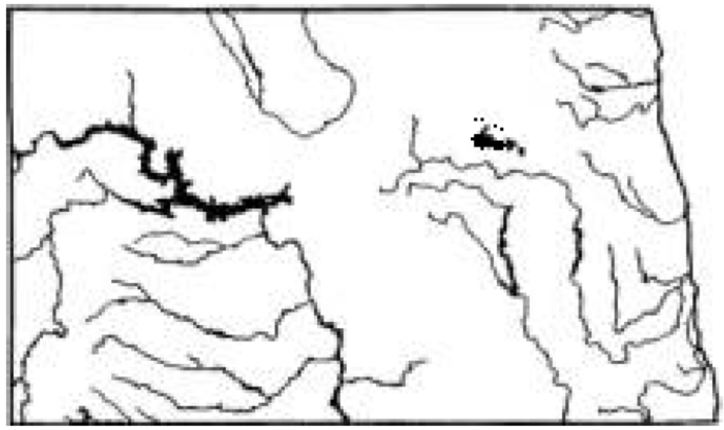

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by

Yangbo He
Thomas DeSutter
Soil Science Department
North Dakota State University
Fargo, ND58108

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Yangbo He[1]
Thomas DeSutter[2]
Soil Science Department
North Dakota State University
Fargo, ND58108

WRRI Graduate Research Fellow[1]
Associate Professor[2], Soil Science Department
North Dakota State University
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ABSTRACT

North Dakota has over 1.9 million ha of sodium-affected soils, influencing water movement and crop production. Study examined different aspects of sodic soils. Swelling is associated with hydration of clays, which forces clay tactoids to separate. Four soil series from North Dakota field sites were used. To assess swelling, field capacity (FC) was used as proxy. The study found that soil Na and soluble salt concentrations were two important chemical factors influencing FCW. The FCW increases with increased SAR and lower levels of EC. These results indicate that maintaining an EC level above 4 dS m^{-1} may mitigate swelling, which is an issue considered in tile drainage.

Over- and under-application of amendments in sodic soils was studied in a 8.1 ha sodic soil field. At each site, samples were taken from two depths; electromagnetic (EM38) and elevation readings were done. Elevation was significantly correlated with soil variables except for Na%. The EM38 was reliable to express soil EC and was correlated with Na% and dispersion. Therefore, conducting the EM38 and RTK may allow site-specific management of Na. Improved knowledge of sodic soils dispersion, swelling, and field distribution will benefit researchers and farmers in managing their fields.

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FIELD CAPACITY WATER AS INFLUENCED BY NA AND EC: IMPLICATIONS FOR SUBSURFACE DRAINAGE

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 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 tile-drained Na-affected soils. The impact of six EC levels on the amount of water retained in the soil at field capacity was determined in subsurface soil collected from four sodium-affected soils. Field capacity water (gravimetric water content) for all soils increased with increasing and decreasing sodium absorption ratio (SAR) and 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 increased from 7 to 28, respectively. For the same soil, 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; the presence of calcite in these soils may have reduced the potential for water retention and may have reduced field capacity values. 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.

Introduction

Many sodium-affected 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 sodium-affected soils within this region (J. Brennan, personal communication, NRCS North Dakota, 2008) and since sodium-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 reduced water flow through soils (Sumner and Naidu, 1998). 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 of clays, and when the force of hydration is greater than electrostatic attractive forces, clay sheets layers separate and the distance between them increases (Foster, 1954; Sumner and Naidu, 1998). Dispersion occurs when repulsive forces continue to be greater than attractive forces, clay particles separate into individual particles (Sumner and Naidu, 1998). The hydration of Na forces clay layers apart and results in a weak bridge between clay layers due to their low charge, so bigger quaisicrystals (QC) of clay break down into smaller ones 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 the adjacent bulk solution by diffusive forces (as the repulsive forces) in order to reduce the enthalpy of the system (Engel and Reid, 2012). When this process continues, clays are more widely separated, i.e. dispersed, and finally a new equilibrium will be reached after attractive and repulsive forces equilibrate. However, the Na induced shrink and swell path is not reversible in situations of dominant water loss compared to the shrink and swell path of normal swelling soils (Tripathy et al., 2002).

The specific mechanism for swelling is related to both Na and electrical conductivity (EC) (Essington, 2004). Swelling reduces soil pore size and therefore reduces saturated hydraulic conductivity (K_{sat}) (Ben-Hur et al., 2009; Cass and Sumner, 1982) and aeration (Sumner and Naidu, 1998). In addition, swelling increases gravimetric water retention at field capacity (-33 kPa), 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). To prevent further land degradation, improved knowledge of soil swelling and water retention at field capacity is needed. 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 tile drained, Na-affected soils.

Materials and Methods

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). The pH, ECe and soluble cations (SARe) were determined from saturated paste extracts and were subsequently analyzed using a pH meter (13-636-AB15B, Fisher Scientific), EC meter (Sension 378; Hach Co., Loveland, CO, USA), and by atomic absorption spectroscopy (AAS) for calculation of SAR (Model 200A; Buck Scientific, Inc.). Soil cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were calculated (USDA-NRCS, 2011). 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 four soils with the greatest SAR using X-ray diffraction (XRD) (Whittig and Allardice, 1986) (Table 1). The general analysis can be found in Appendix Fig. B1 to B4.

Field capacity water

In this study, the field capacity water (FCW) will be used as an indicator for swelling (Curtin et al., 1994). Solutions were prepared with the same SAR simulating the SARe of each depth of soil. At each SAR, 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 Eq. (1) and (2):

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

$$EC = \sum (C_i f_i) \tag{2}$$

where the assumption in Eq. (2) is that EC is obtained by summing product values of each ion (*i*) 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 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). During preparation, the Ca/Mg ratio of 1:1 was adopted which may be different from the actual Ca/Mg ratios in actual soil samples since the Ca/Mg ratio was found to have no significant influence on pure montmorillonite dispersion (He et al., 2013). The SAR and EC of solutions were all rechecked by AAS (Model 200A, Buck Scientific) and 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 influence of SAR and EC on FCW was determined by measuring the amount of water imbibed at an applied pressure of 33 kPa, which is a gravimetric water content **(**Curtin et al., 1994). Each EC solution at the respective SAR 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 soil and EC-SAR combination, four replications were used. The ceramic plate was washed between runs using deionized water.

Another solution was prepared having SAR of 0 and EC of 15 dS m^{-1} 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.

To determine the exchangeable cations and ESP in the high EC soils (Ryan and Bearden soils) one depth from each series was washed of naturally occurring salts (Table 1). Washing 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 670 × *g* for 20 minutes. 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 was air-dried and ground to pass through a 75 μm sieve.

Exchangeable cations (Ca, Mg, or Na) and ESP were determined following the methods of Warncke and Brown (1998).

Statistical analysis

Analysis of variance (ANOVA) was performed using the PROC ANOVA procedure in SAS 9.3 (SAS Inc., Cary, NC). Effect of successive values of EC at the same SAR and the overall SAR effect for different depth of soil FCW at the same EC were compared by SAS by using least significant difference (LSD) to test for differences. 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.).

Results and Discussion

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 as depth below the soil surface increased and ranged from 2.7 to 27.6 across all soils. Based on the CEC and XRD analyses the dominant clay mineral in each of the four samples was smectite (montmorillonite). Using Handbook 60 (U.S. Salinity Laboratory Staff, 1954) the Exline, Stirum, Ryan, and Bearden soils were generally classified as sodic, sodic, saline-sodic, and saline, respectively.

Effect of electrical conductivity

Although not all of the reference-solution FCW values were significantly different from FCW obtained at EC of 15 at each respective SAR (Table 3), the differences between respective depths were small. Therefore, FCW can help to indicate the degree of swelling using the FCW obtained at an EC = 15 dS m^{-1}, at least up to the SAR values in Table 1.

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

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

† SP, Saturation percentage of saturated paste.

‡ Sm, Smectite; Kao, Kaolinite; I, Illite; Qz, Quartz.

Water adsorption increased as EC decreased and 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). These results were similar to those of Curtin et al. (1994) who reported that in 5 of 6 southern Saskatchewan Canada soils water retention had a greater response to SAR than EC.

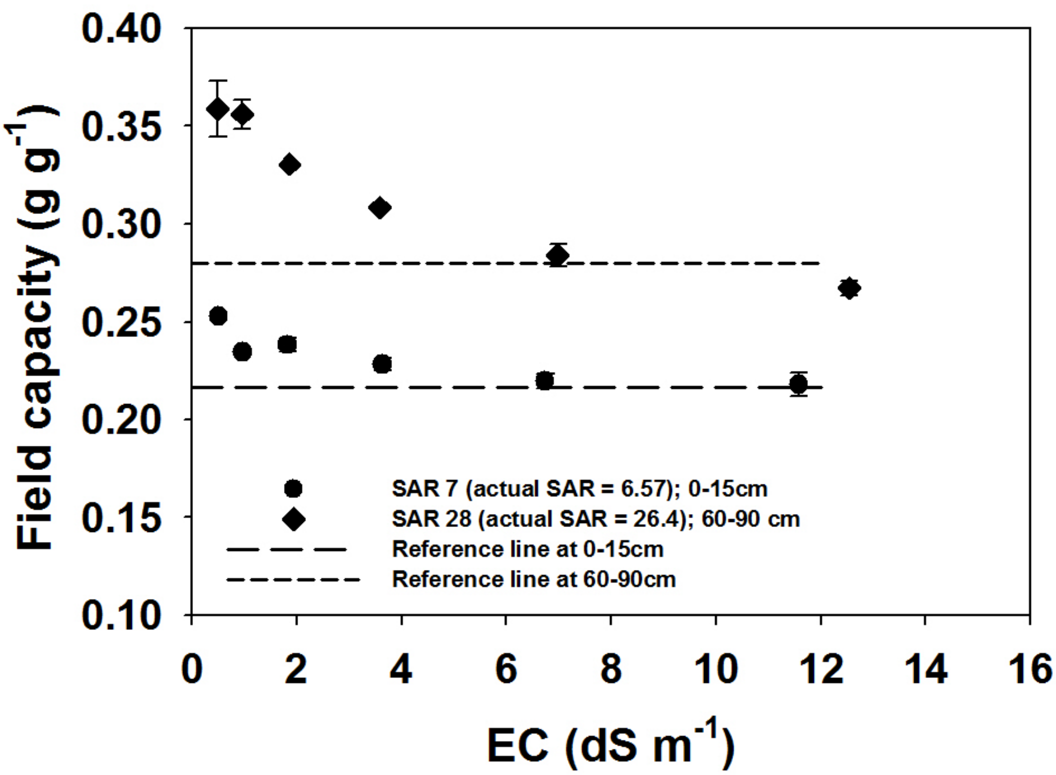

Fig. 1. Relationship between field capacity and solution EC for Exline soil from two depths.

Conversely, fewer differences existed for the Ryan and Bearden soils, which may have been due to their higher salt levels or the inability to reduce their natural soluble salt concentrations (Table 1) during the saturation step. 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 deionized 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).

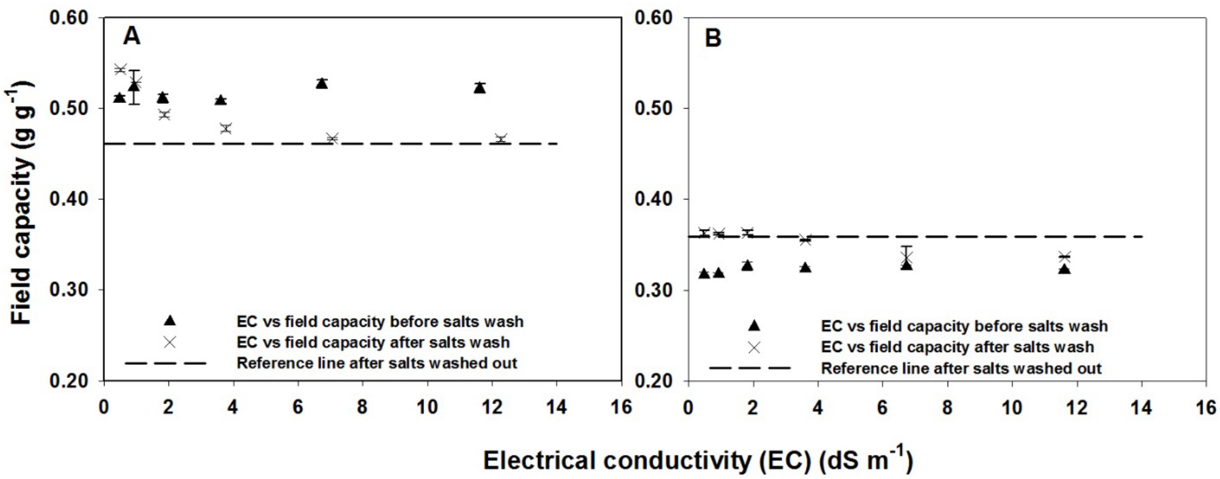

Fig. 2. Change of field capacity with EC before and after salts were washed out for A: Ryan soil at depth of 15-30 cm and B: Bearden soil at depth of 60-90 cm.

The removal of salts using the washing steps could be considered as a drainage simulation, and similar to the findings of Bao et al. (2013) who observed a decline of soil EC due to subsurface drainage. As noted by many authors, each soil has threshold concentrations (the minimum salt solution to prevent soil from dispersion) of EC and 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 threshold EC across all SAR values was about 4 dS m^{-1} (Table 2).

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 small size of Na allows it to reside in the pseudohexagon of clay silicon tetrahedron sites causing an increase in the “water net” thickness and swelling (Grim, 1968; Velde and Meunier, 2008). Disruption of the “water nets” and reduction of soil swelling occurs when Ca is present and when the EC of the soil solution is high, both conditions required to decrease the thickness of the diffuse-double layer (Grim, 1968; Pils et al., 2007). The decreasing sizes of the quasicrystals allow for more swelling and imbibed water, and may lead to dispersion (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 porosity of a sodium-affected soil decreased (no 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).

Chemical factors (SAR and CaCO3) effect

Sodium adsorption ratios had significantly different ($P < 0.05$) effects on FCW at different soil depths, 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. In order to compare to relatively healthy soils, the FCW at reference treatments were compared with that treated by highest EC (15 dS m^{-1} in our study) and found to be no significant difference for most of soils (Table 3). This indicates that different values of FCW at the highest and lowest EC of the same soil can be viewed as estimation of magnitude of swelling.

The presence of $CaCO_3$ may also influence water absorption for soils. For example, the 30 to 90 cm depths for the Ryan and Bearden soils had much greater concentrations of $CaCO_3$ than the upper depths of these two soils (Table 1). The FCW of the deeper depths was generally significantly lower than the upper soil depths with only $CaCO_3$ being greatly different (Table 2). Calcium hydroxide ($Ca(OH)_2$) is commonly used in civil engineering projects to stabilize swelling soils through “pozzolanic activity” (Bell, 1996; Guney et al., 2005). In this pozzolanic activity the reaction occurs at a very high pH (greater than pH 12) due to $Ca(OH)_2$ (Guney et al., 2005), which is not naturally found in northern Great Plains soils. Due to the low solubility of $CaCO_3$ it is unlikely that EC will be increased more than about 0.3 dS m^{-1} at saturation to effectively control excessive swelling, as was hypothesized by Keren and Ben-Hur (2003). The low solubility of $CaCO_3$ is a major factor in why it is not regularly used for sodium-affected soil management. The likely reason why $CaCO_3$-enriched soils had lower FCW than the upper soils was due to pore soil particle cementation (Cheng et al., 2013). At field capacity or lower water saturation concentrations, $CaCO_3$ bridges across soil particles, increasing soil stability, and thus likely minimizing swelling. Further exploration of $CaCO_3$ bridging may allow for increased use of calcium carbonate ($CaCO_3$) for sodium-affected soil management, and thus increased trafficability across these problem soils.

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

Soil	Depth	Target SAR‡	Target electrical conductivity values (dS m^{-1})†					
			0.5	1	2	4	8	15
	cm		----Water content (g g^{-1})----					
Exline	0-15	7	0.25a§ D#	0.23b D	0.24b C	0.23c C	0.22d B	0.22d B
	15-30	14	0.28a C	0.26b C	0.25b C	0.23c C	0.22c B	0.19d C
	30-60	24	0.31a B	0.28b B	0.27c B	0.25d B	0.21e C	0.18f C
	60-90	28	0.36a A	0.36a A	0.33b A	0.31c A	0.28d A	0.27e A
Stirum	0-15	5	0.19a C	0.19a BC	0.20a A	0.19a A	0.19a A	0.19a A
	15-30	9	0.22a B	0.20ab B	0.20ab A	0.18bc A	0.18bc A	0.17c B
	30-60	12	0.18a D	0.17b C	0.17b B	0.15c B	0.15c B	0.14d C
	60-90	18	0.24a A	0.24a A	0.20b A	0.19c A	0.18c A	0.16d B
Ryan	0-15	10	0.53ab A	0.53ab A	0.54a A	0.52bc A	0.52bc B	0.51c B
	15-30	12	0.51cd B	0.52ab A	0.51bcd B	0.51d A	0.53a A	0.52abc A
	30-60	14	0.43a C	0.43a B	0.43a C	0.43a B	0.43a C	0.43a C
	60-90	13	0.44bc D	0.45ab C	0.45a D	0.44bc B	0.44ab D	0.44c D
Bearden	0-15	3.0	0.36a A	0.35bc A	0.35bc A	0.34c A	0.35b AB	0.35bc B
	15-30	3.5	0.36ab A	0.35b A	0.36ab A	0.34b A	0.37a A	0.36ab A
	30-60	3.2	0.30a C	0.29ab C	0.28bc C	0.28cd C	0.27d C	0.27d D
	60-90	2.7	0.32c B	0.32c B	0.33a B	0.32ab B	0.33a B	0.32b C

† Target EC values were used here since variation of actual EC values occurred for all soils and depth compared to target EC.

‡ Target SAR values were produced to match original soil SARe.

§ Different lowercase letters in each row indicate that the field capacity was significantly different between EC values at the same SAR.

Different uppercase letters in each column for each soil indicate that the field capacity was significantly different between SAR values in different depths at the same EC.

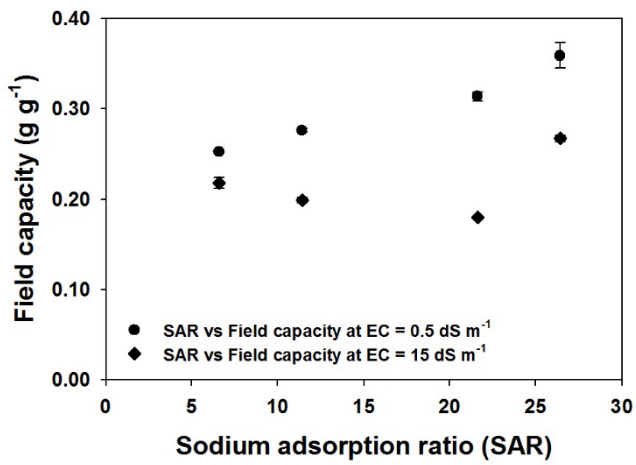

Fig. 3. Example relationship between field capacity and solution SAR for the Exline soil from two EC levels of 0.5 and 15 dS m^{-1}.

Table 3. Comparison of field capacity water (FCW) obtained at the highest EC of each depth (SAR = X, EC = 15 dS m^{-1}) to FCW obtained at reference solution (SAR = 0, EC =15 dS m^{-1}).

Soil	Depth	FC obtained at EC of 15dS m^{-1}	FC at reference solution	Difference	*P* value
	cm	-------------------------------g g^{-1}	--------------------------		
Exline	0-15	0.243	0.219	0.025	0.005*†
	15-30	0.188	0.203	-0.015	0.414
	30-60	0.180	0.190	-0.010	0.108
	60-90	0.267	0.280	-0.013	0.006*
Stirum	0-15	0.191	0.192	-0.001	0.883
	15-30	0.172	0.165	0.006	0.351
	30-60	0.142	0.136	0.005	0.195
	60-90	0.159	0.173	-0.015	0.093
Ryan	0-15	0.51	0.539	-0.028	0.008*
	15-30	0.522	0.504	0.018	0.05
	30-60	0.428	0.511	-0.083	0.001*
	60-90	0.437	0.539	-0.102	0.000*
Bearden	0-15	0.347	0.348	-0.001	0.905
	15-30	0.357	0.351	0.006	0.474
	30-60	0.272	0.326	-0.054	0.007*
	60-90	0.322	0.431	-0.11	0.000*
Ryan salts washed	15-30	0.466	0.461	0.005	0.079
Bearden salts washed	60-90	0.337	0.354	-0.017	0.030*

† Asterisks indicates that the difference is significantly different at *P* = 0.05.

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). In soils where SAR increased with soil depth, which was consistent with the findings of McClelland et al. (1959) for many North Dakota soils, swelling 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). Drainage performance problems may occur in the affected horizons and may greatly reduce the drainage of precipitation-derived gravitational water. However, upward moving groundwater may still be removed without restrictions because EC generally remains high at deep depths in Aquifer in the Sheyenne delta (Baker and Paulson, 1967).

This research showed that each soil-Na level has a threshold EC where water movement is not restricted, stability is maintained, and swelling is minimized in agreement with the findings by Quirk and Schofield (1955). Considering Fig. “7, 8, and 9” in Shabtai et al. (2014), the reduction in Ksat is mainly dominated by swelling and partially by dispersion, both related to ESP and EC. In their study, when swelling increased from 36 to 97% the saturated hydraulic conductivity (Ksat) decreased from 400 to 0 mm hr^{-1}. 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 $0.7x10^{-6}$ mm hr^{-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 by as little as 16 to 25% can decrease Ksat to one third of the original value. 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. It was found that 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 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.

However, 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 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).

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 imbibing 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 high-risk soils should include chemical amendments such as gypsum, elemental S, or possibly agricultural lime as a means to maintain or increase EC, provide Ca^{2+}, and/or increase trafficability.

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ENVIRONMENTAL AND SOIL FACTORS FOR PREDICTIONS WHERE AMENDMENTS FOR SODIC SOILS SHOULD BE APPLIED: A CASE STUDY ON A NEARLY-LEVEL LANDSCAPE

Abstract

High spatial variation of sodicity can lead to inadvertent over- and under-application of amendments such as gypsum which is why site-specific management of sodic soils is difficult. The objective of this study was to characterize the spatial variation of Na and its relationship to environmental (elevation using RTK GPS and topographic wetness index (TWI)) and soil factors ($EC_{1:1}$, $pH_{1:1}$, Na%, ECa, and dispersion) to determine the likelihood of making site-specific amendment recommendations for sodic soil management. A grid sampling pattern having 544 geo-referenced sites in a 8.1 ha sodic soil study area in North Dakota was used for this case study. At each site soil samples were taken from the 0 to 0.3 and 0.3 to 0.6 m depths, and electromagnetic (EM) induction was also done. Although the study area was nearly level (< 0.5 m change in elevation), elevation was significantly correlated with soil variables except for Na%. In addition, dispersion, Na%, and EC were correlated which was expected since both EC and Na control a soil's ability to swell and disperse. All of the soil variables exhibited patchiness across the study area. The EM38, used to determine ECa, was determined to be highly reliable to express soil EC distribution and was correlated with Na% and dispersion. Therefore, the use of an EM38 may allow for site-specific management of Na on this low EC, nearly-level landscape. However, due to the variation encountered within the data, electronic methods should not be the sole measurement and used in place of direct soil sampling for determining the distribution and concentration of soil Na.

Introduction

Sodic soils often have high spatial variability at the field scale and have a significant relationship with microtopography and waterlogging (Hopkins et al., 2012; Yang et al., 2011), shallow groundwater quality (Derby et al., 2013), and subsurface drainage (Moustafa and Yomota, 1998). Therefore, the non-heterogeneity of sodicity makes it difficult for site-specific management. Sodic soil quality can be reflected in crop production within fields (Corwin et al., 2003), and can be used to predict soil degradation, locate soil sampling sites, and make amendments maps (Amezketa, 2007). An understanding about the distribution and relationship of Na and EC may be helpful in managing these problem soils.

To investigate the distribution of sodic soil properties, sodium adsorption ratio (SAR), electrical conductivity (ECe), exchangeable sodium percentage (ESP), and soil physical properties have all been used. In addition, geostatistical methods have been used to interpolate the sodic conditions (Amezketa et al., 2007; Shouse et al., 2010). However, these measurements can be costly and labor-intensive and therefore the use of electromagnetic inductions (EM) techniques have been found to be able to successfully estimate EC distribution in saline soils which oftentimes has a close relationship to SAR (Corwin et al., 2003; Shouse et al., 2010). These measurements are most often conducted by agronomists for zone-sampling strategies but the value of the measurements can be lessened if the spacing between measurements is too great or if the soil is too dry. Furthermore, ground elevation has been shown to be an important environmental factor influencing the spatial variation of soil salinization (Gokalp et al., 2010; Yang et al., 2011), so the coupling of elevation, EM, and SAR may hold promise for predicting sodicity.

As subsurface tile drainage installation increased in the northern Great Plains, and farmers are looking for ways to improve the production potentials of sodic soils, questions exist about where to apply amendments such as gypsum and sulfur sodic-soils. Currently, one may suggest applying amendments by Natric soil-mapping units but given the variability of these sodic soils (varying degrees of severity) this may lead to unnecessary application and costs. The cost for pelletized gypsum is currently about $218 US Mg^{-1} (A. Hoiberg, personal communication, 2014) and synthetic gypsum is not yet available to this region.

The results from papers 2 and 3 indicate that dispersion and swelling will likely reduce the flow of soil water when the EC of the soil solution decreases through losses of water and electrical-conductive ions out of the tiles. To date, limited data exists in the northern Great Plains in connecting nearly-level land surface properties with the distribution of Na in soils classified as being Natric (Soil Survey Staff, 1999). Therefore, the objective of this study was to characterize the spatial variation of Na and its relationship to environmental (elevation and topographic wetness index) and chemical factors ($EC_{1:1}$, $pH_{1:1}$, %Na, ECa, and dispersion) to determine the likelihood of making site-specific amendment recommendations for effective sodic soil management.

Materials and Methods

Site description

The study area was 8.1 ha in size and was located in southeastern North Dakota, USA (Lat. 46.28 N, Long. 97.25 W) (Fig. 4). The soils in this area were developed from when the Sheyenne River emptied into Lake Agassiz and created the Sheyenne Delta (Bluemle, 2000). The soils in study area are Exline (Fine, smectitic, frigid, Leptic Natrudolls) and Stirum-Arveson (Stirum: Coarse-loamy, mixed, superactive, frigid, Typic Natraquolls; Arveson: Coarse-loamy, mixed, superactive, frigid Typic Calciaquolls). The change in elevation above sea-level at the site is less than 0.5 m. The 30-yr average annual precipitation is 580 mm, annual potential evapotranspiration is about 1160 mm (North Dakota Agricultural Weather Network), and the depth to groundwater in spring within this region is often less than 0.3 m from soil surface (Baker and Paulson, 1967). Prior to use as cropland, the field was used as hayland for over 20 years, and then had subsurface tile drain installed (24.4 m spacing, about 1.2 m deep) during the fall 2012, and cropped corn (*Zea mays*) in both 2013 and 2014.

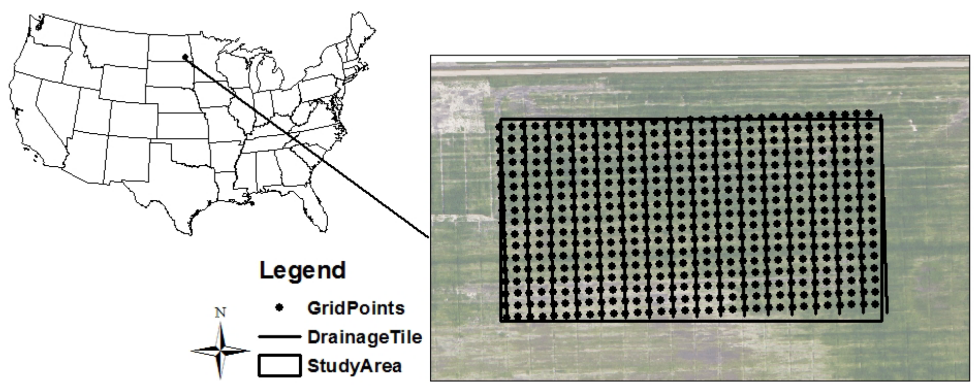

Fig. 4. Map showing the relative location of the study site and the grid sample locations (n = 544).

Data collection and measurement

Using a 12.2 m×12.2 m grid pattern 544 sampling sites were determined using ArcGIS (version 10.1) and the sampling sites were selected over existing tile drains and directly between drainage tiles (Fig. 4) to determine if tile installation and short-term drainage influenced soil properties. All measurements were geo-referenced with Real Time Kinetic (RTK) GPS (Model: R4 Receiver and TSC2 Data Controller, Trimble Navigation Limited, Sunnyvale, CA). Error of RTK is less than 0.01 m in horizontal and between 0.01 and 0.02 m in vertical. To determine the elevation using RTK in study area, an average distance of 2.3 m was used. After that an elevation shape file was created and was later converted into a Digital Elevation model (DEM) raster file through a Topo to Raster function in ArcMap. The elevation of grid points (n = 544) were extracted through “extract values to points” in spatial analysis tools of ArcMap. Although LiDAR data is available for this region its resolution was not sufficient for this nearly-flat landscape.

Apparent electrical conductivity (ECa) at horizontal and vertical directions were determined at each sampling point using EM38 (Geonics, Ltd. Mississauga, ON, CA) and readings were corrected for temperature and calibrated using ECe (EC from saturated paste extract) following the procedures outlined in McKenzie et al. (1989) and Wollenhaupt et al. (1986). For calibration seven points that reflected the spatial heterogeneity of the ECa measurements were used to determine weighted ECe and then to determine ECa (Fig. 5).

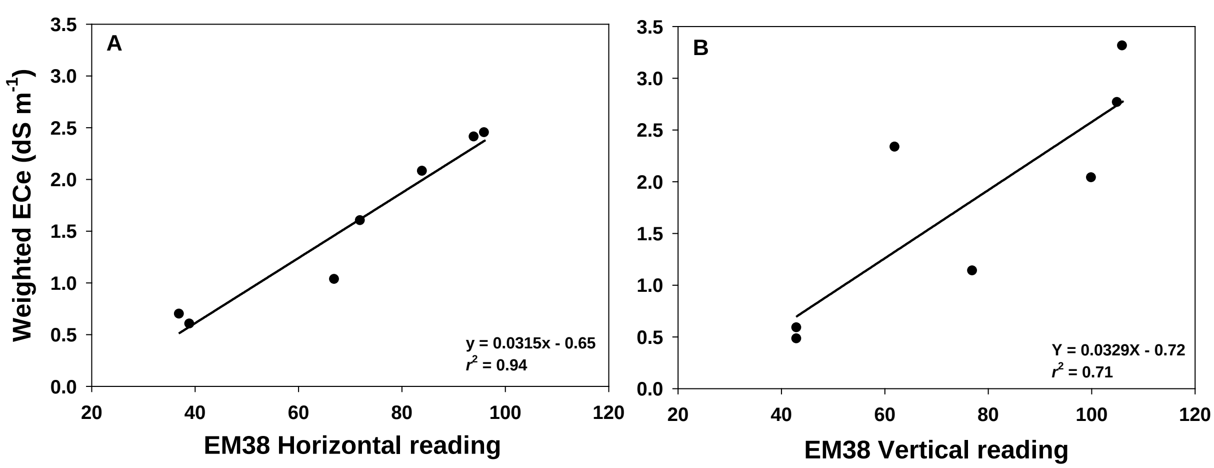

Fig. 5. Correlation of weighted profile ECe and EM38 readings taken in horizontal (A) and vertical (B) positions.

At each location, two 3.2 cm diameter soil cores were taken to a depth of 0.6 m and respective 0-0.3 m and 0.3-0.6 m depths composited into paper bags, followed by being air dried, and ground to pass through 2 mm sieve. Extraction of soluble and exchangeable phase Na was accomplished by shaking 1 g of soil with 20 mL of 1M NH_4OAc, followed by centrifugation at 647 ×*g* for 10 min. After centrifugation, Ca, Mg, Na, and K were quantified by atomic adsorption spectrophotometer (Model 200A, Buck Scientific). The extractable Na% was calculated as Na/(Ca + Mg + Na + K) where units of each cation were $cmol_c\ kg^{-1}$, which include both soluble and exchangeable ions and is a little bit different from ESP. Soil EC and pH were measured using a 1:1 soil slurry (U.S. Salinity Laboratory Staff, 1954).

The dispersion of soils was determined using the Crumb Test following ASTM method D 6572 (American Society for Testing and Materials, 2004) where 1.5 cm cubes of soil were prepared by hand with distilled water (DW) and gently lowered into petri dishes containing DW water. The grade of dispersion, which ranged from 1 (no dispersion) to 4 (severe dispersion) was recorded at 2 min, 1 h and 6 h. Binary categories were set as 1 = dispersion when the grade was 3 or 4 and 0 = no dispersion when the grade was 1 or 2.

Data statistical analysis

Variograms are a useful method to determine the average sample variance for samples between each other taken at increasing distances (Li et al., 2009). Variograms in isotropic models were produced by GS+ 10.0 (Gamma Design Software, LLC, Plainwell, Michigan). Isotropic models were selected in the study because preliminary data showed that isotropic models had higher percentage variation explained by model than anisotropic models. A lag distance of 12.2 m was used for the semivariance analysis since the sampling design for the field was based on a 12.2 m ×12.2 m grid. Descriptive statistics were conducted for original data, however, the geostatistical analysis were based on logarithmic transformation of data to increase the normality in the study.

Interpolation of index kriging for soil dispersion data was performed based on the input of variogram in GS+10.0. The remaining spatial data were all entered into a geographic information system (GIS) using ArcMap10.1 (ESRI ArcMap 10.1, Redlands, CA). Maps of soil $EC_{1:1}$, ECah, ECav, $pH_{1:1}$, Na%, and elevation data were prepared by interpolating the measurements using inverse-distance-weighted (IDW) in order to aid in visualization and comparison of data in ArcMap. Different terrain variables were derived from elevation DEM, including slope, flow direction, flow accumulation, and topographic wetness index (TWI). Both flow accumulation and TWI were found to useful to help quantify the influence of topography on soil chemical properties (Sorensen et al., 2006). Flow accumulation models were developed using elevation DEM (1 m resolution). The TWI combines local slope and flow accumulation, and has effects on hydrological processes. The TWI is defined as $TWI = \ln(\alpha/\tan\beta)$, where α is a potential flow accumulation to a specific location, $\tan \beta$ indicates the local drainage potential (Beven and Kirkby, 1979). Finally, Pearson correlation coefficients (r) were calculated for all pairs of variables ($EC_{1:1}$, $pH_{1:1}$, ECa horizontal (ECah), ECa vertical (ECav), Na%, dispersion, elevation, and TWI) to determine the strength of relationships. In r calculation, elevation and TWI were originally raster based, so they were extracted to grid points for their value at each grid point. Environmental factors for this study were elevation, TWI and the remaining soil variables were $EC_{1:1}$, $pH_{1:1}$, ECa horizontal (ECah), ECa vertical (ECav), Na%, and dispersion.

Results and Discussion

Environmental factors

The elevation of the study site changed less than 0.5 m with a slope of less than 0.8%, indicating the study area was very flat. Overall, one long and two short flow accumulation networks were observed in the field in the northwest corner and southeast corner and they had higher number of pixels in high flow accumulation categories than the rest of study area (Fig. 6). The network indicated in which direction the outflow from a given cell will be distributed to the neighboring downslope cells (Rampi et al., 2014). Correspondingly, TWI also indicated that there were a few spots in the south and northeastern corners of study area that displayed higher TWI values, probably influencing the following patterns of the soil chemical variables (Fig. 6).

Among many terrain variables, TWI is a factor that considers both field slope and flow accumulation, and is considered to be a good indicator of soil moisture distributions at different landscape positions (Pei et al., 2010). In addition, TWI was found to be effective at predicting soil organic matter distribution (Pei et al., 2010), soil water content (Barling et al., 1994), and locating wetland locations with other ancillary data (Rampi et al., 2014). Compared to other studies, the TWI in our study site was small. However, exception occurs in the middle of study area where a line going across west to east was not a natural feature and was probably caused by historical surface drainage.

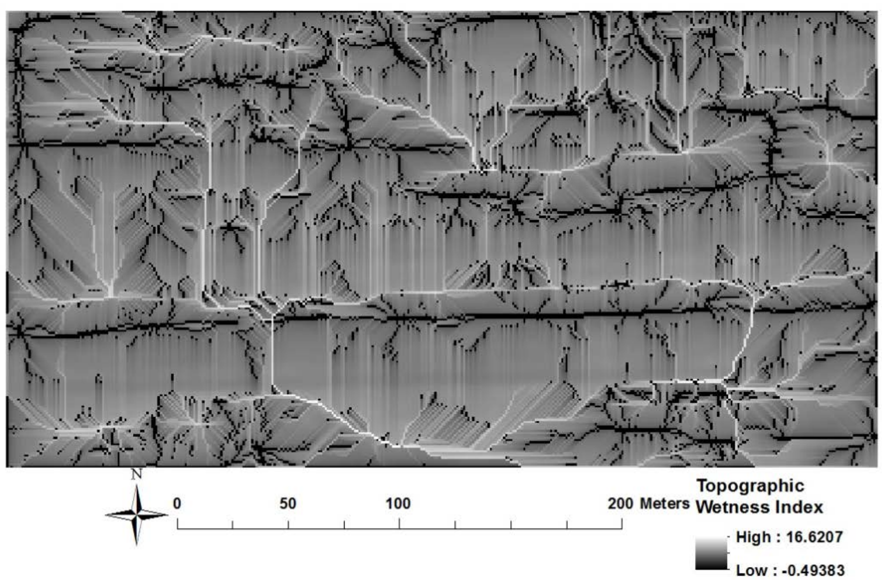

Fig. 6. The topographic wetness index (TWI) of the study area in field.

Spatial analysis

The extent of spatial dependence is expressed as the proportion ($C/(C_0+C)$) (Table 4) (Rodriguez et al., 2009) where the value lies between 0 and 1 and values close to 1 indicate spatial dependence inherent in the dataset while a value of 0 indicates no spatial dependence through the data range. The extent of spatial dependence of the soil varaibles specified in our study ranged from 0.501 to 0.878 and from 0.503 to 0.885 in 0 to 0.3 and 0.3 to 0.6 m, respectively (Table 4). The range values represent the distance at which the asymptote is reached, and when the distance is beyond this range the samples are independent (Ettema and Wardle, 2002). The range distances in our study were much greater than the lag distance 12.2 m (Table 4) which indicates that our sampling design was appropriate and can accurately detect variations within the soil variables. These statistical results indicated that the IDW and kriging are reliable interpolations across the distances because we are not attempting to interpolate outside the effective range in our field (Ettema and Wardle, 2002).

Soil chemical factors

Across the study site the ECa was less than 3 dS m^{-1} from both soil depths but there was a trend of EC to increase with depth (Fig. 7). However, $EC_{1:1}$ values were mostly less than 1 dS m^{-1} (Fig. 8) which can be expected since saturated-paste derived EC is about two times greater than the EC of a 1:1 diluted sample (Sonmez et al., 2008). Irrespective of the EC approach, similarity between Fig. 7 and 8 exists which can be represented by the comparative *r* value near 0.60 between them (Table 5). The pattern of EC can be attributed to microtopography (Derby et al., 2013) where in our study site the higher values of EC were found on lower depression areas located in areas of high water accumulation and TWI, where salts accumulate after evaporation.

This was also in agreement with the results from Douaik et al. (2005) in that the elevation was a major factor influencing soil salinization.

Table 4. Descriptive statistics and geostatistical summary of soil factors. Geostatistical analysis was conducted on log-transformed data.

Statistic	$EC_{1:1}$	$pH_{1:1}$	Na%	Dispersion	ECav†	ECah‡
	----------------------------0 to 0.3 m----------------------					
Model§	Spherical	Spherical	Exponential	Exponential	Spherical	Spherical
Sill (C_0+C)§	0.044	0.001	0.629	0.011	0.066	0.010
Nugget (C_0)§	0.022	0.0004	0.077	0.001	0.014	0.003
Proportion (C/[C_0+C])§	0.501	0.577	0.878	0.872	0.779	0.708
Range§	82.40	126.7	72.00	48.6	76.80	75.40
r^2§	0.877	0.951	0.967	0.481	0.985	0.977
Mean¶	0.451	8.454	1.871	-	1.419	1.209
Minimum¶	0.236	7.68	0.151	-	0.469	0.516
Maximum¶	0.947	9.77	14.07	-	2.772	2.374
SD¶	0.103	0.287	1.744	-	0.37	0.328
Skewness¶	1.410	0.720	2.990	-	0.910	0.650
Kurtosis¶	3.790	1.550	13.05	-	0.990	2.140
	--------------------------0.3 to 0.6 m---------------------					
Model	Spherical	Exponential	Exponential	Exponential	Spherical	Spherical
Sill (C_0+C)	0.157	0.001	0.645	0.019	0.066	0.01
Nugget (C_0)	0.078	0.0001	0.074	0.002	0.015	0.003
Proportion (C/[C_0+C])	0.503	0.884	0.885	0.875	0.779	0.708
Range	97.30	47.10	50.10	37.50	76.80	75.40
r^2	0.882	0.909	0.929	0.751	0.985	0.977
Mean	0.420	8.975	2.772	-	1.419	1.209
Minimum	0.168	7.47	0.162	-	0.469	0.516
Maximum	2.680	9.89	15.78	-	2.772	2.374
SD	0.242	0.362	2.236	-	0.370	0.328
Skewness	4.160	-0.550	2.060	-	0.910	0.650
Kurtosis	25.64	1.120	6.250	-	0.990	2.140

† ECav, ECa in vertical direction.
‡ ECah, ECa in horizontal direction.
§ Geostatistics.
¶ Descriptive statistics, where SD is standard deviation.

Variations of Na% were quite small in the upper soil profile, indicating considerable field uniformity to a depth of about 0.3 m (Table 4). With depth, however, the average Na% increased at 0.3 to 0.6 m and was distributed in patches (Fig. 9). Relatively higher Na% was observed in the corners while lower Na% was located in the middle of of the study area. The Na% values above 10% were mainly found in the southern portion of the study area. High Na% may have resulted in a rise of pH, and their respective distributions were consistent ($r \approx 0.6$) (Fig. 9). About 90% of the 0.3 to 0.6 m depth had pH values greater than 8.6, likely explained by the hydrolysis effect of Na (Guerrero-Alves et al., 2002).

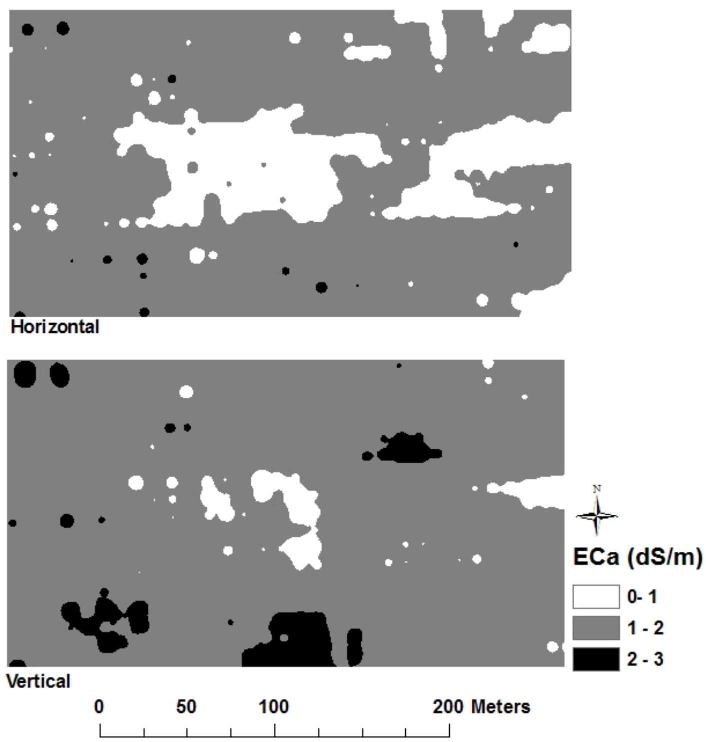

Fig. 7. Inverse distance weighted interpolated maps of ECa at 544 sites.

The patchiness of the study area was likely due to variable textures due to slight changes in elevation, which would drive capillary water movement from groundwater (Shouse et al., 2010). However, no significant correlation was found between Na% and elevation, probably because Na in our study was mainly from the soil exchange sites instead of in the soluble phase. The shallowest water table in this region is about less than 0.3 m below the surface during spring thaw (Baker and Paulson, 1967). The North Dakota Geological Survey in 1967 reported that the groundwater of Dakota sandstone aquifer had a Na concentration of 1,010 ppm in the Township 132 N and Range 52 W, near where the study area was located (Baker and Paulson, 1967). Therefore, groundwater is the likely source of Na to the soils in this region and can be accentuated by low precipitation and high evaporation (NDAWN). Even though the TWI was not significantly related with Na% (Table 5), the four estimated water accumulation locations in Fig. 9 showed high Na% patches with values ranging from 10 to 16%. Support of this finding was also noted by Derby et al (2013) where high soil Na and EC were linked to depressional areas near Oakes, North Dakota.

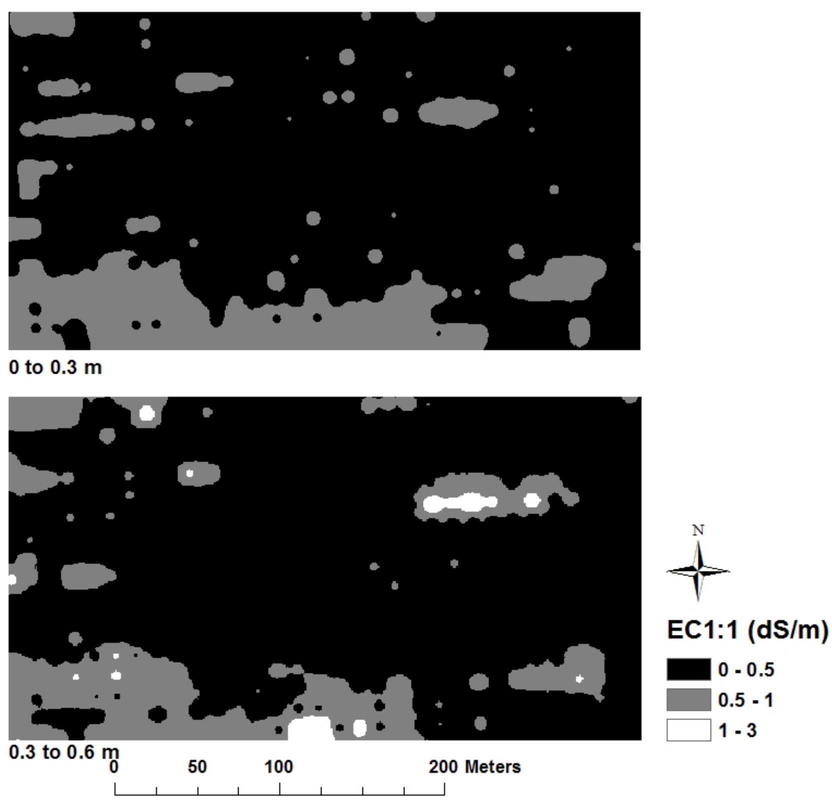

Fig. 8. Inverse distance weighted interpolated maps of $EC_{1:1}$ at 544 sites.

Dispersion

Dispersion was evident for about one-half of the samples and also displayed heterogeneity for both soil depths (Fig. 10). There were many patches and sharp discontiuities relecting “hot” and “cold” spots, and this pattern was similarly described by Ettema and Wardle (2002). About 30% of soils showed dispersion in the surface 0 to 0.3 m of the field whereas more than 60% of soils in 0.3 to 0.6 m depth showed dispersion. Notable, dispersion was observed even in areas with Na values around 5%.

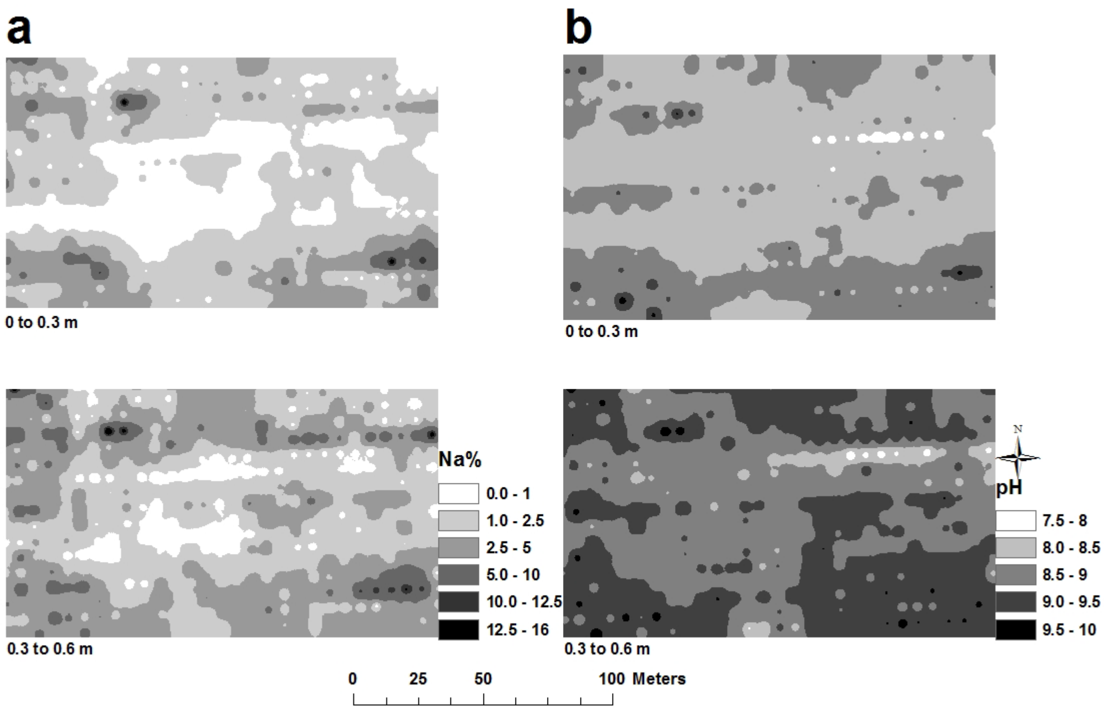

Fig. 9. Inverse distance weighted interpolated maps of Na% and pH, a: Na%, and b: pH at two depths of 544 sites.

Dispersion was influenced by interactive factors of Na and EC (Essington, 2004; He et al., 2013; Quirk and Schofield, 1955). Therefore, the pattern of dispersion in the study field should be related with Na% and EC. The EC values were less than 3 dS m^{-1} all across the field, probably not meeting the field flocculation value which was defined by Amezketa et al. (2003) as the minimum electrolyte concentration required to prevent soil dispersion at a given SAR. The Na% should be a limiting factor affecting sodic soil dispersion and in this study the Na% was found to be highly correlated with dispersion (r = 0.67) for both depths (Table 5).

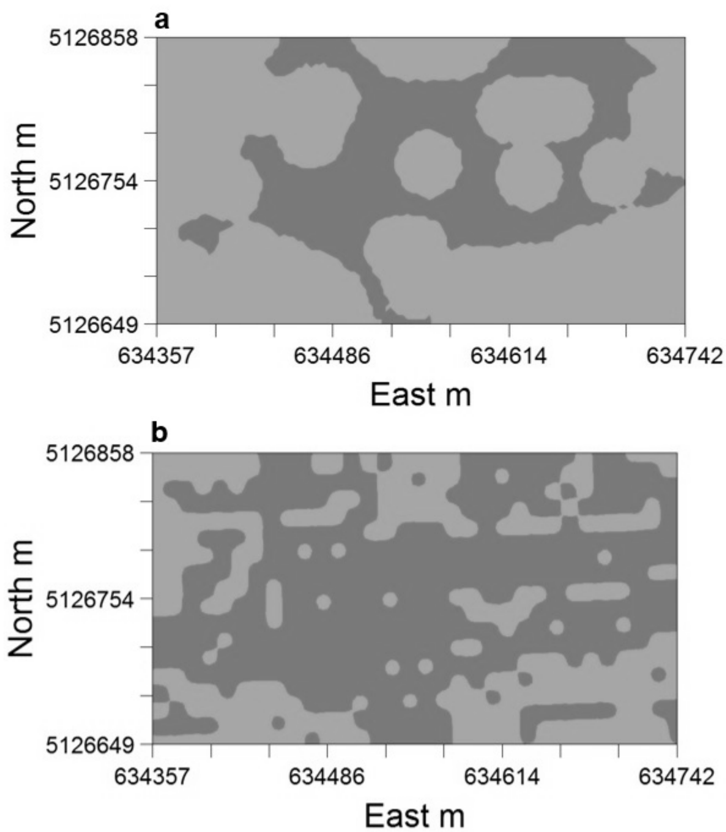

Fig. 10. Index kriging maps of dispersion for 544 sites at two depths, a: 0 to 0.3 m, b: 0.3 to 0.6 m, the lighter grey pattern color indicates no dispersion.

Targeted sodic soil management

As hypothesized, the soil parameters EC, Na%, pH, and dispersion varied aerially and with depth across the study area and sampling location (over the tile vs. between the tiles) was not considered to be a confounding variable (Appendix Table C1). For example, low Na% soils were interspersed by high Na% soils (Fig. 9) and EC measurements were significantly correlated with elevation, in addition to dispersion and pH (Table 11). Unfortunately, aerial photos taken during the growing season (Appendix: Figures) were not able to predict Na% (Greeness index was calculated, data not shown), but non-uniform crop greeness was undoubtedly related to soil and environmental factors, which was supported by Sorensen et al. (2006) in that 52% of variation in plant richness was related with TWI. Although Na% and elevation were not correlated, Na% was highly correlated with $EC_{1:1}$ and the EM38 EC readings, which gives promise to being able to predict where sodic soil amendments could be directed.

Table 5. Pearson correlation (*r*) of all data (n= 544) in the study area.

Parameters	Elevation	TWI†	$EC_{1:1}$	$pH_{1:1}$	Na%	Dispersion	ECav	ECah
			----------------0 to 0.3 m--------------					
Elevation	1.00	-0.23*	-0.35*	-0.20*	-0.06	-0.15*	-0.32*	-0.34*
TWI	-0.23*	1.00	0.06	0.04	0.05	-0.003	0.08*	0.09*
$EC_{1:1}$	-0.35*	0.06	1.00	0.29*	0.54*	0.40*	0.58*	0.64*
$pH_{1:1}$	-0.21*	0.04	0.29*	1.00	0.68*	0.55*	0.40*	0.48*
Na%	-0.06	0.05	0.54*	0.68*	1.00	0.68*	0.49*	0.57*
ECav‡	-0.32*	0.08*	0.58*	0.40*	0.49*	0.34*	1.00	0.89*
ECah§	-0.34*¶	0.09*	0.64*	0.48*	0.57*	0.40*	0.89*	1.00
Dispersion	-0.15*	0.00	0.40*	0.55*	0.68*	1.00	0.34*	0.40*
			----------------0.3 to 0.6 m-------------					
Elevation	1.00	-0.23*	-0.21*	-0.04	0.07	0.01	-0.32*	-0.34*
TWI	-0.23*	1.00	0.02	-0.02	-0.01	-0.02	0.08*	0.09*
$EC_{1:1}$	-0.21*	0.02	1.00	0.02	0.43*	0.27*	0.64*	0.62*
$pH_{1:1}$	-0.04	-0.02	0.02	1.00	0.64*	0.63*	0.28*	0.34*
Na%	0.07	-0.01	0.43*	0.64*	1.00	0.67*	0.52*	0.57*
ECav	-0.32*	0.08*	0.64*	0.28*	0.51*	0.37*	1.00	0.89*
ECah	-0.34*	0.09*	0.62*	0.34*	0.57*	0.39*	0.89*	1.00
Dispersion	0.01	-0.02	0.27*	0.62*	0.67*	1.00	0.37*	0.39*

† TWI, Topographic wetness index.
‡ ECav, ECa in vertical direction.
§ ECah, ECa in horizontal direction.
¶ Significant at 95% of confidence interval.

Nearly-level landscapes, such as what is found in the Red River Valley of the North Dakota, an alluvial landscape developed about 9,000 yr ago, pose a challenge to predicting soil properties based on elevation changes. LiDAR has been a common tool to look at watershed water-flow modeling but this elevation tool fails at the smaller landscape scales (hectares) due to surface vegetation and obstacles (e.g. cattle, hay bales, weeds) and the attempt to interpret elevation changes within the study area using LiDAR for this study failed. The use of RTK, however, coupled with TWI modeling may be practical approach for determing soil EC which can then be used for modeling Na%.

Spatial variability influences the size and number of soil samples required to characterize the propeties in an area of intrest (Corwin et al., 2003). Therefore, the spatial variability displayed in Table 4 indicated that a grid distance of 12.2 m was effective in determining samples for Na% levels. Given that the location of the tiles did not influence the variables, a 24 m distance was also acceptable but may yet not be practical for routine soil sampling. In very flat areas without influence of TWI, the sampling distance can be greater than 24 m, similar to results found in Franzen et al. (2002) where a grid (33 or 66 m) or topographic approach could be correlated with Order 1 survey-based sampling for N-management. Therefore, the sampling number could be decreased to about 200 or less in our study area.

When high Na exists soil dispersion and or swelling will occur which can affect the spatial variation of soil water potentials (Gokalp et al., 2010). Therefore, Na may cause soils to adsorb water more than their liquid limit and remain wetter longer (Grim, 1968), which is supported by the first study that field capacity water was greatly increased due to high Na and low EC. The study found that an SAR of greater than 5 could cause an increase of field capacity water and a swelling increase as little as 16 to 25% can decrease saturated hydraulic conductivity to one third of its original value (Curtin et al.,1994; Shabtai et al., 2014). In an unpublished study Na% was significantly related with SAR (SAR = 1.04 Na% - 0.35, r^2 = 0.92) (DeSutter, unpublished data, 2014) and therefore it is reasonable to use Na% in place of SAR to predict soil-water relations and therefore a Na% of 5 corresponds to an SAR of 5.

Using the information from this study and a target Na% of 5 or less, gypsum rates and costs can be determined for site-speficic management. Considering only the 0-0.3 m depths, 24 of the 544 sample locations require gyspum. For this situation each sample location (12.2 x 12.2 m) would require between 0 and 0.64 Mg (0 and 0.7 tons). Using the estimate for gypsum of \$218 Mg^{-1} (\$240 ton^{-1}), the cost for gypsum for this 8.1 ha, considering only the 0-0.3 m depth, would be about \$1,100 (US) which include the recommended 25% increase in application rate to account for lack of 100% efficiency (U.S. Salinity Laboratory Staff, 1954). For the 0.3-0.6 m depth, which largely had Na% greater than 5%, costs can significantly increase if complete remediation is the objective. See Appendix D for example calculations.

Conclusions

In this nearly-level landscape high spatial variability was observed for soil Na, EC, pH, and dispersion. The Na% and EC were found to be effective for estimating dispersion zones and EM38 for estimating soil EC. Except for Na% the environmental factor elevation was related with all other soil variables and can be used to target sampling sites within problem areas. Therefore, on this nearly-level landscape one could use EM38 or other apparent electrical conductivity sensor and elevation (RTK) for determination of areas that may likely be sodic but soil sampling should also be done to verify modeled data.

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