach Co., Loveland, CO, USA), and atomic absorption spectroscopy (AAS) (Model 200A; Buck Scientific, Inc.), respectively. Soil cation exchange capacity (CEC) was determined by 1 M NaOAc treatment, washed by 95% ethanol followed by 1 M NH_4OAc extraction, and Na quantified using AAS. The exchangeable sodium percentage (ESP) was determined according to Eq. (1) (Soil Survey Staff, 2011, method 4.5.6.1.2).

$$\mathrm{ESP} = 100[\mathrm{Na}_{\mathrm{ex}} - (\mathrm{Na}_{\mathrm{ws}}(\mathrm{H_2O}_{\mathrm{ws}}/1000))]/\mathrm{CEC} \tag{1}$$

where Na_{ex} = extractable Na (NH_4OAc extractable Na as described above, cmolc kg^{-1}), Na_{ws} = water-soluble Na (mmolc L^{-1}) determined from saturated paste extract, H_2O_{ws} = water saturation percentage of

Table 1
Taxonomic classification and physical and chemical properties of the studied soils.

Soil series	Depth cm	Soil texture			Soil saturated paste extract				Total $CaCO_3$ %	CEC cmol kg^{-1}	ESP %	Ca/Mg	XRD of minerals[b]
		Sand	Silt	Clay	SP[a]	EC_e	pH_e	SAR_e					
		g kg^{-1}			%	dS m^{-1}							
Exline	0–15	575	226	200	48.4	1.47	8.0	7.38	0.12	12.7	6.36	0.73	
	15–30	557	243	200	46.1	1.70	8.4	14.1	0.08	11.3	10.6	0.75	
	30–60	649	152	200	49.3	2.27	8.8	23.9	0.86	9.2	28.2	0.79	
	60–90	392	245	363	73.3	2.12	8.8	27.6	15.1	12.7	20.6	0.64	Sm, Kao, I, Qz
Stirum	0–15	629	184	188	46.7	1.36	8.3	4.71	1.75	11.5	4.47	0.82	
	15–30	644	119	238	44.3	1.33	8.7	9.30	1.92	11.8	10.1	0.86	
	30–60	661	114	225	36.8	1.60	8.6	11.6	1.58	8.5	14.2	0.82	
	60–90	573	177	250	42.6	1.32	8.9	17.5	10.9	7.5	18.5	0.88	Sm, Kao, I, Qz
Ryan	0–15	84.0	389	528	84.6	9.60	8.0	10.0	0.5	25.3	4.60	0.34	
	15–30	45.0	300	655	86.9	13.0	8.0	12.0	1.23	25.0	8.03	0.42	
	30–60	36.0	315	650	79.6	12.5	7.9	13.4	15.1	20.7	9.29	0.50	Sm, Kao, I, Qz
	60–90	47.0	303	650	83.2	11.6	7.9	13.2	16.1	20.2	10.4	0.30	
Bearden	0–15	159	591	250	57.2	10.2	7.7	3.05	0.95	21.3	2.81	1.03	
	15–30	139	606	255	57.4	9.25	7.7	3.47	1.32	20.3	2.56	1.32	Sm, Kao, I, Qz
	30–60	103	622	275	46.4	7.79	7.8	3.16	17.4	12.4	2.92	0.91	
	60–90	58.0	567	375	61.2	6.73	7.8	2.70	15.7	14.1	3.72	0.69	

[a] SP, saturation percentage or gravimetric water content of soil saturated paste.

[b] Sm, smectite; Kao, kaolinite; I, illite; Qz, quartz.

the saturated paste, CEC = CEC as determined above (cmolc kg^{-1}), 1000 = conversion factor to (cmolc kg^{-1}), and 100 = conversion factor to percent. Total calcite present in soils was determined from a modified version of Sherrod et al. (2002). Mineralogy of the clay fractions was determined for the 4 soil samples with the greatest SAR using X-ray diffraction (XRD) (Whittig and Allardice, 1986) (Table 1).

2.2. Field capacity water

In this study, the field capacity water (FCW) was used as an indicator for swelling (Curtin et al., 1994). Field capacity water is the upper limit of water that can be used by plants from soils (Cassel and Nielsen, 1986). Swelling of sodic soils is associated with clay interlayer spacing ion hydration and water accumulation (Essington, 2004; Grim, 1968) and therefore, FCW was used to indicate the extent of sodic soil swelling in this study. Treatment solutions were prepared with the same SAR simulating the SARe of each depth of soil. At respective SAR solutions, six EC levels (0.5, 1, 2, 4, 8, and 15 dS m^{-1}) were prepared using NaCl, $CaCl_2$, $MgCl_2$, and deionized (DI) water. Solutions were prepared following He et al. (2013) based on Eqs. (2) and (3):

$$SAR = Na^{+}/\left(\left(Ca^{2+} + Mg^{2+}\right)/2\right)^{1/2} \tag{2}$$

$$EC = \sum(C_i f_i). \tag{3}$$

In Eq. (2), the unit of ion concentration is mmol L^{-1}. In Eq. (3) the EC is assumed to be obtained by summing product values of each ion concentration (C_i) of species i in solution (Na^+, Ca^{2+}, Mg^{2+}, and Cl^-) (mg L^{-1}) with the conductivity factor (f_i) for each ion species, where f_i equals 2.13, 2.60, 3.82, and 2.14 (μS cm^{-1} per mg L^{-1}), respectively, and the unit for EC is μS cm^{-1} (Tolgyessy, 1993). In order to solve the amount of salts required to prepare the target solution using both equations, ions in Eq. (2) were converted from mmol L^{-1} into mg L^{-1} for Eq. (3). For example, the Na, Ca, and Mg mmol L^{-1} in Eq. (2) were converted into mg L^{-1} in Eq. (3) as 23 × Na, 20 × Ca, and 12 × Mg mg L^{-1}, and Cl can be expressed as 35.5 × (Na + Ca + Mg). The detailed step-by-step unit conversion and calculation can be found in He et al. (2013). During preparation, although the Ca/Mg ratios of the soils were not all 1:1 (Table 1) this ratio was adopted for all solutions since Ca and Mg have been shown to have similar beneficial flocculating effects (He et al., 2013; Rahman and Rowell, 1979; U.S. Salinity Laboratory Staff, 1954; Yousaf et al., 1987). The SAR and EC of solutions were all rechecked by AAS (Model 200A, Buck Scientific) and a conductivity meter (Sension 378, Hach Co.), respectively. The actual EC was very similar to the target EC at low values, varying only slightly, but EC varied higher at high EC (Marcus and Hefter, 2006). For example, for target EC of 15 dS m^{-1} the actual value was 12.1 ± 0.35, while for target EC of 1 dS m^{-1}, the value was 0.97 ± 0.02. Actual SARe of the solution was very similar to the target SAR. The large deviation of EC values was probably associated with ion-pairing and the corresponding activity reduced, thus a reduction in EC (Faure, 1998).

The influence of SAR and EC on FCW was determined by measuring the amount of water retained at an applied pressure of −33 kPa (Curtin et al., 1994). Each EC solution at the respective SAR of the depth was added to the ceramic plate to the height of the soil-containment ring (5 cm diameter, height of 1 cm) and allowed to saturate for 20 h. Pressure (−33 kPa) was then applied for 48 h followed by determination of gravimetric soil water content. For each EC-SAR combination, four replications were used. Between runs the ceramic plate was first washed by DI water to remove soil particles from the plate surface followed by being washed using the next treatment solution. For example, if the next treatment solution to be used was SAR = 14 and EC = 8 dS m^{-1}, this solution was added onto the ceramic plate then subjected to pressure to drain out remnant solution from the previous solution until the drainage stopped. Using the methods described above another solution was prepared having a target SAR of 0 and EC of 15 dS m^{-1} with only $CaCl_2$ and $MgCl_2$ salts and was used as a reference solution for each soil and depth. This solution was used to best describe FCW if the soils were not impacted by Na. The gravimetric soil water content was determined as above.

In addition, high natural salts (high EC) existed in Ryan and Bearden soils, so washing steps were conducted for both soils to evaluate the influence of salts before and after salt wash. One depth from each series was washed of naturally occurring salts (Table 1) and was accomplished by shaking using 50 g of soil with 150 mL of washing solution (SAR = 0 and EC = 15 dS m^{-1}) for 12 h. The solution was centrifuged at a relative centrifuge force of 4870 ×g for 20 min. The supernatant was discarded and the entire process repeated three times. After equilibration, soil was washed three times with 150 mL of 95% ethanol to remove excess ions. Finally, the equilibrated soil samples were air-dried and ground to pass through a 75 μm sieve for further FCW determination. Exchangeable cations (Ca, Mg, or Na) after washing were determined using 1 M NH4OAc following the methods of Warncke and Brown (1998).

2.3. Statistical analysis

Analysis of variance (ANOVA) was performed using the PROC ANOVA procedure in SAS 9.3 (SAS Inc., Cary, NC). The effect of successive values of EC at the same SAR for each soil depth was evaluated. For each soil, the effect of solution SAR at each solution EC was also evaluated. All comparisons were done using SAS and differences were assessed using Fisher's least significant difference (LSD) test. The difference of FCW obtained at respective SAR and EC of 15 dS m^{-1} solution were compared to that at reference line of each depth of soil by a t-test using MINITAB Student Release 14 (1972–2003 Minitab Inc.).

3. Results and discussion

3.1. Soil properties

The main differences in native soil properties were clay content and EC where the Exline and Stirum soils were lower in both properties (Table 1). Sodium adsorption ratios generally increased with depth and ranged from 2.7 to 27.6 across all soils. Based on the XRD analyses, and the CEC values, the dominant clay mineral for all soil samples were smectite (montmorillonite). Using Handbook 60 (U.S. Salinity Laboratory Staff, 1954) the Exline and Stirum were classified as sodic, Ryan as saline-sodic, and Bearden as saline.

3.2. Effect of electrical conductivity

Water retention increased as EC decreased for Exline at two depths and Stirum soil for three depths. A graphical representation of this relationship for two depths of the Exline soil can be seen in Fig. 1. Here, from a high to low EC, at a SAR of 6.57 there was a 14% increase in FCW whereas at an SAR of 26.4 there was a 47% increase. Although exceptions exist, the Exline and Stirum soils had significantly different ($P < 0.001$) FCW across EC for the same depth of soil at the same SAR (Table 2). The comparisons for the EC effect were conducted at the same depth for each soil. Curtin et al. (1994) reported that for five Canada soils swelling could occur at high EC which was different from the situation of dispersion where a more defined value of EC dictates dispersion or not.

Smaller FCW differences across EC levels at the same SAR existed for the Ryan and Bearden soils, which may have been due to their high natural soluble salts concentrations and subsequent EC (Table 1). Even though the high natural salts of Ryan and Bearden were changed by equilibration with the treatment solution, the treatment EC effect across the same depth was not significantly different. It is probably related to the fact that when EC of soils is high, the ionic strength (I) of soil is

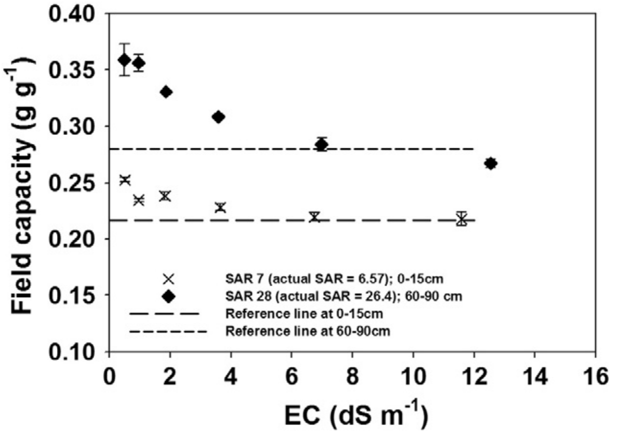

Fig. 1. Example relationship between field capacity and solution EC for Exline soil from two depths.

also high (Alva et al., 1991), the thickness of diffuse-double layer is small, where the thickness of the diffuse-double layer is inversely related with the valent charge of each cation and I (Essington, 2004). During this condition adjacent diffuse-double layers do not overlap and cause repulsion, and thus swelling is prohibited. The high clay content of these soils likely also contributed to water not being drained out under pressure. The washing steps remove the natural soluble salts out of soils. When salts were washed from the Ryan and Bearden soils the effect of solution EC on water adsorption was significantly greater than before salts were washed out (Fig. 2). This indicates that high levels of EC would be beneficial for prohibiting clay separation and extra water imbibing for soils with high SAR. The result is consistent with the results from Ben-Hur et al. (2009) where DI water resulted in a greater swelling value than saline water for both clay and loamy-sand soils. However, high EC is normally not desirable for growing most plants (Ogle et al., 2004).

As noted by many authors, each soil has threshold concentrations (the minimum salt solution to prevent soil from dispersion) of EC at a SAR, so that swelling and/or dispersion may not occur (He et al., 2013; Panayiotopoulos et al., 2004; Quirk and Schofield, 1955). In our study, the general threshold EC across all soils was greater than 4 dS m^{-1} but less than 8 dS m^{-1}, and was obtained by comparing the LSD across successive EC values for each depth of soil (Table 2). An EC value was thought to be a threshold EC when the value above this specific value did not have a significant effect on the FCW. Changes in water holding capacity are attributed to clay swelling because at low EC values the Na present on external clay surfaces begins to migrate into the clay-sheet interlayers of quasicrystals of smectite whereby it replaces/demixes other monovalent and divalent cations (Pils et al., 2007).

The effect of EC on FCW in our study indicates a reduction in soil condition that may occur during tile drainage. For example, Pons et al. (2000) showed that the effects of sodium decreased macropores, which in turn inhibited early winter wheat (*Triticum aestivum* L.) root development. In addition, clay swelling in deeper soil horizons together with dispersion adversely affects soil structure for water movement and drainage performance (Dikinya et al., 2006).

3.3. Chemical factors (SAR and $CaCO_3$) effect

Sodium adsorption ratios had significantly different ($P < 0.05$) effects on FCW within respective soils across depth, where FCW increased with SAR (Fig. 3). This effect was most noticeable for the Exline and Stirum soils which also had the greatest ranges in SAR (Table 2). The SAR effect was decreased as the EC of the solution increased from 0.5 to 15 dS m^{-1} (Fig. 3). However, the effect of SAR was not noticeable for Ryan and Bearden soils at constant EC. The FCW at reference treatment solutions were compared with that treated by the highest EC (15 dS m^{-1} in our study), which was used to mimic a soil not impacted by the negative effects of Na, and found to be no significant difference for most of soils. This indicates that different values of FCW at the highest and lowest EC of the same soil sample can be viewed as estimation of magnitude of swelling. For example, for Exline at depth of 0 to 15 cm, FCW at EC of 15 dS m^{-1} (0.22) was subtracted from the value at EC of 0.5 dS m^{-1} (0.25), where the difference between 0.22 and 0.25 is the magnitude of swelling $(0.25–0.22) / 0.25 * 100 = 12\%$ (Table 2).

The possible beneficial effect of $CaCO_3$ on soil water retention can be associated with the pozzolanic reaction (Guney et al., 2007), cation exchange, flocculation and aggregation (Muller, 2005). The pozzolanic reaction occurs only at pH values greater than 12 as a result of the application of $Ca(OH)_2$, commonly done in engineering projects where as the clay minerals dissolve and react with calcium hydroxide the formation of calcium-silicate-hydrate and calcium-aluminate-hydrates occurs and cements soils (Al-Mukhtar et al., 2012; Muller, 2005). However, since the pH of $CaCO_3$ rich soils, such as those in our study, are not greater than 8.2 (Lindsay, 2001) cementing by pozzolanic

Table 2
Gravimetric field capacity water content at −33 kPa under each combination of solution SAR and EC.

Soil	Depth cm	SAR[b]	Electrical conductivity values (dS m^{-1})[a]					
			0.48 (0.03)	0.97 (0.02)	1.85 (0.03)	3.67 (0.22)	6.84 (0.22)	12.35 (0.34)
			g g^{-1}					
Exline	0–15	7.07 (0.73)	0.25a[c] D[d]	0.23b D	0.24b C	0.23c C	0.22d B	0.22d B
	15–30	12.2 (0.95)	0.28a C	0.26b C	0.25b C	0.23c C	0.22c B	0.19d C
	30–60	21.4 (2.07)	0.31a B	0.28b B	0.27c B	0.25d B	0.21e C	0.18f C
	60–90	26.1 (2.31)	0.36a A	0.36a A	0.33b A	0.31c A	0.28d A	0.27e A
Stirum	0–15	4.95 (0.26)	0.19a C	0.19a BC	0.20a A	0.19a A	0.19a A	0.19a A
	15–30	8.85 (0.52)	0.22a B	0.20ab B	0.20ab A	0.18bc A	0.18bc A	0.17c B
	30–60	11.6 (0.46)	0.18a D	0.17b C	0.17b B	0.15c B	0.15c B	0.14d C
	60–90	18.6 (2.31)	0.24a A	0.24a A	0.20b A	0.19c A	0.18c A	0.16d B
Ryan	0–15	10.9 (0.67)	0.53ab A	0.53ab A	0.54a A	0.52bc A	0.52bc B	0.51c B
	15–30	12.6 (0.95)	0.51 cd B	0.52ab A	0.51bcd B	0.51d A	0.53a A	0.52abc A
	30–60	13.3 (0.84)	0.43a C	0.43a B	0.43a C	0.43a B	0.44a C	0.44a C
	60–90	13.3 (0.84)	0.44bc D	0.45ab C	0.45a D	0.44bc B	0.43ab D	0.43c D
Bearden	0–15	3.92 (0.31)	0.36a A	0.35bc A	0.35bc A	0.34c A	0.35b AB	0.35bc B
	15–30	3.92 (0.31)	0.36ab A	0.35b A	0.36ab A	0.34b A	0.37a A	0.36ab A
	30–60	3.52 (0.31)	0.30a C	0.29ab C	0.28bc C	0.28 cd C	0.27d C	0.27d D
	60–90	2.61 (0.44)	0.32c B	0.32c B	0.33a B	0.32ab B	0.33a B	0.32b C

[a] The values for electrical conductivity are average values and the number inside parentheses are standard deviations.
[b] The average SAR values of solution that were produced to match original soil SARe, the values inside parentheses are standard deviation.
[c] Different lowercase letters in each row indicate that the field capacity was significantly different ($P \leq 0.05$) between EC values at the same SAR.
[d] Different uppercase letters in each column for each soil indicate that the field capacity was significantly different ($P \leq 0.05$) between SAR values in different depths at the same EC.

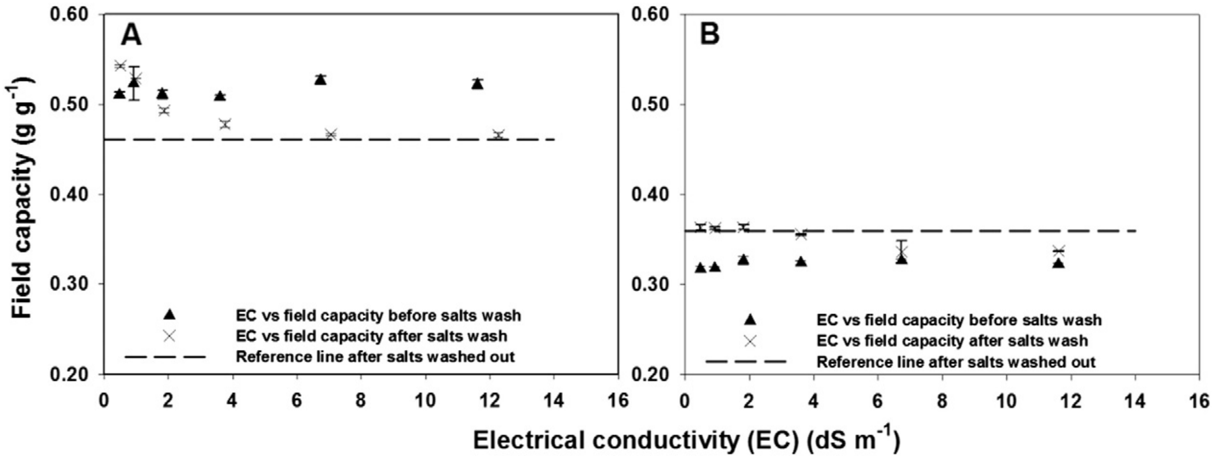

Fig. 2. Change of field capacity with EC before and after salts were washed out for A: Ryan at depth of 15–30 cm and B: Bearden at depth of 60–90 cm.

reaction was not likely. The $CaCO_3$ can dissolve to provide Ca to replace Na on soil exchange site but EC is not likely to change due to the low solubility of $CaCO_3$ (Muller, 2005). Calcium carbonate may however help reduce swelling through its bridging across soil particles at their contact boundary which increases soil stability (Cheng et al., 2013). Further exploration of $CaCO_3$ bridging may allow for its increased use in sodic soils where trafficability is oftentimes problematic. For example, high $CaCO_3$ values existing in 30 to 90 cm depth soils may help to prevent swelling and to explain why there were no significant differences in FCW.

3.4. Implications for subsurface drainage

Results in our study support that both SAR and EC are responsible for swelling, which has been stated by many authors (Ben-Hur et al., 2009; Curtin et al., 1994; Sumner and Naidu, 1998). The results can also be applied to field soils since SAR increases with depth in many North Dakota soils (McClelland et al., 1959). The reduction of EC due to salt loss through tile drainage likely contributes to swelling in sodic zones and may help to explain the phenomenon that the drainage performance in some sodium-affected soils decreases after several growing seasons (Cihacek et al., 2012; Hopkins et al., 2012). Tile drainage is also being used to remediate saline and saline-sodic soils, for example in China (Wang et al., 2007), where the Chinese government has implemented a 121.4 million ha “red line” agricultural land quota which will likely bring marginal lands such as these into production.

Each soil-Na level has a threshold EC (Quirk and Schofield, 1955) that needs to be maintained to minimize swelling and to improve soil structural stability and water movement. Shabtai et al. (2014) and Zhu et al. (2013) had similar results and reported in bentonite and smectitic clays where Ksat decreased from 3.2 to 0.7×10^{-6} mm h^{-1} with the increase of final swelling pressure from 3 to 4.5 MPa. Using the relationships developed by Curtin et al. (1994) and Shabtai et al. (2014), swelling values by as little as 16–25% can decrease Ksat to one third of the original value. The swelling value at the lowest EC in Curtin et al. (1994) and Shabtai et al. (2014) studies were used as reference values and the reference value unit is water content (g H_2O kg^{-1}) for Curtin et al. (1994), and swelling percentage for Shabtai et al. (2014). Therefore, results from above studies of Shabtai et al. (2014) and Zhu et al. (2013) were used to estimate the effect of swelling on water movement (Ksat) in our study. Therefore, if tile drainage was responsible for decreasing EC from 4 to 0.5 dS m^{-1} and SAR remained constant at 14 (Exline soil) (Table 2), Ksat can be predicted to decrease to about one third of its original value. Although this relationship is not likely to be linear, decreasing EC without decreasing the relative ratio of Na in soil will undoubtedly decrease water movement and expected tile performance.

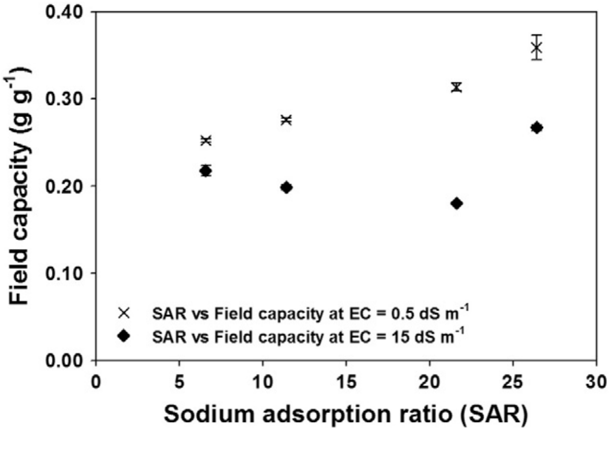

Fig. 3. Example relationship between field capacity and solution SAR for Exline soil from two EC levels of 0.5 and 15 dS m^{-1}.

Limitations may exist for applying this study's laboratory results to the field settings, and more environmental factors have to be considered to allow for field assessment. For example, the freeze and thaw process in northern Great Plains soils would result in accumulation of winter deposits of salts in the freezing zone from the shallow water table and leaching of salts in spring snow melt (Fullerton and Pawluk, 1987; Miller and Brierley, 2011). The resulting redistribution of salts would be expected to influence EC, soil water retention, and therefore drainage. The spatial variability in soil series and textures in the field is another factor that will influence water movement (Ben-Hur et al., 2009), as would crops that were planted and their rooting depths (Ghane et al., 2012). Bulk density, influencing water storage and permeability, may change and decrease after many years as result of tile drainage as found by Bucur and Moca (2012).

4. Conclusion

Soil Na and soluble salt concentrations were found to be two important chemical factors influencing FCW, an indicator of swelling in our study, where FCW generally increased as SAR increased and EC decreased. However, an increase in percent $CaCO_3$ appears to help decrease the likelihood of the soil retaining excess FCW, irrespective of EC. These results indicate that maintaining an EC level above 4 dS m^{-1} may prevent swelling. In addition, if tile drainage removes soluble salts from those soils that have an SAR greater than 5, the FCW may increase and thus decrease the rate of water movement. Long-term management plans for these problem soils should include chemical amendments such as gypsum, elemental S, or possibly agricultural lime as a means to improve EC, and to provide Ca for Na replacement.

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