SOIL SALINITY AND SODICITY IMPACTS ON SOIL SHRINKAGE, WATER MOVEMENT AND RETENTION

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Saline, sodic, and saline-sodic ground waters are problematic throughout the Northern Great Plains and Red River Valley. High sodium adsorption ratio (SAR) and low electrical conductivity (EC) of soil solution and irrigation waters are known to create issues with saturated soil hydrologic conductivity. Our objective was determine the impact of saline, sodic and saline-sodic solutions on soil shrinkage and soil hydrologic properties. Soil shrinkage, water retention, and hydraulic conductivity were determined on a variety of soil textures following saturation with salt solutions of variable EC and SAR combinations. Data were fitted with simple theoretical models then model parameters statistically compared. Increasing SAR and decreasing EC of increased soil shrinkage, decreased hydraulic conductivity, and increased water retention near saturated conditions (i.e., > -100 cm H_2O). Whereas saline-sodic waters resulted in the greatest rate of decline in saturated conductivity over time such as when salts would be managed without maintaining divalent cations.

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INTRODUCTION

Purpose of Study

Saline and sodic soils are commonly found in the Northern Great Plains region, including North Dakota (USDA, 1996). The acreage of saline and sodium affected soils found in North Dakota has increased in recent years due to the region entering a climatic wet cycle since the early 1990s (Franzen, 2013; Hoerling et al., 2010; Wiche et al., 2000). The recent increases of salinized soils further reduce producer’s crop yields due to the intolerance of many agricultural row crops to salinity. One type of salinity issue is known as sodicity; when sodium salt concentrations are relatively higher than calcium and magnesium salts. Sodicity can limit water movement and root extension in soils creating conditions for poor crop production (Rengasamy, 2002). The increase in saline and sodic soils from saline ground waters create difficult land management decisions for producers as how to maintain and preferably increase crop yields in the impacted areas. Salinity and sodicity impacts on soil physical and chemical properties are important not only for maximizing crop production but also in the formation of and remediation of these saline and sodic soils. These impacted areas need further soil hydrologic evaluations of their saturated and unsaturated states to help inform land managers of management options. A better understanding of how soil physical properties are impacted along a range of simulated saline, sodic and saline-sodic ground waters will improve the theory on water and salt management in these soils. Such knowledge will provide insights for optimizing best management practices for the removal of salts from the root zone in ground-water-impacted saline and sodic soils.

Literature Review

Formation of Saline and Sodic Soils

Saline and sodic soils are found throughout the world in aggregate totaling approximately 351 million hectares of saline soils and 581 million hectares of sodic soils (Szabolcs, 1989). They can be formed by pedogenic processes, saline groundwater intrusion, soil management (e.g., irrigation waters, waste applications, etc.), and industrial brine spills (e.g., produced saline waters during oil, gas, geothermal, and other kinds of deep earth drilling operations). Natural saline soils include saline seeps, evaporite basins, areas with shallow saline groundwater and zones where salt water intrusion has occurred (Salama et al., 1999). Salt water intrusion occurs when saline ocean water flows into freshwater aquifers due to a lower pressure head in the freshwater aquifer than in the saline ocean water (Barlow and Reichard, 2010). Saline soils can also form along natural and man-made drainage ditches where high electrical conductivity (EC) > 4 dS m^{-1} water is drained from adjacent lands (Skarie et al., 1986). However, soil salinity levels > 1 dS m^{-1} are often derived from soluble salt minerals in the groundwater and/or parent materials (Rengasamy 2002). In general, the most common occurrences of salinized soils occur in arid and semi-arid regions that have greater evaporative demand than net downward movement of water through the soil profile (Salama et al., 1999).

In areas similar to the North American Great Plains, soluble salts move with the groundwater and concentrate in the upper parts of the soil profile when evaporation is the dominate process as compared to rainwater recharge. Dissolved salt concentrations can increase along groundwater flow pathways until levels, if present, exceed the solubility limit. In geologic formations containing high soluble salt levels (e.g., EC > 4 dS m^{-1}), the regional groundwater flow can transport these salts to areas with shallow water tables near the soil surface (Arndt and Richardson, 1989). In locations where the groundwater is less than 4 m relative to the soil surface, capillary rise can further transport dissolved ions upward to the soil surface (Miller et al., 1985). These dissolved ions will accumulate and precipitate near the soil surface if capillary waters are allowed to evaporate. Salt deposition and accumulation can also occur where saline seeps have formed on hill sides and toe slopes. These saline seeps occur when a perched water table transports water and salts from a recharge area to adjacent discharge areas where the perched water table is shallow relative to the soil surface (Arndt and Richardson, 1989).

Sodic soils naturally form from parent materials that are high in sodium containing minerals and where shallow groundwater has high sodium concentrations (i.e., sodium adsorption ratio (SAR) > 6) (Charles 1993). Soil sodicity can also be induced via soil management practices either by 1) irrigation waters high in sodium ions relative to calcium and magnesium ions or 2) in subsurface drained saline-sodic areas where calcium and magnesium losses in the drainage waters are greater than sodium losses (Sumner 1993; Oster and Schroer, 1979). In ground waters that contain relatively high levels of sodium bicarbonate and sodium carbonate, the solution pH may increase causing calcium-based dissolved salts to precipitate from solution therefore causing groundwater SAR levels to become greater (Munn and Boehn, 1983). Such an increase in solution pH and subsequent SAR can cause a greater effect on soil properties by forming pH dependent charges on cation exchange sites; thus, creating the potential for nutrient toxicities and deficiencies, restricted water and oxygen transport, and a less conducive environment for soil organisms (Suarez et al., 1984).

When sodium ions on soil cation exchange sites are relatively high as compared to calcium and magnesium ions, soil clays will have a propensity to swell and disperse. This dispersion is responsible for the formation of low hydraulically permeable natric horizons. The natric horizon has columnar or prismatic structure, a high SAR level, can become very hard when dry, and have low soil water permeability (Munn and Boehm, 1983). The SAR of a soil or soil solution is calculated as

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca+Mg}}{2}}} \tag{1}$$

where Na, Ca and Mg are ion levels in the saturated paste extract ($\mathrm{SAR_e}$) expressed as meq $\mathrm{L^{-1}}$ (US Salinity Laboratory Staff, 1954).

Criteria for Diagnosing Saline and Sodic Soils

North Dakota has approximately 5.8 million acres of saline and 1.6 million acres of sodic soils and more acres have appeared in the last 20 years (Brennan and Ulmer, 2010). Soils are considered saline if they have an electrical conductivity in the saturated paste extract ($\mathrm{EC_e}$) greater than or equal to 4 dS $\mathrm{m^{-1}}$ and have a pH of 8.5 or less. Soils are considered sodic if the pH is greater than 8.5 and have exchangeable sodium percentage (ESP) is greater than 15%, or if the SAR of the saturated paste extract greater than 12 (US Salinity Laboratory Staff, 1954). Soils are considered as saline-sodic if the SAR is greater than 12, the $\mathrm{EC_e}$ is greater than 4 dS $\mathrm{m^{-1}}$ and the pH is less than 8.5 (US Salinity Laboratory Staff, 1954). These were the initial criteria established to diagnose saline and sodic soils but there has been disagreement in the literature as to lower levels of SAR that initiate degradion of soil physical properties. In Australia, sodic soils are defined as having ESP values greater than or equal to 6% (Northcote and Skene, 1972). Sodic soils can have either high pH (i.e., ≥ 8.5) or somewhat low (e.g., pH of 6) pH values. The term “alkali soil” was initially coined for sodic soils by the US Salinity Laboratory due to the high pH from $NaHCO_3$. However, soils that contain significant quantities of Na_2SO_4 or NaCl can have high SAR and ESP levels with a pH < 8.5 (Charles 1993).

The SAR_e value at which a soil begins to degrade, with respect to vegetative growth and crop production, is a function of the soil solution’s electrolyte concentration (McNeal et al. 1968). For example, Crescimanno et al. (1995) reported that soil at an ESP level of 15% had a 50% decrease in saturated hydraulic conductivity at a percolating solution salt concentration of 5 mole m^3 (EC approximately 0.75 dS m^{-1}) using mixes of NaCl and $CaCl_2$ and a 90% decrease at a percolating solution salt concentration of 1 mole m^3 (EC approximently 0.1 dS m^{-1}) relative to when solution EC is > 1 dS m^{-1}. Soil solutions with low concentrations of electrolytes have increases in clay dispersion and decreases in permeability at a lower SAR value as compared to soil solutions with high concentrations of electrolytes. The SAR level that causes degradation depends on both the soil particle size distribution and clay mineralogy. For example, Frenkel et al. (1978) and McNeal et al. (1968) reported that the detrimental effect of SAR on the hydraulic properties of soil clay mineral types, in order from worst to least, follows: montmorillonite > vermiculite > illite > kaolinite > sesquioxides. As the amount of 2:1 layer clays in the soil clay fraction increases, the degradation effect of sodium also increases (Frenkel et al., 1978; McNeal et al., 1968). A kaolinitic soil with 10% clay can have a 2% decrease in relative hydraulic conductivity at an ESP of 20%

whereas a smectite dominant soil with same percentage clay can have a 99% decrease in relative hydraulic conductivity when DI water is infiltrated (Frenkel et al., 1978). Since the level of soil EC and SAR combination that detrimentally effects soil varies depending on the amount of sand, silt, and clay as well as the clay mineralogy, the precise levels when soil physical properties begin to degrade has and continues to be an item of disagreement in the scientific literature.

Management of Saline and Sodic Soils

Saline and sodic soils reduce agricultural productivity. For example, non-saline soils with an EC_e of < 4 dS m^{-1} in wheat (*Triticum aestivum*) systems yielded 2.93 Mg ha^{-1} as compared to only 1.80 Mg ha^{-1} in soils with EC_e levels of 12 to 16 dS m^{-1} (Datta and Jong, 2002). The large negative osmotic soil water potential (Ψ_o) in saline soils reduces soil water availability to plants (Qadir and Oster, 2004). The osmotic soil water potential can be estimated by

$$\Psi_0 = -0.36\ \mathrm{EC_e} \tag{2}$$

where the osmotic soil water potential is in bars and the EC_e is in dS m^{-1} (US Salinity Laboratory Staff, 1954). Although some crops have higher salinity tolerances than others, yields of all crop will decline to zero once a salinity threshold has been exceeded. Corn (*Zea mays*) and sugar beet (*Beta vulgaris*) yields approach zero at EC_e of 10 and 24 dS m^{-1}, respectively (Franzen, 2013; Maas and Hoffman, 1977). In contrast to saline soils where osmotic soil water potential and toxicities of chlorides and sodium restricts plant growth and development, sodic soils impact crop yields due to low water infiltration, high bulk density, and poor soil aggregation causing difficulty with tillage management and aeration (Naidu and Rengasamy, 1993). For example, the bulk density of soil aggregates < 1mm in diameter at 10% and 4.5% ESP levels were 1.32 and 1.23 g cm^{-3}, respectively, for irrigated Israeli soils even though the salt contents were higher in 10% ESP soils than the 4.5% ESP soils (Ben-Hur et al., 2009). Additionally, tensile strength was greater than 200 kPa in a Tarlee soil series (Vertic Palexeralf) when the soil EC_e was 1.0 dS m^{-1} and the SAR was 20 and decreased to less than 100 kPa when the SAR level was decreased to 5 (Barzegar et al., 1996). Thus, plant germination and rooting can be difficult in sodic soils due to increased soil bulk density and soil hardening at lower soil water contents (Sumner, 1993; Mullins et al., 1990).

One land management approach is to promote the net downward flux of water in the soil root zone to alleviate detrimental impacts of soil salinity. Subsurface drainage is commonly installed in saline soils to increase depth below soil surface of saline ground water, promote downward transport of water, and either translocate salts deeper in the soil profile or remove them from the soil profile entirely via drain flow (Ritzema et al., 2008). The infiltration of low EC waters (i.e., < 1 dS m^{-1}) can leach soil accumulated salts and improve crop production. Leaching requirement (LR) can be calculated by

$$\mathrm{LR} = \frac{1}{5}\frac{\mathrm{EC_w}}{\mathrm{EC_e}} - \mathrm{EC_w} \tag{3}$$

where EC_w is the electrical conductivity of the infiltrating water, and EC_e is the desired electrical conductivity for the crop of interest (Watson and Knowles, 1999; US Salinity Laboratory Staff, 1954). Soils can also be covered with organic (e.g., plant residues, mulch, etc.) and inorganic materials (e.g., sand and gravel mixtures) to reduce evaporation and further promote the net downward water movement in the soil profile (Dong et al., 2008; Tejedor et al., 2003). By maintaining continuous plant growth, and therefore plant uptake of soil water, the upward flux of water within the plant root zone is limited and open pore space for infiltrating waters created as compared to leaving production fields fallow (Daigh et al., 2014). In other words, the uptake of water by plants reduces the quantity of water lost to soil evaporation and increases the depth of downward movement of precipitated water. Management practices that maintain plant growth throughout the year when soils are not frozen are good strategies for reclaiming or limiting the area impacted by saline seeps (Halvorson, 1984). Deep rooted crops, such as alfalfa (*Medicago sativa*), are commonly recommended for areas surrounding saline seeps (Franzen, 2013).

To ameliorate sodic soils, the application of divalent cations via soil amendments (e.g., $CaSO_4$, $CaCl_2$, etc.) and irrigation water can replace sodium on cation exchange sites. Gypsum is commonly the preferred soil amendment to remediate sodic soils. The calcium amendment dissolves into the soil solution with the calcium ions replacing sodium on soil exchange sites and the sodium ions being released into the soil solution (Oster and Frenkel, 1980). Water is necessary for the dissolution of calcium amendments to occur and the subsequent replacement and removal of sodium from the crop rooting zone (Yang et al., 2014). The exchanged sodium can then be leached downward in the soil profile, preferably out of the rooting zone, while calcium from the amendment continues to dissolve and further replace sodium on additional exchange sites (Oster and Frenkel, 1980). However, soils that contain substantial quantities of antecedent sulfate salts limit gypsums effectiveness due to a resulting low calcium activity in soil solution (Skarie et al., 1987). Sodic soils can also be remediated by application of calcite ($CaCO_3$), $CaCl_2$, sulfuric acid (H_2SO_4)and elemental sulfur if the soils previously contain lime, and phytoremediation; However, the best success of remediating sodic soils has been obtained with Ca-based amendments and sodium tolerant perennial crops such as alfalfa (Qadir and Oster, 2004). In general, to successfully remediate saline and sodic soils, excess salts must be removed from the soil profile in order to improve and sustain healthy soil physical, chemical, and biological properties.

Chemical Properties of Saline and Sodic Soils

Saline soils can contain numerous types of accumulated salts; some salts having greater solubility than others. The solubility of calcite ($CaCO_3$) is 0.06 g L^{-1}, gypsum ($CaSO_42H_2O$) is 1.9 g L^{-1}, epsom salt ($MgSO_4$) 252 g L^{-1}, table salt (NaCl) 264 g L^{-1}, $CaCl_2$ is 427 g L^{-1} and glauber's salt (Na_2SO_4) is 161 g L^{-1} (Doner and Lynn, 1989). Common cations in saline soils are Ca^{+2}, Mg^{+2} and Na^{+} and common anions are Cl^{-}, SO_4^{-2} and CO_3^{-2} (Seelig, 2000; Doner and Lynn, 1989). These ions can accumulate in soils due to weathering of minerals, capillary rise of ground waters, discharge areas of subsurface waters, long-term repeated fertilizer applications, and application of salinized irrigation waters (Seelig, 2000). Sodium and soluble salts effects on soil properties is a function of soil mineralogy and particle size distribution (Frenkel et al., 1978; Jayawardane et al., 1978). Smectite dominant soils are more sensitive to composition of soil solution with greater increases in dispersion at solution SAR values 6 or greater than kaolinite or sequioxides (He et al., 2013; McNeal et al., 1968). The greater the CEC of the soil the greater effect that sodium has on soil colloids and aggregates (Chorom et al., 1994). The pH dependent charge of soil clays increases the soil's CEC as the pH increases, compared to non pH dependent permanent charges on clays which require a greater amount of cations to saturate the cation exchange sites (Suarez et al., 1984).

Ionic strength (I) is important in soil solution and can determine the size of double diffuse layer by the following equation (Debye and Huckel, 1923).

$$\mathrm{I} = \frac{1}{2}\sum(\mathrm{C_i} * \mathrm{Z_i}^2) \tag{4}$$

Ci is the molar concentration of the ith dissolved ion and Z_i is the charge of the ith dissolved ion. Divalent cations increase the ionic strength more than monovalent ions at the same molarity. The Guoy Chapman model which quantifies the diffuse double layer thickness can be estimated from the following equation.

$$\mathrm{K}^{-1} = \frac{3.42 * 10^{-10}}{zI^{0.5}} \tag{5}$$

Where K is the double layer thickness in meters, z is the valence of the ions in solution and I is the ionic strength of the solution (Essington, 2004). Increasing valence of ions in solution and increasing ionic strength, or both will decrease the size of the double diffuse layer. This is due to greater ionic strengths resulting in smaller width of the soil’s diffuse double layer (Kshirendra et al., 2012). As ionic strength of a soil increases the diffuse double layer of a soil becomes smaller and the electrolyte concentration becomes greater. This is why high EC soils or divalent cation rich soils are well aggregated and less likely to disperse than sodium rich low EC soils. A sodium cation absorbed to clay particles will occupy a larger surface area as compared to divalent cations such as calcium or magnesium. Sodium has only one equivalent of positive charge as compared to divalent cations that have two equivalents of positive charge. Sodium wants to be hydrated where calcium wants to be hydrated in which clays disperse and swell more when the electrolyte concentrations of the soil is low and sodium levels are high (He et al., 2013; Dane and Klute, 1977).

Leaching of divalent cations from solution reduces the soils ionic strength, which increases the effect of sodium on soil solution. Maintaining sufficient divalent cations in soil solution will saturate a soils cation exchange sites more thoroughly than monovalent cations. This is due to an ion charge density of divalent cations being higher (i.e. more ionic strength) and hydrated radius being smaller than the monovalent sodium ion. There also is a greater attraction of divalent cations to the exchange sites. Divalent cations in soil solution will flocculate clay particles forming small aggregates. Monovalent cations are less effective than divalent cations at fulfilling the negative charge of soil clays leading to conditions that degrade soil properties.

Swelling and Dispersion of Saline and Sodic Soils

Sodic soils have a larger double diffuse layer compared to soils dominated by divalent cations. This causes dispersion to occur within soil particles which allows water and sodium to enter the inner layers of smectite clays, and hydrate the clay particles, thus increasing the spacing between each clay particle (Foster, 1954). This results in greater repulsion between clay particles which, reduces aggregation of clay particles. Increasing the EC_e or having a calcium and magnesium dominant soil will prevent the dispersion of clay particles and form tactoids of clay particles (Essington, 2004). A soil’s exchange site complex dominated by divalent cations will reduce the amount of water that can enter the interlayers of smectite clays. When the aggregated smectite clays are wetted, they begin to swell from water increasing the distance between the clay interlayers. As SAR increases and ionic strength decreases in soil solution, the degree of soil swelling increases due to water being able to enter clay interlayers more easily and repulsion of negatively charged clay particles ensues (Lebron et al., 1994; Malik et al., 1992). Soil swelling causes a decrease in saturated soil hydraulic conductivity and infiltration rate by blocking pores that conduct water (Agasi et al., 1981). Therefore, if soil ionic strength is sufficient, greater infiltration and lower runoff rates are experienced, across a broad range of SAR values, than for soils with low ionic strength and high SAR values (Agasi et al., 1981).

Porosity and Pore Connectivity of Saline and Sodic Soils

The swelling, slaking and dispersion of clay particles in sodium affected soils weaken aggregate stability (Levy et al., 2003). An unstable aggregate is more likely to disperse and slake when water enters the soil aggregate, slaking occurs from air exiting the aggregate and swelling within the aggregate which is uneven. Slaking is the breakdown of large aggregates into smaller aggregates by water entering an aggregate and compressed air escaping from aggregates creates unequal forces with subsequent breakdown of the large aggregates into small aggregates (Hillel, 1998). Dispersion is the disintegration of small aggregates into individual particles due to repulsion of charged particles. Swelling is the expansion and shrinkage of soil aggregates due to fluids entering and leaving the soil changing spacing between clay particles and interlayers. When sodic soils are wetted the soil particles tend to swell, slake, and disperse. Percent aggregation of soil was found to decrease as soil solution SAR levels increased for a variety of coarse and medium textured soils in North Dakota with the largest decrease in percent aggregation occurring in the coarse textured Parshall soil (Costa et al. 1991). Due to these processes, the large > 2mm diameter and medium

1µm-2mm diameter soil pores shrink which makes flow path more tortuous in high SAR_e > 6 and low EC_e < 4 soils (Lebron et al., 2002; Dane and Klute, 1977).Clay dispersion reduces soil pore size distributions and shifts the distribution range towards the micropore range of < 1mm diameter pores due to the loss of these larger, structural pores on Madera, Hanford and Las Animas soil series (Lebron et al., 2002). In a study conducted on remediating sodic soils with a gypsum application and leaching waters, the macroporosity increased in the 0-30 cm soil depth during the one year after application on a silt loam textured soil with improved remediation as more water infiltrated (Yang et al., 2014). More importantly the shape and connectivity of the pores, based on x-ray tomography, was also increased after one year of remediation practices (Yang et al., 2014).

Hydrologic Properties of Saline and Sodic Soils

Soil hydrologic functions include soil water retention, fate, and transport. Water retention is the amount of water a soil can retain at given soil water potentials. Gravitational soil water movement occurs at soil water potentials near saturation and transitions to capillary water movement as the soil dries. The threshold that gravitational soil water movement ceases is defined as the volumetric soil water content at the moment soil water movement significantly decreases in a well-drained, semi-infinite soil (Hillel, 1998). This soil water content (field capacity) is commonly assumed to be well approximated at a soil water potential of -1/3rd bar (336 cm H_2O) but it is variable depending on soil texture (Cassel and Nielsen, 1986). However, thorough research on soil water retention has yet to verify field capacity as a real physical property though conceptually it has many beneficial interpretations (Cassel and Nielsen, 1986). This is due to hydraulic conductivity approaching zero at high potentials (i.e., > -336 cm H_2O) in coarse textured soils whereas conductivity is still well above zero in finer textured soils at a potential less than -336 cm H_2O (Cassel and Nielsen, 1986; Davidson et al., 1969). Soil water available for plant uptake is commonly approximated as the water retained in soil between soil water potentials of field capacity and at an assumed plants permanent wilting point which can vary depending upon plant species (i.e., -15,000 cm H_2O).

Dissolved salts decreases the osmotic, and thus total, soil water potential by decreasing potential of solution and creating a more negative potential required to move soil water in the X,Y, or Z direction, but is a factor on water movement in most field soils only when the soil solution has extremely high salinity values (Hillel 1998). Application of high SAR > 6 and low EC <4 dS m^{-1} infiltrating waters for multiple pore volumes have been shown to increase the amount of water a soil can retain at matric potentials greater than -15,000 cm H_2O (Crescimanno et al.,1995; Lebron et al., 1994 and Malik et al., 1992). Observed soil water contents were greater down to -15,300 cm H_2O soil water potential for high SAR (50) and concentration of 3.125 mole m^3 (EC of approximately 0.3 dS m^{-1}) at 0.35 cm^3 cm^{-3} volumetric water content than for SAR 0 solution application with a volumetric water content 0.30 cm^3 cm^{-3} at the same EC levels (Malik et al., 1992). Soil swelling and dispersion due to monovalent cations and low solution EC allow for more water to be retained at high water potentials (i.e., wet end of the water retention curve) due to a reduction of soil pore diameters (Lebron et al., 1994; Jayawardane and Beattie, 1978). The plant availability of water in high SAR_e to low EC_e soils is lower than in high EC_e to low SAR_e soils due to degradation of soil structure and dispersion of clay particles creates a more negative potential before water moves in the soil and can move deeper or be evaporated.

Soil pore size affects what potential energy water will be released at; so decreasing soil pore diameters will cause the water to be released at a lower water potential (Radulovich et al., 1989). Assuming that the soil pores are continuous and of the same diameter, the height of capillary rise (h) is calculated by the formula.

$$\mathrm{h} = \frac{2\,\gamma\cos\alpha}{\mathrm{p_w g r}} \tag{6}$$

Where γ = surface tension of water which is 0.0728 N m^{-1}, the wetting angle of the soil (α) is commonly assumed to be 0, the density of water p_w is the density at a temperature given of water, the g is the force of gravity (9.8 m^2 s^{-1}), the r is the pore radius in m. Poiseuille's law describes the fluid flow rate in a cylindrical tube as

$$\mathrm{Q} = \frac{\pi\,\mathrm{R}^4\,\Delta\mathrm{P}}{8\,\eta\,\mathrm{L}} \tag{7}$$

where Q is discharge cm^3 s^{-1}, Δ P is change in pressure, R is radius in cm, ή is viscosity in dyne seconds cm^{-2} of the liquid, π is pi, and L is length in cm. Poiseuille's law assumes laminar flow occurs and is proportional to width of the tube, the change in pressure and the length of the flow column. The smaller the pore diameters, the lower the amount of water will be that will flow downward in the pore at the same flow velocity. Smaller pores however have an increased height of rise via capillary forces due to their smaller diameters and greater adhesion to small pores and particles.

Water movement in soils is affected by sodicity and electrolyte concentrations in the soil solution. Gravitational water mainly moves through macropores (> 2mm diameter), whereas capillary water mainly moves through mesopores and micropores (approximately <1000µm and 50µm diameters, respectively) (Hillel, 1998; Beven and

Germann, 1982). The dispersive nature of sodium as well as soil solution ionic strength can alter soil pore size distributions, shapes and connectivity, affecting water flow in soils (Yang et al., 2014; Lebron et al., 2002; Jayawardane and Beattie, 1978).

High EC solutions reduce soil swelling and improve soil aggregation, which improves saturated and high water potential water flow through the soil. Low EC (< 4 dS m^{-1}) and high SAR > 6 of wetting solutions increase soil swelling and dispersion, reducing the soils saturated hydraulic conductivity of a variety of soil types (Crescimanno et al., 1995; Frenkel et al., 1978 and McNeal et al., 1968). In a loam textured soil from North Dakota, higher EC levels were required to maintain the same infiltration rates when SAR levels increased in irrigation waters (Oster and Schroer, 1979). There has been some disagreement that high calcium concentrations are more effective than magnesium levels as exchangeable cations, at maintaining saturated hydraulic conductivities. Jayawardane et al. (2011) and Curtain et al. (1994) reported that soils with high SAR percolating solutions decreased in saturated hydraulic conductivity more with magnesium chloride dominated solutions than calcium chloride solutions even when both were at the same electrolyte concentration. Some other studies have reported very small or no differences in dispersion and saturated hydraulic conductivities when the Ca^{2+} to Mg^{2+} ratios were varied (He et al., 2013; McNeal et al., 1968).

Unsaturated hydraulic conductivity is important in the movement of ions through the soil and in plant uptake of water. Capillary water and the dissolved salts contained within the soil solution can move in any direction. Unsaturated hydraulic conductivity of sodic soils has been shown to be lower from 0 to -15,300 cm H_2O matric soil water potentials after application of sodic infiltrating waters (Crescimanno et al., 1995; Malik et al., 1992 and Dane and Klute, 1977). An $EC_e > 5$ dS m^{-1} and low SAR < 6 of infiltrating irrigation waters was shown to increase the unsaturated movement of soil water from saturated water content and a volumetric water content of 0.30 cm^3 cm^{-3} (Malik et al., 1992). Understanding the impact of salinity and sodicity on soil physical properties and water transport is important for determining salt and water fates in agricultural soils throughout North Dakota, the North Central Plains Region, and other regions globally (e.g. Australia, Middle East, etc.) with saline or sodic soils.

Objectives

The objectives of this study are to determine the impacts of simulated saline and sodic solutions after saturating with approximately one pore volume of water containing sodium and calcium in different ratios and concentrations (i.e., simulation of ground water wetting) on soil shrinkage, water retention, and conductivity in soils across states of desaturation and to create simple regression equations (i.e., pedotransfer functions) to predict these impacts based on solution composition and antecedent soil properties. Therefore, we hypothesize that 1) high sodicity and low salinity will increase water retention at -15,000 cm H_2O and greater water potentials, 2) unsaturated hydraulic conductivity will be decreased to some negative potential when there is high SAR and low EC compared to low SAR and high EC treatments, and 3) Soil shrinkage will be highest for highest SAR and lowest EC treatments. The soil containing the greatest percentage of smectite within the bulk soil will have the largest differences from the saturating waters. Determining salinity and sodicity impacts on soil water retention, swelling and unsaturated hydraulic conductivities will improve our understanding of the fate and transport of salts and water in these soils. This will aid in defining effective remediation practices in agricultural soils with potential for saline, sodic and saline-sodic conditions.

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PAPER 1. SOIL COEFFICIENT OF LINEAR EXTENSIBILITY AS AFFECTED BY SOLUTION COMPOSITION AND MINERAL CONTENT

Abstract

Clay content, clay types and solution composition are known to create differences in soil coefficient of linear extensibility (COLE) values. The Northern Great Plains and Red River Valley has many acres of soils affected by ground waters containing soluble salts which may impact soil shrinking and swelling. Management of salinity levels such as subsurface drainage may increase clay swelling if sodium levels increase and electrical conductivity (EC) decreases. Our objective was to determine the effect of solution compositions varying in electrical conductivity and sodium adsorption ratios (SAR) on the soil shrinkage characteristic curve of smectitic soils and soil mixes during desaturation and to develop a simple stochastic-based parametric model to predict this shrinkage. Soils were initially saturated with salt solutions of varying EC and SAR and then formed into rods. The rods were initially allowed to air dry and then were oven dried. Gravimetric water contents and coefficient of linear extensibilities (COLE) were measured during and after drying. A portion of the dataset was used to develop multiple regression equations using soil shrinkage curve parameters and soil physical and chemical properties to predict COLE values; thus developing a pedotransfer function. These equations were then validated using the remaining portion of the soil rod characterization dataset. The EC 0.5 dS m^{-1} by SAR 20 solutions generally induced the highest COLE values at 0.157 mm mm^{-1} whereas the EC 8 dS m^{-1} by SAR 0 solutions obtained the lowest COLE values at 0.133 mm mm^{-1} on average. Solution composition did not always change the initial water content or the slope of the soil

shrinkage characteristic curves. Solutions less than 2 dS m^{-1} and SAR values greater than 6 increased the overall soil shrinkage. Total soil shrinkage is an indication of soil swelling which is conditions that occur when salts are leached via management practices from saline-sodic soils. The impacts of solution composition on the slope and shape of the soil shrinkage characteristic curves were considerably less than the impacts due to the percent clay.

Introduction

Soil mechanical properties are important for the agricultural and engineering industries. The ability of soils to shrink and swell impacts a wide variety of soil uses ranging from agricultural land use to the construction of roads and buildings (Smith et al., 1985; Davidson and Page, 1956). This process occurs while a soil is undergoing wetting and drying cycles. When a soil is wetted, clays sorb water and an outward force is created causing clay particles to expand due to the water films absorbing onto clay surfaces (Hensen and Smit, 2002). The distance of expansion between clay surfaces is dependent on the thickness of the diffuse double layer which is governed by the soil solution’s cation concentration and type (Hensen and Smit, 2002; Young and Smith, 2000).

Low quantities of salts in soil solution or solutions dominated by monovalent cations will increase the thickness of the double diffuse layer. This will then increase the swelling of some clay types with smectite clay dominant soils having the largest increases in volume based upon the solution composition (Churchman et al., 1993). Soil swelling forces extend outward in the soil and deform interaggregate pore spaces, whereas soil shrinkage tends to form voids between soil aggregates (Horn and

Smucker, 2005; Davidson and Page, 1956). The impact of shrinking and swelling of the clay fraction on a soil’s structural properties therefore impacts soil hydraulic properties (Bouma, 1980). Soil pores change in size while a soil shrinks thus altering water and solute transport throughout the soil and creates multiple flow regimes between soil cracks and within aggregates (Horn and Smucker, 2005). Soil solution composition has been shown to change the width of a soils double diffuse layers and cause shrinkage of soil clods, pastes, and clays in many soils (Malik et al., 1992 and McNeal et al., 1966). These changes in soil structure from shrinking and swelling can have large impacts on soil quality and site hydrology when at the landscape level.

Soil shrinkage occurs simultaneously as water leaves the soil, and clay interlayers and other soil particles begin to converge back together. The soil shrinkage characteristic curve can be divided into four parts which include structural, normal, residual, and zero shrinkage (Stirk, 1954). The structural shrinkage occurs when the soil is near saturation and large pores rapidly lose water initiating shrinkage between structural units (Stirk, 1954). Normal shrinkage occurs as water is leaving the soil and shrinkage is linear with change of water content (Haines, 1924). Normal shrinkage commonly occurs above -15,300 cm H_2O matric soil water potentials in the soil (Yule and Richie, 1980). Residual shrinkage occurs when the slope of soil shrinkage to the change in water content lessens. This range commonly occurs when the soil water content is below -15 bar matric soil water potential (Yule and Ritchie, 1980). Zero shrinkage occurs when the soil continues to lose water but does not decrease in volume (e.g., when the soil approaches air dry conditions).

A variety of soil physical and chemical properties impact soil shrinkage characteristics including clay types, clay content, and specific surface area (Smith et al., 1985; Ross, 1978). Clay mineralogy causes large differences in the swelling of soils with smectite dominated soils having higher rates of shrinkage compared to kaolinite and mica dominant soils (Ross, 1978). Soil chemical composition also has impacts on soil shrinkage. An increase of exchangeable sodium percentage (ESP) has been reported to increase soil shrinkage (Crescimanno et al., 1995; Smith et al., 1985). However, a high electrical conductivity (EC) can counteract soil swelling in soils with a high ESP or sodium adsorption ratio (SAR). These effects of solution composition have been observed on soil coefficient of linear extensibility (COLE) using the rod method (Chaudhari, 2001; Malik et al., 1992). In Malik et al. (1992) COLE values of a Vertisol were greater than 0.2 mm mm^{-1} when solutions were applied with an SAR of 50 and concentration of 3.125 mole m^{3} (EC of approximately 0.35 dS m^{-1}). In contrast, they observed COLE values of only 0.175 mm mm^{-1} when applied solutions had an SAR of 0 and solution concentration 3.125 mol m^{3} (EC of approximately 0.35 dS m^{-1}). Additionally, soil ESP levels greater than 10% combined with electrolyte concentrations 50 meq L^{-1} (EC levels less than approximately 4.5 dS m^{-1}) have been reported to increase soil clay hydration and swelling limit water contents (i.e., maximum water content that a soil can retain)(Crescimanno et al., 1995; McNeal et al., 1966).

These general trends have been long observed and reported in various literature from the 1920’s up to the 2010’s. However, little effort has been focused on characterizing and predicting soil shrinkage during desaturation for soils across a fine gradient of infiltrated saline solutions. Such efforts are needed to advance our understanding of hydrologic processes and our predictive power to simulate water flows in the environment of Red River Valley, Northern Great Plains region and other regions which are vulnerable to salinization from shallow ground waters. Therefore, the objectives of this study are to 1) quantify the impact of infiltrated solution composition on the soil shrinkage characteristics curves, 2) how these impacts, if any, vary among soils with differing textures and smectite concentrations, and 3) to develop a calibrated and validated pedotransfer function using simple multiple regression techniques. We hypothesize 1) increased infiltrating solution SAR levels and decreased solution EC levels will result in more soil shrinkage 2) the largest differences among solution composition to be observed in high clay and percent smectite clay soil (i.e., the most total shrinkage and steepest slope to the shrinkage curve) 3) these differences can be precisely predicted using newly developed pedotransfer functions.

Methods and Materials

Soil Collection and General Physical and Chemical Analysis

Three soil types were collected and used to create seven soil mixes of varying textural classes. The three soil types included a Fargo silty clay (fine, smectitic, frigid, Typic Epiaquert) collected from a 0-15 cm depth near Gardner, ND (47.172974N, 96.90037W), a Serden sand (sandy, mixed, frigid, Typic Udipsamment) collected from a 0-15 cm depth near Wyndmere, ND (46.474364 N, 97.226595 W), and a Portwing clay (fine, mixed, active, frigid, Oxyaquic Glossudalf) collected from a 25-50 cm depth near Cornucopia, WI (46.837577 N, 91.082729 W). Particle size distributions were determined using the pipette method (Gee and Or, 2002). Soil cation exchange capacity (CEC) was determined using a pH 7 ammonium acetate extractant. Initial soil pH_e and

EC_e were determined using a saturated paste extract and a Sension 378 conductivity probe (Hach Co., Loveland, CO, USA; Rhoades, 1996). The soil SAR was determined using a saturated paste extract with cations measured by flame atomic adsorption (Model 200A, Buck Scientific). The mineralogy of the < 2µm equivalent diameter fraction was determined semi quantitatively using X-ray diffraction with a Panalytical X'Pert Pro diffractometer by Activation Labratories, Ancaster, Ontario Canada. The < 2µm fraction was separated by sedimentation and quantitative clay type fractions determined by basal peak area ratios. The Portwing clay, Fargo silty clay, and five mixes of Fargo silty clay + Serden sand were used for all salt solution treatments. The Fargo silty clay and Serden sand was mixed at 5:1, 2:1, 7:5, 1:1, and 1:2 ratios on an air dry mass basis. The physical and chemical properties of the seven soil and soil mixes are reported in Tables 1 and 2.

Experimental Design and Coefficient of Linear Extensibility

To determine the effect of salt solution composition on soil shrinkage, a modified COLE rod procedure was performed for each of the EC vs. SAR salt solution treatments (Schafer and Singer, 1976). Solution treatments applied to the soil made with EC values of 0.5, 1, 2, 4 and 8 dS m^{-1} and SAR values of 0, 3, 6, 12 and 20 were used made from NaCl and $CaCl_2$ using conductivity factors (He et al., 2013). For the procedure, 100 g of soil was saturated for 24 hours with a salt solution treatment level. The soil was then extruded from a syringe into four rods, at 6 to 10 cm long per rod, on a plexiglass plate with the surface covered with petroleum jelly. The rod length was measured with a caliper at time zero and at approximately 2 hr increments during the 0 to 12 hr period of air drying and then at 24 hr increments thereafter. Weights of the plexiglass plate plus rods were also measured for each time the rod length was determined. Once air dried, the samples were placed in an oven at 55 °C for 24 hr to further dry the samples. The total change in soil rod length is referred to as the oven dry COLE value. After cooling from the 55 °C oven, the weight and lengths of the rods were recorded along with the weight of the plexiglass plate. The rods were then placed in a 105 °C oven for 48 h and the weight of plexiglass of each treatment was recorded. The weight at a given time, oven dry soil weights, and the empty plexiglass plate weight were used to calculate the average gravimetric water content at a given time during the drying process for the four soil rods per plexiglass plate. The COLE, or percent shrinkage of the soil, at a given time was calculated as COLE = $(L_{wet}-L_{dry})/L_{dry}$ where L_{wet} is length of wet soil rod and L_{dry} is length of dry soil rod in mm (Schafer and Singer, 1976).

Statistical Analysis

To compare how salt solution composition affects shrinkage across a range of soil textures, the solution EC, solution SAR, soil type, and their interactions on COLE values (i.e., determined after oven-drying at 55°C) were compared using an analysis of variance (ANOVA) for the Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and the Portwing soils in (SAS® 2002). A mixed model ANOVA was used and means were separated using Tukeys at the 0.05 alpha level (SAS® 2002). The percent of each effect’s and interaction’s contribution to the models variance was then determined using the model’s total sum of squared error and each effects and interaction’s F-value and degrees of freedom.

Table 1. General physical and chemical properties of pretreated soils and soil mixes.

Soil Series/ Soil Mixes	Sand	Silt	Clay	Texture	CEC	EC_e	SAR	pH	OM
	---------	%	----------		cmole kg^{-1}	dS m^{-1}			%
Fargo	3	44	53	Silty clay	27.2	0.46	0.45	7.52	5.4
5:1 Fargo:Serden mix	19	42	38	Silty clay loam	-	0.68	-	7.18	4.6
2:1 Fargo:Serden mix	34	30	32	Clay loam	17.4	0.49	0.48	7.70	3.9
7:5 Fargo:Serden mix	43	31	26	Loam	-	0.44	-	6.98	3.4
1:1 Fargo:Serden mix	49	30	21	Loam	-	0.48	-	7.08	3.1
1:2 Fargo:Serden mix	71	13	16	Sandy loam	4.3	0.40	0.44	7.70	2.2
Portwing	35	24	39	Clay loam	14.6	0.16	0.27	4.76	0.9

Table 2. Clay mineralogy and bulk soil clay mineral contents for Fargo soil series, Fargo: Serden mixes, and Portwing soil series.

Soil Series/ Soil Mixes	Smectitie	Illite	Kaolinite	Chlorite
	-----------------------	% of clay	-----------------------	
Fargo	55	34	11	0
Portwing	38	37	15	10
	-----------------------	% of bulk soil	-----------------------	
Fargo	29.2	18.0	5.8	0.0
5:1 Fargo:Serden mix	20.9	12.9	4.2	0.0
2:1 Fargo:Serden mix	17.6	10.9	3.5	0.0
7:5 Fargo:Serden mix	14.3	8.8	2.9	0.0
1:1 Fargo:Serden mix	11.6	7.1	2.3	0.0
1:2 Fargo:Serden mix	8.8	5.4	1.8	0.0
Portwing	14.8	14.4	5.9	3.9

Soil shrinkage characteristic curves for all seven soil and soil mixes were described by fitting a modified equation from Cornelus et al. (2006) and Groenevelt and Grant (2001)

$$\frac{L_{rel} - L_{dry}}{L_{sat} - L_{dry}} = L_{dry} + ae^{-b/\theta^{c}} \tag{8}$$

$$\mathrm{Lrel} = 1 - \frac{\mathrm{Lsat} - \mathrm{Lt}}{\mathrm{Lsat}} \tag{9}$$

where L_{rel} is the relative soil rod length to the saturated soil rod length in mm mm^{-1}, L_{sat}, L_{dry} is the dry relative soil length after oven drying at 55°C oven (i.e., intercept of the curve), the *a*, *b* and *c* are empirical fitting parameters, θ is the average gravimetric water content of the soil rods in g H_2O g^{-1} oven dry soil, and L_t is soil rod length at time t. Fitting parameters were determined by ordinary least squares. The a parameter changes based on describing the slope of the normal shrinkage portion, the b parameter changes based on describing the size and slope of residual shrinkage portion, and the c parameter changes based on describing the structural shrinkage portion of the curve (Cornelus et al., 2006).

$\mathrm{Lrel} = 1 - \frac{\mathrm{Lsat} - \mathrm{Lt}}{\mathrm{Lsat}}$ was used to compare the L_{dry}, a, b, and c parameters from equation 8 among the solution EC, solution SAR, soil type, and their interactions, a mixed model ANOVA was used and means were separated using Tukeys at the 0.05 alpha level. The percent of each effect's and interaction's contribution to the models variance was then determined using the model's total sum of squared error and each effects and interaction's F-value and degrees of freedom.

Multiple regression models (i.e., linear, quadratic, and logarithmic) were fitted to oven dry COLE values by ordinary least squares using only a portion of the solution EC and SAR combinations for all seven soil and soil mixes dataset. The models were then validated with the remaining solution EC and SAR combinations of the dataset (i.e., data not used in the model fitting). The oven dry COLE values used for model fitting included solution EC levels 0.5, 2, and 8 dS m^{-1} and SAR levels 0, 6, and 20 for all seven soils and soil mixes. These models were then validated with the oven dry COLE values of solution from EC levels 1 and 4 dS m^{-1} and SAR levels 3 and 12 for all seven soils and soil mixes. Inputs for each of the three regression models included solution EC and SAR level, soil organic matter content, percent clay, and percent smectite in the bulk soil.

The linear regression model is

$$\mathrm{COLE} = \mathrm{yo} + \mathrm{aEC} + \mathrm{bSAR} + \mathrm{cclay} + \mathrm{dsmectite} + \mathrm{eOM} \tag{10}$$

where *yo a, b, c, d* and *e* are fitting parameters, clay is the percent clay, smectite is the percent smectite in the bulk soil, and OM is the percent soil organic matter content. The quadratic regression model is

$$\mathrm{COLE} = \mathrm{yo} + \mathrm{aEC^f} + \mathrm{bSAR^g} + \mathrm{cclay^h} + \mathrm{dsmectite^i} + \mathrm{eOM^j} \tag{11}$$

where *yo, a, b,* …, *j* are fitting parameters.

The logarithmic base 10 model is,

$$\begin{aligned} \mathrm{COLE} &= \mathrm{yo} + \mathrm{a}\log(\mathrm{fEC}) + \mathrm{b}\log(\mathrm{gSAR}) + \mathrm{c}\log(\mathrm{hOM}) \\ &+ \mathrm{d}\log(\mathrm{Ismectite}) + \mathrm{e}\log(\,\mathrm{jPb}) \end{aligned} \tag{12}$$

where *yo, a, b,* …, *j* are fitting parameters.

These calibrated models were then used to predict oven dry COLE values in mm mm^{-1} using inputs from the remaining data not used previously for the model fitting. These predicted oven dry COLE values were then compared and validated against the measured oven dry COLE values. The root mean square error (RMSE) and bias were calculated for the predicted vs. measured oven dry COLE values by

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{P_i} - \mathrm{F_i})^2} \tag{13}$$

$$\mathrm{Bias} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{P_i} - \mathrm{F_i}) \tag{14}$$

where P_i is the predicted oven dry COLE values, F_i is the measured oven dry COLE value, and N is the number of observations.

Results and Discussion

Coefficients of Linear Extensibility

Soil oven dry COLE values were significantly affected by solution EC, solution SAR, soil type, each two-way interactions, and the three-way interaction (P values between 0.03 and <0.0001). The soil type main effect and the three-way interaction accounted for 95% and 1.6% of the mode’s variance, respectively. The Fargo soil had the largest oven dry COLE values among all soils within each solution EC and SAR combination (Tables 3 and 4). In contrast, the 1:2 Fargo:Serden mix had significantly lower oven dry COLE value than all other soils within each solution EC and SAR combination (Tables 3 and 4). This was expected due to the large differences in soil particles sizes (Tables 1 and 2). As expected, the 2:1 Fargo:Serden mix and the Portwing were more similar to each other than to the Fargo soil or the 1:2 Fargo:Serden mix, likely due to their similar soil particles size classification. However, oven dry COLE values for the Portwing was significantly larger than the 2:1 Fargo:Serden mix for the solution EC 2 and 4 dS m^{-1} when averaged across all SAR values (Table 3). The Portwing soil had larger values than the 2:1 Fargo:Serden mix for all solution SAR levels when averaged across EC levels, except in one case (Table 4). This was due to contrasting and opposite effects of EC and SAR levels in the two soils. For instance, the Portwing soil was not affected by EC levels whereas the 2:1 Fargo:Serden mix decreased in oven dry COLE values as the solution EC increased (Table 3). In contrast, the 2:1 Fargo:Serden mix was not affected by SAR levels whereas the Porwing soil increased in oven dry COLE values as the solution SAR increased (Table 4). This may have been due to the large differences in soil organic matter contents (i.e., 3.9% for the 2:1 Fargo:Serden mix and 0.9% for the Portwing soil) or compounding effects due to other, although slight, differences in soil physical and chemical properties (Table 1). In general, the oven dry COLE values for the Fargo soil and 2:1 Fargo:Serden mix decreased as solution EC level increased whereas the 1:2 Fargo:Serden mix and the Portwing soil did not change with solution EC level (Table 3). As for solution SAR impacts on oven dry COLE values, the Fargo and Portwing soils significantly increased as solution SAR level increased whereas no changes were observed in the 2:1 and 1:2 Fargo:Serden mixes (Table 4).

Table 3. Mean oven dry coefficient of linear extensibility (COLE) values for two soils and soil mixes saturated with various solution EC levels and averaged across SAR levels.

Solution EC	Fargo	2:1 Fargo: Serden mix	1:2 Fargo: Serden mix	Portwing	All soils
	--	----------mm mm^{-1}----------		------------------------------	
dS m^{-1}					
0.5	0.230aA	0.155abB	0.047aC	0.160aB	0.147a
1	0.231aA	0.157aB	0.042aC	0.160aB	0.147a
2	0.225aA	0.146cC	0.043aD	0.166aB	0.144a
4	0.203bA	0.130dC	0.023bD	0.153aB	0.128b
8	0.211bA	0.149bcB	0.047aC	0.156aB	0.143a
All solutions	0.220A	0.147C	0.040D	0.159B	

Different lower case letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.
Different capital letters within a row are significantly different using Tukey pairwise analysis at the 0.05 level.

Table 4. Mean oven dry coefficient of linear extensibility (COLE) values for soils and soil mixes saturated with various solution SAR levels and averaged across EC levels.

Solution SAR	Fargo	2:1 Fargo: Serden mix	1:2 Fargo: Serden mix	Portwing	All soils
	mm mm^{-1}				
0	0.208cA	0.142aC	0.037aD	0.154cbB	0.135c
3	0.220bA	0.153aB	0.040aC	0.151cB	0.142b
6	0.220bA	0.144aC	0.036aD	0.159cbB	0.140b
12	0.219bA	0.145aC	0.046aD	0.161bB	0.144b
20	0.233aA	0.150aC	0.043aD	0.171aB	0.149a
All solutions	0.220A	0.147C	0.040D	0.159B	

Different lower case letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.

Different capital letters within a row are significantly different using Tukey pairwise analysis at the 0.05 level.

In this study, the oven dry COLE values increased as clay content increased and is consistent with other reports that compared soils of similar clay percentage and minerology (Ross, 1978). Oven dry COLE values increased with SAR values of applied waters as has also been reported for Vertisols in Sudan and India (Chaudhari, 2001; Malik et al., 1991). The effects of SAR on oven dry COLE values are greater for soils with relatively high clay content and with larger differences across SAR treatments as smectite clay content increases. Similar trends of SAR and clay content on oven dry COLE values were also reported by Malik et al. (1991). In general, an increase in soil SAR and or a decrease in soil EC has been reported to increase oven dry COLE values which was also observed in this study (Malik et al., 1991). However, some treatments of solution EC of 2 dS m^{-1} or greater produced oven dry COLE values near the highest values with some soil textures. Other studies have reported larger differences among applied solution EC vs SAR treatments to the soil that are similar to those used in this study (Chaudhari, 2001). This may be due to differences in how saline solutions are applied to soils (i.e., initial saturation vs. multiple pore volumes of surface infiltrating waters) and subsequent effects on the increase in the SAR of the soil.

Soil Shrinkage Characteristic Curves

Similar to the oven dry COLE values, the parameters of the soil shrinkage characteristic curves as a function of gravimetric soil water content were significantly and dominantly affected by soil type (P values <0.0001) except for the c parameter which was set at 1 due to structural shrinkage being absent in soil pastes. However, these parameters were not affected by solution EC, solution SAR, or any of their interactions when analyzing all seven soils and soil mixes (P values > 0.05). Solution EC and SAR levels had some slight, although significant, effects on the soil shrinkage characteristics curve parameters when each soil and soil mix was analyzed individually (i.e., P values < 0.05).

The Fargo soil had the highest initial water content whereas the 1:2 Fargo:Serden mix had the lowest initial water content at time zero (i.e., the soil rods at initial saturation; Figure 1; Table 5). The Groenevelt and Grant equation fit well ($r^2 > 0.96$) to the soils with low sand content (e.g., Fargo, 2:1 Fargo: Serden mix, Portwing soil), but the model fit became poorer ($r^2 < 0.70$) as sand content increased (i.e., the 1:2 Fargo:Serden mix; Table 5). The dry relative soil length parameter, L_{dry}, was lowest for the Fargo soil, highest for the 1:2 Fargo:Serden mix, and similar among the 2:1 Fargo:Serden mix and the Portwing soil (Table 5). When the ANOVA was rerun for each soil individually, the L_{dry} values numerically decreased as SAR increased but differences among SAR levels were only statistically significant in the Portwing soil. In contrast, the L_{dry} values numerically increased as EC increased but differences among EC levels were only significant for the 2:1 Fargo:Serden mix. The a parameter was highest for the Portwing soil, lowest for the 1:2 Fargo:Serden mix, and similar for the Fargo and 5:1, 2:1 and 7:5 Fargo:Serden mixes with significant differences occurring between soil types. The solution EC level significantly affected the a parameter in all soils. However, the significant differences in the a parameter along the gradient of EC levels was not consistent and may have been a result of innate variation within some of the treatment level replications. Soil and soil mixes differed significantly in their b parameter, but no effect of solution EC or SAR levels were observed when soils were analyzed together or individually. The Fargo, 5:1, 2:1, 7:5 and 1:1 Fargo:Serden mixes, and the Portwing soils had similar b parameters whereas the 1:2 Fargo:Serden mix had a significantly lower b parameter. Similarly, soil and soil mixes differed significantly in their initial gravimetric water contents, but no effect of solution EC and SAR levels was observed when soils were analyzed together or individually. The initial water content (θ_{gs}) of the soil rods was similar for the Portwing and 1:2 Fargo:Serden mix and increased significantly as clay content in the soil mixes increased (Table 5).

The slope of the soil rod shrinkage curves were nearly linear for gravimetric water contents from saturation to water contents that are greater than -15 bars matric potential (Figure 1). Crescimanno and Prevenzano (1999) and Yule and Ritchie (1980) reported a similar range of linear shrinkage for 2:1 clay soils in Italy and Texas. Others have observed that the slopes of shrinkage curves are similar across a gradient of clay and sand mixes once a clay content threshold is reached if the clay mineralogy is maintained (Bolvin et al., 2004). For instance, Cornelis et al. (2006) used the balloon method for determining soil shrinkage and they observed a and b parameters of the soil shrinkage curve were higher for a Vertisol soil as compared to a highly weathered and oxidized Lixisol (Alfisol with low CEC clays) soil due to the differences in mineralogy. They also observed that the L_{dry} parameter was lower for the Vertisol soil as compared to the Lixisol soil (Cornelis et al., 2006). L_{dry} parameters increased as the clay content decreased in the soil mixes of our study which demonstrates that the L_{dry} parameter is dependent on both clay type and content. The a and b parameters also increased as clay content increased in our soil and soil mixes. However, our observed a and b parameters initially increased as clay content increased but then converged for soils and soil mixes that exceeded 30% clay. The initial gravimetric soil water content at saturation also appeared to increase as clay content increased whereas the oven dry relative length decreased with clay content in our soil and soil mixes. This is expected since an increase in clay content will increase the liquid limit and water content of swelling limit for many soil types and particularly for soils with smectite dominated clay fractions (Groenevelt and Grant, 2007; Bolvin et al., 2004; Taboada 2001; Bradenau et al., 1999; Warkentin, 1972).

Table 5. Fitted parameters of soil shrinkage using the equation of Groenevelt and Grant (2001) for seven soils and soil mixes saturated with solution combinations of EC values of 0.5 to 8 dS m^{-1} and SAR values of 0 to 20. The parameter L_{dry} is the dry relative soil rod length, a and b are fitting parameters, and θ_{gs} is the initial soil moisture content of the soil rods.

Soil Series/ Soil Mixes	L_{dry} (mm mm^{-1})	a	b	θ_{gs} (g g^{-1})	R^2
Fargo	0.82g	0.395b	0.55a	0.755a	0.98
5:1 Fargo:Serden mix	0.84f	0.384b	0.546a	0.631b	0.97
2:1 Fargo:Serden mix	0.87d	0.405b	0.579a	0.532c	0.95
7:5 Fargo:Serden mix	0.88c	0.361b	0.535a	0.490d	0.95
1:1 Fargo:Serden mix	0.92b	0.284c	0.556a	0.491d	0.87
1:2 Fargo:Serden mix	0.96a	0.087d	0.293b	0.430e	0.63
Portwing	0.86e	0.464a	0.531a	0.463e	0.97

Different lower case letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.

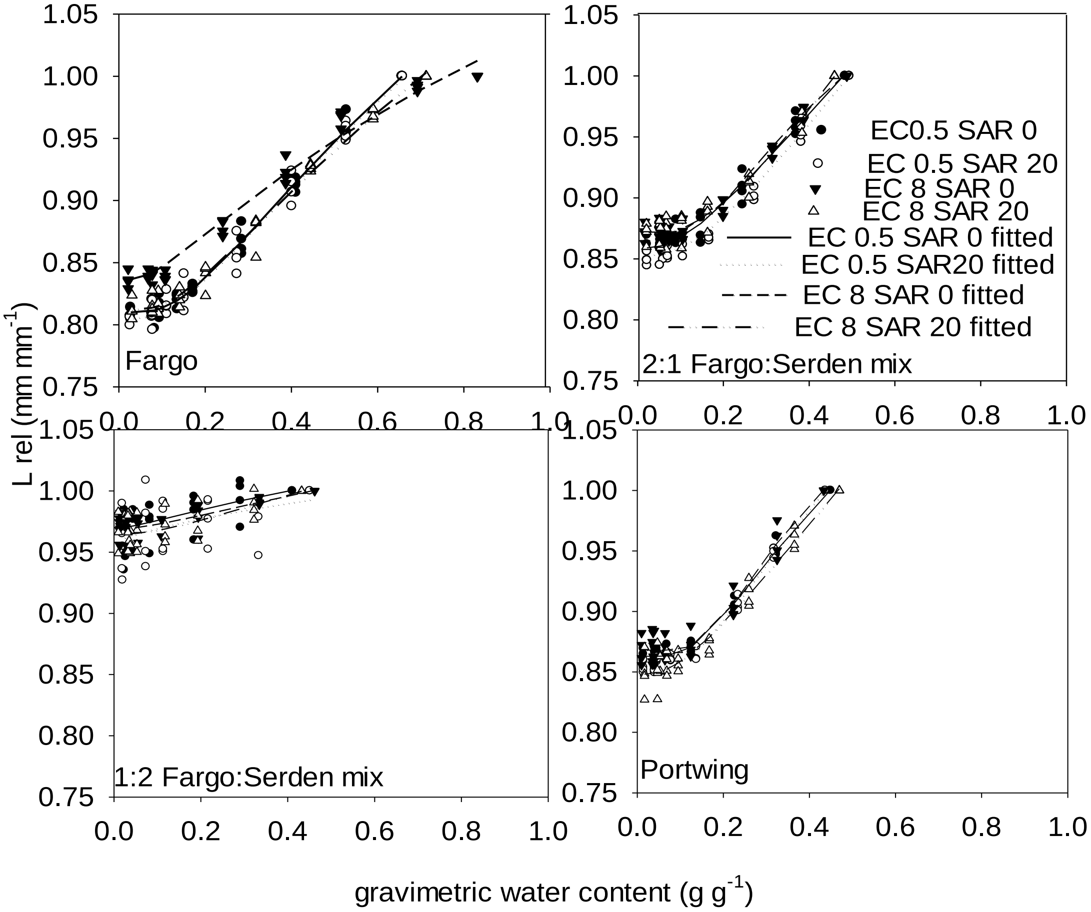

Figure 1. Examples of relative soil shrinkage as a function of desaturation for soil series and soil mixes at EC 0.5 dS m^{-1} and 8 dS m^{-1} and SAR values of 0 and 20. The equation from Groenevelt and Grant (2001) was used to describe the data with fitting parameters listed in Appendix C.

Prediction of Soil COLE Values Using Multiple Regression Models

The calibrated linear, quadratic, and logarithmic multiple regression models used to predict oven dry COLE values were generally similar in RMSE and bias (Figure 2). However, the quadratic model had the lowest RMSE value whereas the linear model had the lowest bias (Table 6). All three models tended to overestimate many of the oven dry COLE values for the majority of soils when values were less than 0.05 mm mm^{-1}.

However, COLE estimates improved as values became larger as a result of increased clay and smectite content (Figure 2). Regression coefficients associated with the clay, smectite, and organic matter are larger and thus imply that they are more dominant factors in determining oven dry COLE values as compared to the wetting solution's composition within the range of EC and SAR levels used in this study. The relatively lower influence of the wetting solution's composition as compared to clay contents was expected due to the large range of soil textures used in this study. However, the salt solutions which were applied may not have altered the soil's chemistry enough to cause large differences in oven dry COLE values and thus prevented larger coefficients associated with solution EC and SAR in the regression models. However, these model coefficients are empirical values that relate input parameters to oven dry COLE values and do not contain any real physical information about the parameters or the shrinking process. Since the sandier soils have little or no differences in COLE values among the solution treatments, whereas the clayey soils had larger differences in COLE values among the solution treatments, the impacts of solution composition may be compounded in other coefficients such as percent clay or smectite. This argument is reasonable since the a, b, and L_{dry} parameters are a function of clay type and content, as discussed in the previous section. Therefore, the use of simple multi-variable regression models may not be sufficiently robust to separate the clay and solution composition terms unless 1) a specific model is built for soil's containing each clay mineral type or 2) a categorical parameter for clay type is included into the model. However, the prediction of oven dry COLE values for soils with somewhat equal parts of mixed mineralogy may still prove difficult.

Table 6. Multiple regression parameters for the linear, quadratic, and logarithmic models, sum of squared error (SSE), root mean square error (RMSE), and bias of multiple regression equation to predict oven dried coefficient of linear extensibility (COLE) values of soil rods.

Parameter	Linear	Quadratic	Logarithmic
yo	-0.090	-0.001	-0.544
a	-0.0004	-0.0590	-0.0037
b	0.0004	0.0090	0.0027
c	0.019	-3.900	0.870
d	-0.038	1.700	-0.669
e	0.077	0.274	0.185
f		0.026	0.663
g		0.134	0.675
H		-0.644	1.280
I		-0.628	0.898
J		0.174	0.878
SSE	0.091	0.077	0.081
RMSE	0.020	0.019	0.020
Bias	-0.00006	-0.00166	0.00185

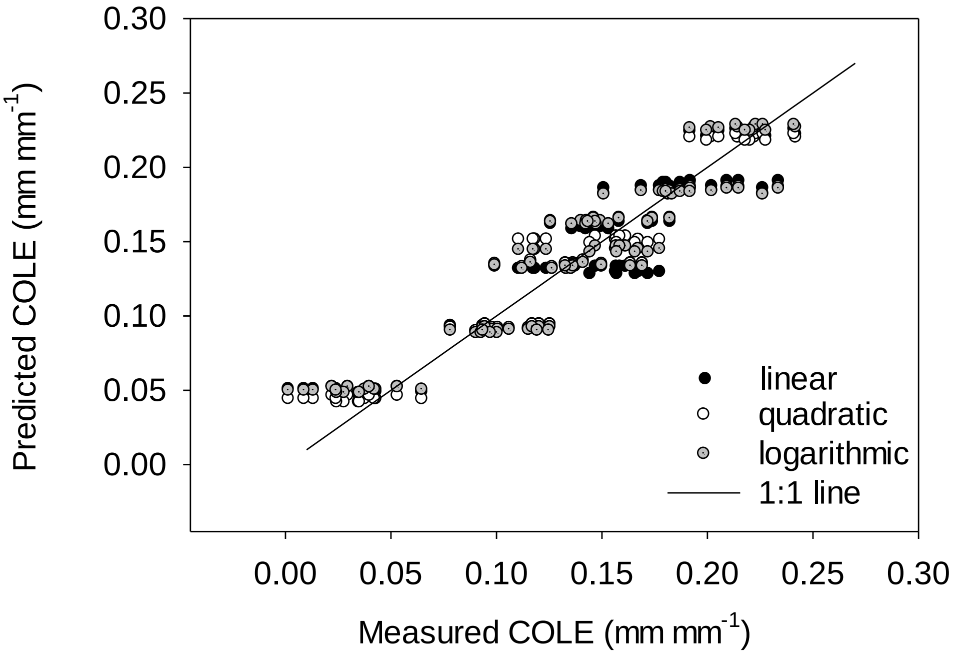

Figure 2. Model validation of measured oven dry coefficient of linear extensibility (COLE) values vs predicted COLE values using Fargo, soil mixes, and the Portwing soils. Linear, quadratic and logarithmic models that used soil chemical and physical properties to predict COLE values a root mean square errors of 0.020, 0.018, and 0.019 mm mm^{-1}, respectively.

Conclusions

Soil salinity and sodicity appear to show some affects on soil shrinkage and swelling. The oven dry COLE values were 0.208 vs 0.230 mm mm^{-1} for Fargo soil and 0.037 vs 0.043 mm mm^{-1} for 1:2 Fargo Serden mix when SAR values were 0 vs 20, respectively, and averaged across EC levels. The dry relative length of soil rods as a function of water content varied greatly with soil texture and dry relative length averaged 0.82 mm mm^{-1} for Fargo soil vs 0.96 mm mm^{-1} for 1:2 Fargo:Serden mix. However, small and irregular changes in the dry relative length of soil rods were observed when soils were initially saturated with waters varying in EC and SAR levels with largest differences being 0.803 vs 0.836 mm mm^{-1} for Fargo soil between solutions of EC 0.5 dS m^{-1} and SAR 20 vs EC 8 dS m^{-1} and SAR 0. The slope of the soil rod relative length as a function of water content was not altered by solution EC and SAR levels until clay content was greater than 30%. An increase in clay content decreased the soil rod dry relative length from 0.96 to 0.82 mm mm^{-1} while simultaneously increased the initial saturated water content from 0.43 to 0.76 g g^{-1} across the range of 1:2 Fargo:Serden mix up to the Fargo soil, respectively. The solutions applied to these soils may not have increased the soil SAR values enough at the low solution EC levels to greatly affect the slope of the soil shrinkage curve and the initial saturated water content of soil rods. Given this, soil shrinkage characteristics were observed at solution values which likely produced saturated paste extract EC and SAR values much less than those used for defining saline, sodic, or saline-sodic classifications. Although the effects of solution composition on soil shrinkage was observed and well characterized at these relatively low EC and SAR levels, this does not imply that the magnitude of change is enough to alter agricultural productivity at the field level. Lowering EC and increasing SAR such as installing tile drainage will increase total overall soil shrinkage and swelling but not the slope of shrinkage characteristic. These results likely have more importance for aiding efforts to precisely describe unsaturated water flow and solute transport near the soil-root interface or civil engineering materials. Simple multiple regression equations described oven dry COLE values well and were most sensitive to the soil's percent clay. However, research efforts to precisely separate the non-linear codependence of soil shrinkage on percent clay and solution salinity should be investigated to improve the predictions.

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PAPER 2. SOIL HYDRAULIC CONDUCTIVITY AS AFFECTED BY SIMULATED SALINE AND SODIC GROUNDWATER

Abstract

Hydraulic conductivity is important in the transport of water and salts in salt affected soils. North Dakota and Northern Great Plains has vast ages of soils impacted by saline and sodic ground waters. When sodium salts are dominate in soil, even at low concentrations, soils can have decreased water flow rates. The objective of this study was to determine how saturation of soil columns with saline and sodic solutions change soil saturated hydraulic conductivity and subsequent salt leaching on a variety of soil textures from a smectite clay dominant soil and a mixed clay mineralogy dominant soil. Soil columns were capillary wetted with solutions of varying electrical conductivity (EC) and sodium adsorption ratio (SAR) combinations ranging from EC values of 0.5 to 8 dS m^{-1} and SAR values from 0 to 20. Saturated hydraulic conductivity was then measured by infiltrating deionized water at the soil surface. Saturated hydraulic conductivity as a function of leachate pore volume was described as an exponential decay. A pedotransfer function was then developed to predict the exponential decay parameters for the saturated hydraulic conductivity vs. pore volume relationship and then validated. Hydraulic conductivity was initially lowest for the EC 0.5 dS m^{-1} SAR 20 solution treatment at 0.32 cm h^{-1} and increased to 1.92 cm h^{-1} for EC 8 dS m^{-1} SAR 0 treatment solution treatment in the smectitic silty clay soil. The steepest decline in hydraulic conductivity vs pore volume such as what would occur while managing soil salinity occurred in mixed clay soil which was 0.56 vs 0.29 cm pore volume h^{-1}, when averaged across EC values at solution SAR 20 vs SAR 0. Higher salt contents in groundwaters

are more successful at increasing soil SAR as compared to low salt content waters which will lead to a more rapid decline in saturated conductivity over time while leaching salts from the soil. The developed pedotransfer functions were insensitive to solution EC and SAR values as compared to clay percentage and predicted the exponential decay parameters with root mean square errors to within 12 to 16% of the maximum observed parameter estimates. Removal of salts brought upward via capillary fringe from soil will decrease saturated conductivity over time especially if salts are sodium dominant.

Introduction

The transport of water, and thus soluble salts, in soils are important processes that should be taken into consideration when managing areas impacted by saline and/or sodic waters (e.g., upwelling groundwater, saline seeps, irrigation, etc.). The Great Plains and Eastern North Dakota, has millions of acres of soils with high water tables containing soluble salts, which has created saline and sodic conditions in the soil profile (Skarie et al., 1987; Miller et al., 1985). These salts are gypsum ($CaSO_4 \cdot 2H_2O$), calcite ($CaCO_3$), epsonite ($MgSO_4 \cdot 7H_2O$), thenardite ($NaSO_4$) and in some locations sodium and magnesium chloride ($NaCl$ and $MgCl_2$) (Doner and Lynn, 1989; Miller et al., 1988; Skarie et al., 1987).

Many studies have evaluated infiltrating saline and/or sodic waters and subsequent change of saturated soil hydraulic properties (Curtain et al., 1994; Oster and Schroer 1979; Frenkel et al., 1978 and McNeal et al., 1968). These studies report that increasing electrical conductivity (EC) level and/or decreasing sodium adsorption ratio (SAR) levels of infiltrating waters can increase saturated hydraulic conductivity for a wide range of soil types (Curtain et al., 1994; Frenkel et al., 1978; McNeal et al., 1968). For example, a study evaluating a variety of California soils found that relative saturated conductivity was at least 25% lower for soils with exchangeable sodium percentage (ESP) ≥ 15%, saturated paste extract SAR (SAR_e) levels ≥ 12, and an infiltrating solution EC of 3 meq L^{-1} (EC approximately 0.35 dS m^{-1}) than for soils with negligible sodium levels (McNeal and Coleman, 1966; US Salinity Laboratory Staff, 1954). However, other studies have reported notable decreases in saturated hydraulic conductivity in soils with SAR levels as low as 5 when the EC level is < 5 mole m^{-3} (EC < approximately 1 dS m^{-1}) of the infiltrating solution for soils that contain > 30% clay (Chaudhari, 2001; Crescimanno et al., 1995). Soils dominated by smectite clay have been shown to have greater sensitivity in saturated hydraulic conductivity changes from use of sodic irrigation waters as compared to illite, kaolinite, and iron oxide clay dominant soils (Frenkel et al., 1978; McNeal et al., 1968). Thus, the scale of impact to saline and sodic waters have on soil water flow depends on the amount of clay and clay type.

Some soils exhibit a decrease in infiltration rates from infiltrating rain water at even lower soil solution SAR values due to the low EC of the rainwater. Shainberg et al. (1981a) reported that the hydraulic conductivity of soil can decrease at ESP values as low as 1% when deionized (DI) water is infiltrated. Saturated hydraulic conductivity of some soils will decrease regardless of the infiltrating solution’s SAR level if the solution’s EC is decreased (Crescimanno et al., 1995). However, a greater decline in conductivity will result as the infiltrating solution’s SAR levels increase (Crescimanno et al., 1995). The saturated hydraulic conductivity decreases as salts are removed from the soil via leachate thus changing the soil's ionic strength (Mace and Amhrein, 2001; McNeal et al., 1966). The decline in hydraulic conductivity values from DI water application varies depending upon soil texture, mineralogy of clays contained within the soil, and gypsum and lime concentrations within the soil (Shainberg et al., 1981a; McNeal et al., 1966). Soils that are saline-sodic may be leached without reductions in saturated hydraulic conductivity if precipitated carbonates or gypsum are present (Harker et al., 1990; Jury et al., 1979). Salts will leach from the soil as low electrolyte waters are infiltrated at the soil surface which can impact soil structural properties due to soil dispersion, slaking, and swelling. Soils that innately contain high SAR levels or that may obtain high SAR levels if divalent cations are leached can have substantial impacts on saturated hydraulic conductivity as these SAR levels increase (He et al., 2015; Shainberg et al., 1981b; Frenkel et al., 1978). Therefore, it is reasonable to expect that the application method of saline waters to soils (i.e. one term saturation of saline waters versus continuous surface infiltration of saline waters) may lead to different saturated hydraulic conductivity values.

Applying irrigation waters containing soluble salts and sodium is known to increase soil EC along with capillary fringe from groundwater containing soluble salts. The total concentration of salts in solution at a given SAR of the water applied to the soil is known to change how the water affects soil SAR_e (saturated paste extract sodium adsorption ratio) (Bajawa et al., 1992). Saline-sodic waters have been shown to be more effective at increasing soil SAR than sodic waters under long term irrigation (Ganjegunte et al., 2008; Bajawa et al., 1992). The previous studies conducted were looking at long term sustainably of irrigation waters applying large loads of solution at a given concentration to the soil. Upward movement of ground waters does not have as much total volume of solution applied to soil and may cause different effects on soil solution SAR compared to long term application of irrigation waters.

In the literature, most studies have focused on the application of infiltrating waters to the soil at a given SAR and salt concentration until saturated hydraulic conductivity reaches a state of equilibrium with the infiltrating solution. A series of subsequent infiltrations are made using solutions with a constant SAR level but with each new infiltrating water being at a lower salt concentration until a steady state hydraulic conductivity is obtained (Shainberg et al., 1981b; Oster and Schroer, 1979). This method is useful for evaluating long term sustainability of irrigation waters containing sodium and soluble salts. However, salt transport in soil field conditions under non-irrigated management occurs from the upward movement of water and solutes under evaporative conditions followed by the downward movement of soluble salts from relatively low EC infiltrating rain water which is non cyclic (Armstrong et al., 1996). Therefore, the accumulation of salts in non-irrigated and irrigated soils are expected to differ and to have differing degrees of impact on soil hydraulic properties. Unfortunately, research using methods that more closely simulate natural, non-irrigated induced soil salinity are rare. To our knowledge, no reports in the peer-reviewed literature exist where saturated hydraulic conductivity was evaluated in the laboratory using strictly initial wetting of soil columns with salt solutions followed by the infiltration of clean waters. Such experimental research will improve our understanding of the sensitivity of soil physical properties to a simulated capillary fringe of sodium and calcium solutions in different ratios and concentrations. This will in turn help to improve and optimize land management strategies for naturally occurring saline, sodic, and saline sodic soils.

The objective of this study was to 1) determine the impact and sensitivity of soil saturated hydraulic conductivity to initial saturation with differing EC and SAR salt solutions (i.e., simulated saline groundwater) and 2) develop and validate a parametric pedotransfer function to predict saturated hydraulic conductivity as a function of leachate pore volume. The hypotheses of this study were 1) the lowest EC and highest SAR solutions will have the lowest initial saturated hydraulic conductivity, whereas highest salt concentrations will increase the initial saturated conductivity the greatest degree 2) saturated hydraulic conductivities as a function of leachate pore volume will have the greatest exponential decay slope factor for soils containing both the most clay and percent smectite as well and highest EC and SAR solution combination.

Methods and Materials

Soil Collection, Soil Mixes, and General Physical and Chemical Properties

A Fargo silty clay (fine smectitic frigid Typic Epiaquert; USDA-NRCS, 2015) was collected from a 0-15 cm depth near Gardner, North Dakota (47.172974N, 96.90037W) and a Portwing clay loam (fine mixed active frigid Oxyaquic Glossudalf; USDA-NRCS, 2015) was collected from a 25-50 cm depth near Cornucopia, Wisconsin (46.837577 N, 91.082729 W). The Fargo and Portwing soils were air-dried and dry sieved to < 2mm equivalent diameter particles and micro aggregates. Antecedent soil physical and chemical properties were determined on the two soils and are listed in (Table 1) and (Table 2) in Chapter 1. Particle density was determined by the pycnometer method (Blake and Hartge, 1986). Soil pH and EC_e was determined using a saturated paste extract (Rhoades, 1996). The soil SAR_e was determined using the saturated paste extract with cations measured using an atomic absorption spectrophotometer (Model 200A, Buck Scientific, Norwalk, CT). The USDA-NRCS soil textural class of soils used were silty clay, clay loam, sandy loam, and clay loam for the Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing, respectively. The particle density of the soils was 2.35, 2.37, 2.50 and 2.56 g cm^{-3} for the Fargo, Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing, respectively.

Experimental Design, Soil Column Preparations, and Hydraulic Properties

To determine the affect of solutions varying in EC and SAR on saturated soil hydraulic conductivity, soil columns were packed with the 2mm sieved, air-dry soil and soil mixes using a standardized uniform packing procedure. Soil was added in fifths and packed by dropping a 126 gram rubber weight from an equivalent soil column height. This was done to evenly pack each soil column and reduce innate spatial variability in pore-sizes among the soil columns. The mean dry soil bulk density was1.05, 1.21, 1.31, and 1.27 g cm^{-3} with 0.043, 0.016, 0.032, and 0.019 g cm^{-3} as the standard deviation among 125 soil columns for the Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing, respectively. Five packed soil columns were placed in a closed container and saturated via capillary wetting for 7 days for each given solution SAR by EC level combination using NaCl and $CaCl_2$ salt solutions for a total of 125 soil columns for each soil and soil mix (total N = 500 soil columns). The simulated conditions of capillary rise wetting with various sodium and calcium ratios were then infiltrated with deionized water.

Salt solutions used in the solution wetted soil columns consisted of a full factorial design of SAR and EC level combinations. Solution SAR levels were 0, 3, 6, 12, and 20 and solution EC levels were 0.5, 1, 2, 4, and 8 dS m^{-1} made with NaCl and $CaCl_2$ based on conductivity factors (He et al., 2013). Constant head saturated hydraulic conductivity was measured on three of the five soil columns for each given solution SAR by EC level combination using marriott bottles and deionized water as the leaching solution (Reynolds et al., 2002). Deionized water was constantly ponded at a 3cm depth until 3 to 4 pore volumes of leachate was obtained from the bottom of each soil column. The remaining two of the five soil columns for each given solution SAR by EC level combination were air dried, combined into one composite sample, and then used to determine saturated paste extract EC_e and SAR_e using a Hach Sension 378. Cations measured using an atomic absorption spectrophotometer (Model 200A, Buck Scientific, Norwalk, CT; Rhoades, 1996).

Modeling and Statistical Analysis

A theoretical regression model was fitted to the empirical saturated hydraulic conductivity data as a function of leachate pore volume using ordinary least squares in SigmaPlot 12.5 (Systat Software, Inc. San Jose, CA). The empirical data was best explained as an exponential decay of saturated hydraulic conductivity vs. leachate pore volume. We used the three-parameter exponential decay function

$$\text{saturated hydraulic conductivity} = \mathrm{e}^{-\mathrm{b}\mathrm{L}_{\mathrm{PV}}} \qquad (15)$$

where a and b are fitting parameters for the regression and L_{PV} is the leachate pore volume from the soil column.

The fitting parameters were determined for each soil column and then compared using a mixed model analysis of variance (ANOVA) to determine differences among solution composition EC and SAR level combinations. Mean saturated hydraulic conductivies was determined when less than one pore volume of leachate was obtained and was then compared using a pairwise analysis to determine differences among solution EC and SAR level combinations that would be representative to infiltration of waters during brief rainfall events. The ANOVA and pairwise analysis was performed using SAS® with means generated using least squares and separated using Tukey at the 0.05 level (SAS® 2002).

Multiple regression equations were developed to predict the exponential decay parameters a and b using the EC levels 0.5, 2, and 8 dS m^{-1}, SAR levels 0, 6, and 20, soil organic matter content, bulk density, and percent smectite in the bulk soil of the four soil and soil mixes by minimizing the sum of squared errors. These equations were then validated with the exponential decay parameters from the EC levels 1 and 4 dS m^{-1} and SAR levels 3 and 12 (i.e., data that were not used in the development of the multiple linear regression equations).

The linear multiple regression function was as follows,

$$\mathrm{a}, \mathrm{b\ parameters} = \mathrm{yo} + \mathrm{cEC} + \mathrm{dSAR} + \mathrm{eOM} + \mathrm{fsmectite} + \mathrm{gPb} \tag{16}$$

where a and b are fitted parameters in equation 15 (i.e., the intercept and slope of the saturated hydraulic conductivity exponential decay function), *yo, c, d, e, f* and *g* are fitting parameters, OM is percent organic matter, smectite is percent smectite, and Pb is bulk density in g cm^{-3}. The data was also fit with quadratic and logarithmic regression to evaluate improved trends of fitted vs predicted parameters.The quadratic function was as follows,

$$\mathrm{a, b\ parameters} = \mathrm{yo} + \mathrm{cEC}^{\mathrm{h}} + \mathrm{dSAR}^{\mathrm{I}} + \mathrm{eOM}^{\mathrm{J}} + \mathrm{fsmectite}^{\mathrm{k}} + \mathrm{gPb}^{\mathrm{l}} \qquad (17)$$

where y_o, *c, d, e, f, g, h, I, j, k* and *l* fitted parameters. The logarithmic model was as follows,

$$\mathrm{a, b\ parameter} = \mathrm{yo} + \mathrm{c}\log(\mathrm{hEC}) + \mathrm{d}\log(\mathrm{ISAR}) + \mathrm{e}\log(\mathrm{jOM}) + \mathrm{f}\log(\mathrm{ksmectite}) + \mathrm{g}\log(\mathrm{lPb}) \qquad (18)$$

where y_o, *c, d, e, f, g, h, I, j, k* and *l* fitted parameters. The root mean square error (RMSE) and bias were used to compare the performance of the multiple regression predicted parameters to the empirically fitted parameters

Results and Discussion

Salt Solution Impact on Soil Chemical Properties

The application of salt solutions to the soils by using simulated capillary fringe wetting changed soil chemical properties from initial conditions. The saturated soil paste extract SAR_e level increased as solution SAR increased; although the SAR_e levels increased at a greater rate when solution EC levels were also high (Table 7). The level of impact of salt solutions on SAR_e was inversely related to the soil's clay content and positively related to the soil's sand content. Soil SAR_e increased the most in the Portwing and 1:2 Fargo:Serden mix and the least in the Fargo soil after being wetted with the salt solutions (Table 7). This is similar to (Costa et al., 1991) who reported that the sandier Parshall soil series had greater increases in soil EC_e and SAR_e levels as compared to the finer textured Barnes, Williams, and Svea soil series in North Dakota when treated with saline irrigation waters. The simulation of groundwater wetting with salt solutions produced the greatest soil SAR_e level of 7.3 and 6.5 in the Portwing and 2:1 Fargo:Serden mix (i.e., both are clay loams). The SAR of the soil is not as high as solution applied due to exchange of sodium cations on exchange sites with calcium and magnesium and some divalent cations present in solution. The Portwing and 1:2 Fargo :Serden mix had CEC values less than Fargo soil in which fewer total cations exchanged between solution and clay interface therefore releasing less divalent cations into solution.

The saturated soil paste extract EC_e increased as solution EC increased and was not affected by solution SAR levels (Table 8). The impact of solution EC on soil EC_e was minimal and appeared to be dominantly a function of initial soil EC_e rather than a function of the soil's physical properties.

Salt Solution Impact on Initial Saturated Hydraulic Conductivity

The initial saturated soil hydraulic conductivities (i.e. mean conductivities measured during the first pore volume of leachate) of the simulated groundwater wetting soil columns were significantly affected by the wetting solution EC and SAR levels, soil type, and their interactions (P values of 0.03 to <0.0001; Table 9). As expected, soil type was the dominate influence explaining 95% of the total variability in the analysis of variance model followed by the three way interaction (i.e., solution EC by solution SAR by soil type) explaining 3% of the total variability. Therefore, we also evaluated the effects of wetting solution EC, SAR, and their interaction on initial saturated hydraulic conductivities for each soil individually.

Table 7. Saturated paste extract SAR$_e$ values of untreated and treated soils with solutions of varying EC and SAR levels. Solutions of varying EC and SAR levels were used to capillary wet the soil columns to simulate groundwater saturation.

Simulated solution Composition		Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing
EC Levels	SAR Levels	------------- Saturated Paste Extract SAR$_e$ -------------			
0	0	0.44	0.48	0.43	0.27
0.5	0	0.22	0.31	0.36	0.49
	3	0.49	0.65	0.98	0.73
	6	0.72	1.12	1.26	0.92
	12	0.79	0.80	0.96	1.45
	20	0.67	1.02	1.11	1.40
1	0	0.26	0.32	0.25	0.37
	3	0.65	1.01	1.10	0.73
	6	0.84	1.42	1.53	1.78
	12	1.02	1.07	1.08	1.60
	20	1.36	1.50	1.73	1.70
2	0	0.36	0.31	0.31	0.56
	3	1.32	1.38	1.48	1.45
	6	1.72	1.98	2.08	2.58
	12	1.45	1.74	2.68	2.70
	20	1.75	2.18	2.56	2.68
4	0	0.22	0.32	0.25	0.30
	3	1.10	0.99	1.05	1.70
	6	1.76	1.76	2.43	2.60
	12	2.57	3.58	3.78	3.62
	20	2.80	3.72	4.48	6.85
8	0	0.33	0.18	0.22	0.40
	3	1.17	1.31	1.64	2.21
	6	2.02	2.92	3.22	2.95
	12	3.21	3.65	5.68	5.05
	20	5.30	6.51	4.36	7.31

Table 8. Saturated paste extract EC_e values of untreated and treated soils with solutions of varying EC and across SAR levels. Solutions of varying EC and SAR levels were used to saturate soil columns to simulate groundwater saturation. Standard errors are reported in parentheses (n=5).

Simulated Solution Composition	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing
EC Levels	------------- Saturated Paste Extract EC_e -------------			
untreated	0.46	0.49	0.40	0.16
0.5	1.15 (0.04)	1.02 (0.03)	0.93 (0.05)	0.50 (0.02)
1	1.56 (0.09)	1.45 (0.04)	1.36 (0.05)	0.81 (0.05)
2	2.38 (0.09)	2.45 (0.09)	2.20 (0.14)	1.59 (0.05)
4	4.11 (0.06)	3.94 (0.22)	3.48 (0.26)	3.03 (0.24)
8	6.93 (0.09)	6.93 (0.03)	7.72 (0.14)	5.71 (0.13)

Solution EC significantly affected the Fargo and 2:1 Fargo:Serden mix with initial saturated hydraulic conductivities significantly increasing as EC increases (Table 9). However, solution EC did not affect the 1:2 Fargo:Serden mix or the Portwing soil. Solution SAR significantly affected saturated hydraulic conductivities when averaged across all soil types but not for any soil individually (Table 9). The interaction of solution EC and SAR had a significant effect on the 2:1 and 1:2 Fargo:Serden mixes with solution compositions of SAR > 12 and EC < 2 dS m^{-1} of saturating waters causing declines in the initial saturated hydraulic conductivity. The solution EC 0.5 and 1 dS m^{-1} treatments had the lowest conductivity values of the saturating waters with conductivities decreasing as the SAR level increased.

Table 9. Mean saturated conductivity of soils treated with solutions of varying EC across SAR levels and SAR across EC levels. Solutions of varying EC and SAR levels were used to saturate soil columns to simulate groundwater saturation with differences between treatments in lowercase letters and differences between soils in uppercase letters.

Simulated Solution Composition	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing	All soils
EC Levels	cm h^{-1}				
0.5	0.40dC	1.54bcB	9.82aA	1.61aB	3.34bc
1	0.47cdC	1.37cB	9.48aA	1.52aB	3.21c
2	0.71cC	1.91abB	9.64aA	1.72aB	3.31bc
4	1.05bC	1.87abB	10.3aA	1.56aBC	3.69ab
8	1.58aB	2.21aB	9.56aA	2.03aB	3.85a
All EC Levels	0.84C	1.78B	9.73A	1.69B	
SAR Levels	cm h^{-1}				
0	0.84aC[†]	1.86aB	9.93aA	1.89aB	3.44b
3	1.03aC	2.08aB	10.1aA	1.64aBC	3.72a
6	0.89aC	1.74aB	10.3aA	1.51aBC	3.61a
12	0.84aC	1.69aB	9.79aA	1.71aB	3.50b
20	0.61aC	1.53aB	8.66aA	1.69aB	3.12b
All SAR Levels	0.84C	1.78B	9.73A	1.69B	

Different lower case letters in a column are significantly different at the 0.05 level.

[†] Different upper case letters in a row are significantly different at the 0.05 level.

Saturated Hydraulic Conductivity vs. Leachate Pore Volumes

Soil type, solution EC and SAR levels, and their interactions significantly affected the exponential decay parameters a and b that were used to describe saturated hydraulic conductivity as a function of leachate pore volume (P values of 0.01 to <0.0001; Tables 10 and 11). Soil type explained 90% and 64% of the total variance of the analysis of variance model for the a and b exponential decay parameters, respectively.

Table 10. Mean a parameter values of soils treated with solutions of varying EC across SAR levels and SAR across EC levels. Solutions of varying EC and SAR levels were used to saturate soil columns to simulate groundwater saturation with differences between groundwater composition in lowercase letters and soils in uppercase letters.

Simulated Solution Composition	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing	All soils
EC Levels	-------------------------------------	------------------------------------- cm h^{-1}	-------------------------------------	-------------------------------------	
0.5	0.44dC	1.86cB	10.1bcA	2.27bB	3.66d
1	0.56dC	1.78cB	11.5aA	2.37bB	4.05bc
2	0.96cC	2.54bB	9.63bcA	2.60bB	3.73cd
4	1.40bC	2.65bB	10.6acA	2.80bB	4.36ab
8	2.20aC	3.37aB	9.38bA	3.62aB	4.61a
All EC Levels	1.10C	2.40B	10.21A	2.64B	
SAR Levels	-------------------------------------	------------------------------------- cm h^{-1}	-------------------------------------	-------------------------------------	
0	1.09bcC	2.16aB	9.79aA	2.75aB	3.75c
3	1.55aC	2.79aB	10.3aA	3.10aB	4.39a
6	1.29abC	2.62aB	11.0aA	2.27aB	4.30ab
12	1.05bcC	2.18aB	9.78aA	2.68aB	3.92bc
20	0.78cC	2.26aB	10.2aA	2.87aB	4.04abc
All SAR Levels	1.10C	2.40B	10.2A	2.64B	

Different lower case letters in a column are significantly different at the 0.05 level.
Different upper case letters in a row are significantly different at the 0.05 level.

Solution EC significantly affected the a parameter (i.e., model intercept that predicts the initial saturated hydraulic conductivity at zero pore volumes of leachate) in all soils with significant increases occurring with an increase in the EC of saturating waters (Table 10). These differences were first detected for solution EC levels as low as between 1 and 2 dS m^{-1} (i.e., average saturated paste extract EC values of 1.36 and 2.45 dS m^{-1}, respectively) for the Fargo and Fargo:Serden mixes and between 4 and 8 dS m^{-1} (i.e., average saturated paste extract EC's of 3.03 and 5.71 dS m^{-1}) in the Portwing soil (Tables 8 and 10). The a parameter was highly and linearly correlated with solution EC in the Fargo and Portwing soils (i.e., r^2 of 0.99 and 0.98, respectively) and poorly correlated in the 2:1 and 1:2 Fargo:Serden mixes (i.e., r^2 of 0.43 and 0.30, respectively). The slopes of the a parameter vs. saturated paste extract EC_e was 0.30

and 0.25 cm h^{-1} per every unit change in dS m^{-1} for the Fargo and Portwing soils. Thus, the initial saturated hydraulic conductivity at zero pore volumes of leachate linearly increased by 5.0, 1.8, 0.9, and 1.6 times for the Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing soil, respectively, when saturated with salt solutions between 0.5 and 8 dS m^{-1} (Table 4). Solution SAR significantly decreased the a parameter but for only the Fargo soil; all other soils had no significant differences as solution SAR level changed (Table 4). The interaction of solution EC and SAR levels was significant for the 2:1 and 1:2 Fargo:Serden mixes with a decrease in the a parameter at high SAR values and low EC values and no clear pattern for the two mixes, respectively.

Table 11. Mean b parameter values of soils treated with solutions of varying EC across SAR levels and SAR across EC levels. Solutions of varying EC and SAR levels were used to saturate soil columns to simulate groundwater saturation. Lowercase levels indicate differences between solution levels with uppercase letters indicating difference between soils.

Simulated Solution Composition	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing	All soils
EC Levels	-------------------------------cm pore volume h^{-1}--------------------------------				
0.5	0.168cB	0.152bB	0.0264aC	0.369cA	0.197b
1	0.254bB	0.144bC	0.0522aD	0.373cA	0.206b
2	0.333aA	0.249aC	0.0430aD	0.446bcA	0.292a
4	0.273bB	0.244aB	0.0495aC	0.547aA	0.293a
8	0.255bB	0.215abB	0.0389aC	0.461abA	0.257a
All EC Levels	0.254B	0.201C	0.0420D	0.439A	
SAR Levels	-------------------------------cm pore volume h^{-1}--------------------------------				
0	0.242aA	0.112cB	0.033bC	0.289cA	0.194 c
3	0.245aB	0.186bB	0.031bC	0.443bA	0.268ab
6	0.285aB	0.194bC	0.025bD	0.416bA	0.236b
12	0.241aB	0.226abB	0.042abC	0.488abA	0.249b
20	0.271aB	0.287aB	0.077aC	0.560aA	0.299a
All SAR Levels	0.254B	0.201C	0.0420D	0.439A	

Different lower case letters in a column are significantly different at the 0.05 level.
Different upper case letters in a row are significantly different at the 0.05 level.

The b parameter (i.e., model slope parameter that predicts the rate of saturated hydraulic conductivity decrease as a function of leachate quantity) was significantly affected by solution EC for all soils except the sandiest soil; the 1:2 Fargo:Serden mix (Table 11). Unexpectedly, the b parameter increased with solution EC levels between 0.5 and 2 dS m^{-1}, but then decreased as solution EC exceeded 4 dS m^{-1}. This was observed either significantly or numerically for all four soil and soil mixes and appeared to be quadratic more than a linear trend (Table 11). The b parameter significantly increased as solution SAR increased for all soil and soil mixes except for the Fargo soil (Table 11). In these soils that were impacted by solution SAR level, the b parameter increased between 1.9 to 2.6 times as the wetting solution SAR levels increased from 0 to 20. In general, the b parameter significantly decreased as clay content decreased in the Fargo and Fargo:Serden mixes although the b parameter was always the largest for the Portwing soil (Table 11). The interaction of solution EC and SAR levels was significant for all soil and soil mixes except for the sandiest soil (i.e. the 1:2 Fargo:Serden mix) with an increase in the b parameter at solution EC levels greater than 2 dS m^{-1} and SAR levels greater than 6.

Parametric Pedotransfer Function

A parametric pedotransfer function was developed to predict the parameters of the saturated hydraulic conductivity exponential decay as a function of leachate pore volume. Inputs to the pedotransfer function included the soil's initial saturated paste extract EC_e and SAR_e levels, percent organic matter, percent smectite, and bulk density. Only a portion of the measured data was used for calibrating the pedotransfer functions whereas the remained measured data was used to independently validate the pedotranfer function predictions. Initially, the linear model (i.e., equation 15) was used to predict the a and b parameters of the exponential decay function. During validation, the model produced a RMSE and bias of 1.83 and 0.31 cm h^{-1}, respectively for the saturated conductivity initial (a parameter) and a RMSE and bias of 0.19 and 0.08, respectively for the b parameter (slope of conductivity vs pore volume). This provided a somewhat good fit considering that the parameter values observed ranged from 0.44 to 11.5 cm h^{-1} and 0.02 and 0.56 for the a and b parameters, respectively; RMSE values were a one full or half a magnitude lower than the maximum observed values (Figure 3; Tables 12). A quadratic and a logarithmic model (i.e., equations 3 and 4, respectively) was then calibrated but provided only a marginally better fit during validation than the linear model (Figure 3; Tables 13 and 14). The logarithmic model provided the best fit to the fitted data with a RMSE of 1.15 cm h^{-1} and 0.08 cm pore volume h^{-1} for the a and b parameters, respectively (Table 14). In general, the logarithmic model helped to reduce over estimation at low values and underestimation at high values for both parameters (Figure 3). However, some sample parameters were still underestimated by 50 to more than 100% of the real fitted values when the a or b parameters were relatively high. Therefore, the Portwing soil was then excluded from the pedotranfer function, model coefficients recalibrated, and predictions validated using only the Fargo derived soil and soil mixes. This was done to evaluate if the pedotransfer functions could be improved by restricting them to soils with the exact same clay mineralogy. This approach produced similar or only somewhat improved estimates among the linear, quadratic, and logarithmic models (Figure 3; Tables 12, 13, and 14).

In general, the pedotransfer models predicted the a parameter better than they predicted the b parameter. However, the b parameter RMSE was reduced by 2 to 4 fold when the Portwing soil was excluded from the analysis (Tables 12, 13, and 14). All soil properties which cause the slope of the soil hydraulic conductivity curve to change as leachate quantity increases may not have been included into the equation. For instance, Shainberg et al. (1981a) reported that soils with a greater degree of weathered parent material may have less weatherable minerals, leading to a greater loss of salts during leaching experiments than contrasting younger soils. Lime and other pedogenic more soluble minerals can dissolve into water increasing electrolyte concentration of solution. In our study, the Portwing soil is considerably more weathered than the Fargo soil and Fargo-derived soil mixes and may be the reason for the 2 to 4 fold reduction in RMSE when the Portwing soil was excluded from the pedotransfer function calibrations.

Table 12. Multiple linear regression for a (saturated conductivity initial) and b (slope of conductivity vs pore volume) parameters using all soils and without Portwing soil with y_o, c, d, e, f and g being empirical fitting parameters, SSE (sum of squared errors), RMSE and bias.

Parameter	a	b-Portwing	b	b-Portwing
y_o	31.7	31.7	-0.52	-0.16
c	0.18	0.21	0.0037	0.0021
d	0.013	0.006	0.0045	0.0020
e	0.83	-8.87	-0.11	0.14
f	-0.68	0.90	0.036	-0.008
g	-15.71	-9.14	0.36	-0.049
SSE	296.29	98.96	2.14	1.44
RMSE	1.83	1.09	0.191	0.084
bias	0.31	0.14	-0.008	0.020

Table 13. Quadratic fitting parameters for a (saturated hydraulic conductivity initial) and b parameters (slope of saturated hydraulic conductivity vs pore volume) with y_o, c, d, e, f, g, h, I, j, k and l empirical fitting parameters, SSE (sum of squared errors), RMSE and bias.

parameter	A	A-Portwing	B	B-Portwing
y_o	-1.14	-1.14	-0.076	-0.076
c	3.38×10^{-6}	1.84×10^{-6}	-0.0011	-0.0011
d	-0.40	-0.40	6.10×10^{-8}	6.16×10^{-8}
e	-0.17	-0.17	-1.67	-1.67
f	12.59	13.17	-3.16	-3.16
g	0.15	0.15	3.87	3.87
h	5.99	6.36	-6.03	-6.03
i	-0.0023	-0.0023	4.46	4.47
j	-24.59	-24.60	0.121	0.12
k	-0.49	-0.50	-0.24	-0.24
l	12.36	12.02	-0.0356	-0.036
SSE	310.91	282.91	1.99	1.35
RMSE	1.79	1.89	0.18	0.095
bias	-0.68	-0.73	-0.032	0.043

Table 14. Logarithmic fitting parameters for the a (saturated hydraulic conductivity initial) and b (slope of saturated hydraulic conductivity vs pore volume) fitting parameters with y_o, c, d, e, f, g, h, I, j, k and l parameters with parameter ran with and without Portwing soils, SSE (sum of squared errors), RMSE and bias.

parameter	a	a -Portwing	b	b- Portwing
y_o	36.33	-22.58	-0.47	-0.19
c	1.17	1.30	0.046	0.039
d	0.25	0.24	0.038	0.011
e	2.10	-44.3	-0.46	0.32
f	-25.03	13.26	0.95	0.26
g	-47.44	-29.02	0.31	-0.29
h	9.68	0.93	0.99	1.00
I	6.20	0.95	1.00	0.96
j	11.28	1.03	0.98	0.95
k	0.009	0.087	0.42	0.51
l	13.89	0.017	1.39	1.28
SE	147.44	102.85	2.03	1.43
RMSE	1.15	1.03	0.080	0.002
bias	-0.092	-0.229	0.022	0.007

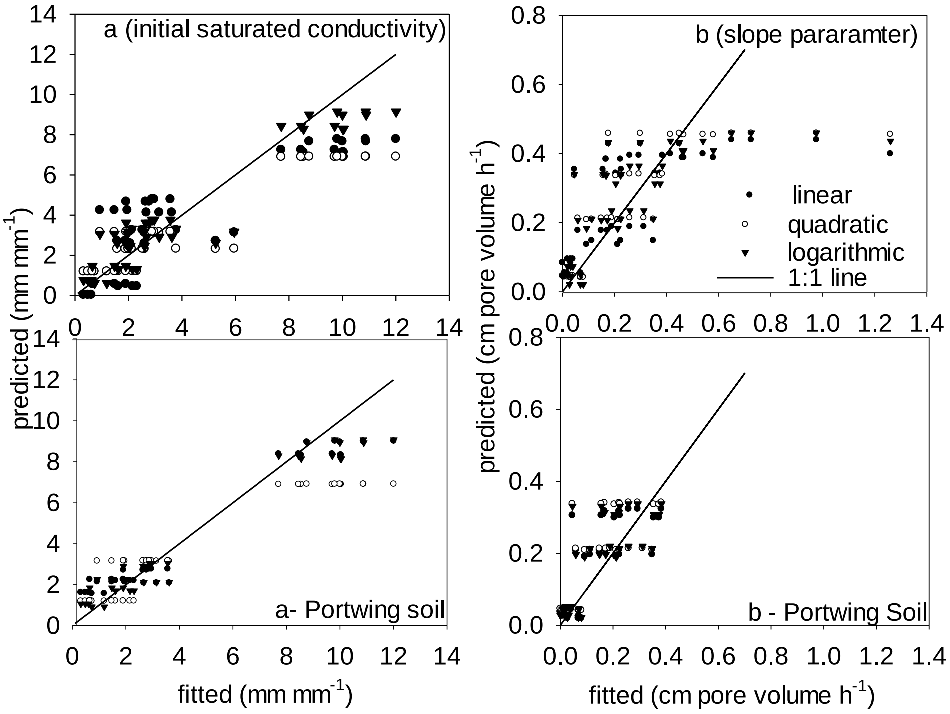

Figure 3. Validation of multiple-linear-regression predicted a (initial saturated conductivity (cm h^{-1} and b (cm pore volume h^{-1}) parameters for the exponential decay of saturated hydraulic conductivity as a function of leachate pore volume a par and b par involve all soils i.e. (Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing soil and soil mixes), Whereas a par- Portwing and b par – Portwing are for fitting the equation to Fargo soil, 2:1 Fargo:Serden mix, and the 1:2 Fargo:Serden mix.

Conclusions

The soils with greater than 30% clay which are smectite dominant appear to initially be most sensitive to solution composition compared to the mixed clay type and sandy smectite dominant soil. Initial saturated hydraulic conductivity was lowest for the highest SAR and lowest EC levels of saturating waters with the largest differences occurring in Fargo soil with hydraulic conductivities of 0.32 and 1.92 cm h^{-1} and the smallest differences occurring in the 1:2 Fargo:Serden mix with conductivities of 7.40 and 9.72 cm h^{-1} for the solution EC 0.5 dS m^{-1} by SAR 20 level vs the solution EC 8 dS

m^{-1} by SAR 0 level, respectively. Saturation with solutions of EC > 2 dS m^{-1} and SAR > 6 increased soil SAR_e above 1.70 in which long-term downward infiltration of low EC infiltrating waters created a decline in saturated hydraulic conductivity. The Fargo and Portwing soils had the greatest decreases with largest differences in a parameters (i.e., initial conductivity) of 0.43 vs 2.2 cm h^{-1} for solutions of EC 0.5 and 8.0 dS m^{-1}, respectively, in the Fargo soil and with the largest differences in b parameters of 0.37 vs 0.47 cm pore volume h^{-1} for solutions of EC 0.5 and 8.0 dS m^{-1}, respectively, in the Portwing soil.

The multiple linear and non-linear regression provided an estimation bias between 0.14 and 0.73 cm h^{-1} for the a parameter estimation and an estimation bias between 0.008 and 0.043 cm pore volume h^{-1} for the b paramater estimation with little improvement when the mixed mineralogy soil was removed from the analysis. Some soils are more susceptible to salt bearing waters than others in which clay content and type appears to impact. However, the regression equations were only slightly sensitive to salt solution EC and SAR levels applied at least within the ranges used in this study.

Increasing SAR and decreasing EC of soil solution can create reduced saturated hydraulic conductivity in all the soils used in this study with significant differences occurring at low SAR_e and EC_e levels. Maintaining EC > 2 dS m^{-1} in soil solution helps to reduce impacts of sodium on saturated hydraulic conductivity. Removal of salts to manage upward movement of salt containing groundwater such as tile drainage installation will lead to decreases in saturated hydraulic conductivity over time with greater decreases as SAR of soil solution increases.

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PAPER 3. HYDROLOGIC PROPERTIES OF SOILS SATURATED WITH VARYING SOLUTION COMPOSITION

Abstract

Soil salinization from shallow ground waters is problematic in numerous regions across the world including the Great Plains in North America. These saline ground waters can degrade soil physical properties and require special land management to keep soil salt contents to maintain levels ideal for crop and rangeland production. Objectives of this study were to 1) evaluate solution salinity and sodicity impacts on soil hydraulic properties during simulated saline and sodic solution saturation in the laboratory and 2) evaluate the combination of measurement methods and hydrologic models for precisely describing these impacts. Four soil and soil mixes, ranging from sandy loam to silty clay, were saturated from below with solutions ranging in electrical conductivities (EC) of 0.5 to 8 dS m^{-1} and sodium adsorption ratios (SAR) of 0 to 20. The hydraulic conductivities and water retention were then measured using pressure plates, HYPROP evaporation method, and a dewpoint potentiometer. Data was then fitted to the van Genuchten and dual porosity models and the model parameters evaluated. As expected, a slight increase in water retention and decrease in hydraulic conductivities were detected when soils were near saturation as solution SAR increased and EC decreased. However, no impacts on unsaturated properties were evident once water potentials became less than -100 cm H_2O. Solutions with greater salt concentrations are expected to behave similarly with impacts isolated to states near or at saturation; although the changes in hydraulic properties would be greater. Water retention method combinations appeared to have some variation between methods but

the fitted curves using the van Genuchten equation agreed well among measurement methods for soils with low and intermediate salt concentrations with the SAR 20 treatments. However, model fits did not agree well among measurement methods for soils with high salt treatments and low clay content. Capillary rise of salt bearing waters alters rates of water transport during conditions when water potentials are near saturation such as during snow melt and after rain events, but water transport rates once soil begins to desaturate would be similar across solution levels achieved from saturating waters.

Introduction

Soil salinity and sodicity is a worldwide problem affecting agricultural productivity and water movement in the landscape. Salinity and sodicity can become problematic in areas where soluble salts are present in ground waters, irrigation waters, or soil parent materials. North Dakota contains such areas throughout the state with areas of high soil electrical conductivities (EC), high sodium adsorption ratios (SAR), and a combination of high EC and SARs. The latter two contain degraded soil structure and low water permeability or be vulnerable to soil degradation if the soil EC level is decreased below a threshold level (Soil Survey Staff. 1987 and Northcote and Skene, 1972). Sodic soils [i.e., saturated paste extract SAR (SAR_e) > 12 and EC (EC_e) < 4 dS m^{-1} based on the USDA classification] are known to have decreased hydraulic conductivity and undesirable soil structural properties (Rengasamy and Olssen, 1991; US Salinity Laboratory Staff, 1954). Sodium salt dominant waters are of concern to land managers since these soluble salts move in soils via water movement; making the soil’s saturated and unsaturated hydrologic properties important in the fate of salts during soil remediation or amelioration efforts (Johnston, 1987).

Many studies have focused on the impact of saturated hydraulic conductivity under varying infiltrating solution compositions of EC and SAR levels. These studies have developed foundational knowledge that increasing soil SAR and/or decreasing solution EC levels will decrease saturated hydraulic conductivity (Cresscimano et al., 1995; Frenkel et al., 1978. Mc Neal et al., 1978). The rate of decrease in saturated hydraulic conductivity varies depending upon clay type and content (Frenkel et al., 1978; McNeal et al., 1968). McNeal et al. (1968) conducted studies on Imperial Valley soils, similar to many soils found in North Dakota, in which they infiltrated solutions of 3 meq l^{-1} (EC approximately 0.35 dS m^{-1}) into sandy (i.e., 6% clay content) and clayey (i.e., 49% clay content) soils containing SAR values of 0 and 25. The relative hydraulic conductivity of the sandy soils was reported to be 1.0 and 0.9 for the 0 and 25 SAR soils, respectively. Whereas, the relative hydraulic conductivities of the clayey soils were reported to be 0.95 and 0.01 for the 0 and 25 SAR soils. Similarly, Curtain et al. (1994) conducted experiments of infiltrating solutions of varying EC levels into coarse and fine textured Mollisols and Vertisols soils in Saskatchewan. They reported that coarse textured soils had little change in saturated hydraulic conductivities when soil SAR level was 0 and infiltrating solutions ranged between 1 mmol L^{-1} (EC approximately 0.1 ds m^{-1}) and 10 mmol L^{-1} (approximately 1.0-1.8 dS m^{-1}). Whereas, fine textured soil's relative conductivities decreased from 1.0 to 0.25 for infiltrating solutions of 10 mmol L^{-1} (EC approximately 1.0-1.8 dS m^{-1}), and 1 mmol L^{-1} (EC approximately 0.1 ds m^{-1}) respectively. Other studies have reported that the degradation of soil physical properties can be observed for soil SAR_e values as low as 5 or 6 when the EC of infiltrating solutions are less than 20 meq L^{-1} (EC approximately 2 dS m^{-1}) for soils with clay fractions dominated by 2:1 clays (Chaudhari, 2001; Crescimanno et al., 1995).

Consideration of soils unsaturated hydraulic properties are also important in land management of salt and sodium impacted soils since the unsaturated state is the most prevalent condition in dry-land agricultural soils (Rengasamy, 2002). Jayawardane and Beattie (1978) reported that Australian red brown clay soils with mixed mineralogy and a solution concentration of 2.5 meq L^{-1} (EC_e level approximately 0.25 dS m^{-1}) retained more water in the saturated to -50 cm H_2O matric soil water potential range (i.e., wet end of the water retention curve) for soil's with an SAR_e of 20 than soil's with an SAR near zero. However, no differences in the water retained in soils with oxide and kaolinite based mineralogy used in this study. More recent studies with Mollisol (Chernozem) and Vertisol soils of Saskatchewan and North Dakota report that water retention at the -336 cm H_2O matric soil water potential (i.e., the commonly used method to estimate a so-called "field capacity") was highest for soils containing both relatively low EC_e and high SAR_e values for a wide range of Northern Great Plains soil types (He et al., 2015; Curtain et al., 1994). The higher water retention near saturation in these soils are due to the swelling and dispersion of clays (Curtain et al., 1994). However, Russo and Bresler (1977) reported that as a loam textured soil became drier and the matric soil water potential became more negative, the water retention curves among soils varying in EC_e and SAR_e levels began to converge. The range of water potentials that this convergence occurs at can vary based on texture; although few studies have evaluated the dry end of the water retention curve for saline, sodic, or saline sodic soils (Malik et al., 1992; Russo and Bresler, 1977). For instance, smectite dominant Vertisols in Sudan were reported to maintain differences in water retention from 0 to -15,300 cm H_2O matric soil water potentials (i.e., -15,300 cm H_2O water potential is the commonly used values to estimate permanent wilting of many agricultural crops) as soil EC_e decreased and or soil SAR_e increased as compared to mildly-saline and non-sodic soils (Malik et al., 1992).

Similar to the water retention studies, most research has evaluated soil hydraulic conductivity at or near saturation for infiltrating waters of varying solution composition (Suarez et al., 1984; Shainberg et al., 1981; McNeal et al., 1968). Whereas, very few studies have attempted to evaluate unsaturated soil hydraulic conductivity under varying EC and SAR levels. In general, saturated and unsaturated soil hydraulic conductivity of smectite clay dominant soils from Colorado and India decreases as the infiltrating solution either 1) deceases in EC level or 2) increases in SAR level (Gupta and Verma, 1985; Dane and Klute, 1977). These differences in hydraulic conductivities have been reported from saturation to 0.18 g g^{-1} soil water contents (Gupta and Verma, 1985). Other studies have used the soil water diffusivity method to evaluate the unsaturated hydraulic conductivity of coarser textured soils and have reported similar results (Chaudhari and Somawanshi, 2003; Gupta and Verma,1995; Russo and Bresler, 1977). These studies describe the general affect of solution composition on soil hydraulic conductivities (i.e., a decrease in conductivity as solution EC decreases or as SAR increases) and are representative of irrigated agriculture. However, to our knowledge, no research efforts have been done to evaluate the magnitude of these affects on hydraulic conductivity that resembles soil saturation via saline, shallow water tables followed by subsequent clean water infiltration.

The previous literature reporting on soil EC and SAR impacts to soil hydraulic properties used a variety of standard soil water retention and hydraulic conductivity methods including hanging water columns, pressure cookers and plates, dew point potentiometers, and psychrometers as well as saturated vertical infiltration and unsaturated horizontal infiltration (i.e. soil water diffusivity; multi step outflow) to evaluate soils during saturation or at dry initial conditions (Gupta and Verma, 1985; Suarez et al., 1984; Shainberg et al., 1981; Dane and Klute, 1977; Russo and Bresler, 1977; McNeal et al., 1968). However, new developments and automation in the evaporation method now presents opportunities for researchers to make high resolution measurements of water retention and unsaturated hydraulic conductivity simultaneously that overlap soil water potentials with many of the abovementioned methods. To our knowledge, the evaporation method has not been used in studies focused on the impacts of soil EC and SAR levels nor has it been evaluated for its performance in saline or sodic soils.

The Northern Great Plains region, and eastern North Dakota, has vast areas of soils where soluble salts have accumulated in the soil from capillary rise of saline shallow ground waters (Skarie et al., 1987). The upward transport and accumulation of salts in soils from groundwater with subsequent infiltration of low EC waters have not been reported in the literature. These conditions likely impact soil hydraulic properties differently than where saline irrigation waters are continuously infiltrated into soils. Improvement in our understanding of saturating soils with varying salt types and their affects on both saturated and unsaturated hydrologic properties will help to improve theory to manage these soils. Therefore, objectives were to 1) simulate saline and sodic conditions in laboratory soil columns and determine the impact of solution composition (i.e., varying EC and SAR levels) on saturated and unsaturated soil hydraulic properties using a parametric approach with the van Genuchten, dual porosity, and Mualem models, 2) determine the magnitude of influence due to soil texture and percent smectite, and 3) empirically compare and evaluate the sensitivity of various soil water retention and hydraulic conductivity measurement methods, including an automated evaporation method, on the fitting parameters of the van Genuchten and dual porosity models.

Methods and Materials

Soils Used in the Experimental Design

The A horizon (0-15 cm depth) of a Fargo silty clay, the Bt horizon (25-50 cm depth) of Portwing clay loam, and the A horizon (0-15 cm) of Serden sand soil series were used in the study. In addition to the Fargo and Portwing soils as sampled from the field, the Fargo and Serden soils were mixed at a 2:1 and 1:2 weight-based ratios to create four soil and soil mixes. The Fargo, Portwing, 2:1 Fargo:Serden mix, and 1:2 Fargo:Serden mix have the textures of a silty clay, clay loam, clay loam, and a sandy loam, respectively. The dominant clay type in all four soils and soil mixes were smectite which is dominant clay type found throughout Northern Great Plains and Eastern North Dakota. Chemical and physical characteristics of these soils prior to being treated with salt solutions are provided in Chapter 1.

Preparation of Cores and Design of Experiment

To evaluate the effects of salt solution varying in EC and SAR levels on soil water movement and retention, a variety of packed soil columns were prepared, treated with a salt solution, and monitored for water flows and water retention under steady-state and non-steady-state conditions. Experimental data was then used for inverse parameterization and determination of soil physical properties using the single and dual-porosity soil hydraulic models.

Five, 5.1 cm diameter 5 cm tall, soil columns were packed with 2mm sieved, air-dry soil using a standardized uniform packing procedure of adding soil in five parts. A 126 g rubber weight was dropped 6 times from five cm above soil column after each part of five parts of 200 g soil was added to the column. This was done to evenly pack each soil column and reduce innate spatial variability in pore-sizes among soil columns used for subsequent analyses. The average bulk density of the columns were 1.05, 1.21, 1.31, and 1.27 g cm^{-3} for the Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing soil, respectively. Salt solutions were prepared using DI water, NaCl, and $CaCl_2$ and consisted of solution SAR levels of 0 and 20 and solution EC levels of 0.5, 1, 2, 4 and 8 dS m^{-1} from $CaCl_2$ and NaCl using same procedure as in Chapter 1 and Chapter 2. The five soil columns for each treatment were placed in a closed chamber, allowed to saturate with a solution of a given EC and SAR combination treatment level, and equilibrated for 7 days. Three of the five soil columns were used to measure saturated hydraulic conductivity. A subsample of the two remaining soil columns was used to determine osmotic soil water retention with a WP4 dew point potentiometer while the soil was at saturation (i.e., matrix soil water potential is zero). The remaining soil of these two soil columns were air dried, combined, crushed to pass through a 2mm sieve, and divided into two subsamples. One subsample was used to determine 1:1 soil: water suspension EC, saturated paste extract EC_e and SAR_e of the salt solution equilibrated columns (Tables 15 and 16). The second subsample was used to determinate water retention with pressure plates.

Saturated Conductivity, Unsaturated Conductivity and Water Retention

Saturated hydraulic conductivities were determined by infiltrating DI water using the constant head method and Darcy's Law (Reynolds et al., 2002).

$$\mathrm{K}_s = \frac{\mathrm{Q}}{\mathrm{A}}\frac{\Delta \mathrm{L}}{\Delta \mathrm{H}} \tag{19}$$

where Q is discharge in $cm^3\ d^{-1}$, K_s is in $cm\ d^{-1}$, L is length of soil core in cm, and H = L + H_{pw} where H_{pw} is the height of ponded water in cm (Darcy, 1856).

Table 15. Measured EC_e values of saturating waters for each solution treatment applied to the soils used to measure hydrologic properties measured from air dried subsamples.

EC treatment	SAR Treatment	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing
		--------------------------------	--------dS m^{-1}--------	--------------------------------	
0.5	0	1.02	1.01	0.81	0.45
1	0	1.56	1.27	1.33	0.75
2	0	2.14	2.20	2.18	1.59
4	0	3.89	3.22	3.44	2.66
8	0	7.00	6.05	7.97	5.37
0.5	20	1.23	1.11	1.05	0.48
1	20	1.74	1.44	1.46	0.94
2	20	2.36	2.33	2.28	1.54
4	20	4.12	4.49	4.20	3.99
8	20	6.96	7.14	7.92	6.15

Table 16. Measured SAR_e values for saturating water equilibrations from saturated paste extracts measured from air dried cores for the four different soil treatments.

EC treatment	SAR treatment	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing
0.5	0	0.22	0.31	0.36	0.49
1	0	0.26	0.32	0.25	0.37
2	0	0.36	0.31	0.31	0.56
4	0	0.22	0.32	0.25	0.30
8	0	0.33	0.18	0.22	0.40
0.5	20	0.67	1.02	1.11	1.40
1	20	1.36	1.50	1.73	1.70
2	20	1.75	2.18	2.56	2.68
4	20	2.80	3.72	4.48	6.85
8	20	5.30	6.51	4.36	7.31

Soil water retention was determined with pressure cookers and pressure plates between -336 to -3,060 and -5,100 to -15,300 cm H_2O matric soil water potentials, respectively, using a modified standard procedure where the porous plates were saturated with the same salt solutions that the soil columns were equilibrated with (Soil Moisture Equipment Corp., Santa Barbara, CA; Dane and Hopmans, 2002). Air-dried soil samples from previously treated columns were placed in 5 cm diameter plastic rings on the pressure plates and cookers, rewetted with the salt solutions, and allowed to equilibrate for 12 hours inside the water retention chambers before applying pressure. Once drainage from pressure cookers and pressure plates ceased, the wet soil samples were weighed, dried at 105 °C for 48 hours, and reweighed at oven-dry conditions to determine gravimetric water content.

Soil water retention from -15,300 to near -100,000 cm H_20 was determined indirectly with a WP4 dew point potentiometer in a 20 °C constant temperature room (Decagon Devices, Inc.). Gravimetric soil water contents were converted to volumetric soil water contents using the bulk densities of evaporation soil cores described in the below sections. The osmotic soil water potential was calculated and subtracted from the measured total soil water potential using

$$\Psi_o = -0.036\ \mathrm{EC_e} \frac{\theta_s}{\theta} \tag{20}$$

where Ψ_o is the osmotic soil water potential in MPa, EC_e is the EC of a saturated paste extract in dS m^{-1}, θ_s is the saturated volumetric soil water content measured at the beginning of each evaporation experiment in cm^3 cm^{-3}, and θ is the measured volumetric soil water content corresponding to the total soil water potential measured by the dew point potentiometer in cm^3 cm^{-3} (Decagon Devices Inc, 2014).

Unsaturated hydraulic conductivity and water retention was also determined with the evaporation method using Hyprop soil sensor units (UMS Munchen Germany). Soil columns of 5 cm diameter by 5 cm in height were packed with the Fargo, 2:1 and 1:2 Fargo:Serden, and the Portwing soil and soil mixes at bulk densities of 0.90, 1.10, 1.27, and 1.21 g cm^{-3}, respectively with 30 columns packed for each soil type or mix. The soils were equilibrated with salt solutions containing EC levels of 0.5, 1, 2, 4 and 8 dS m^{-1} and SAR levels of 0 and 20 using a full factorial design. Equilibration was done under a 1,000 cm H_2O vacuum for three days. Tensiometers were filled with degassed, DI water and installed at 1.25 and 3.75 cm heights above the bottom of each soil column (Schindler, 1980). The soil surface was allowed to evaporate in the laboratory and total weights recorded every 12 hours. The laboratory relative humidity varied between 16 and 25% with a few instances where the relative humidity increased temporarily to 45%. The upward water flux in the columns were determined based on Darcy's law

$$\mathrm{K_{h,mean}} = \frac{\Delta V}{2\ A\ \Delta t_{im}} \tag{21}$$

$$\text{im} = \frac{1}{2}\left(\frac{h_{t_i,z=3.75} - h_{t_i,z=1.25}}{2} + \frac{h_{ti+1,z=3.75} - h_{t_{i+1},z=1.25}}{2}\right) \tag{22}$$

where V is volume of water in cm^3, t is time in hr, im is hydraulic gradient in cm H_2O, t_i is the time in i^{th} hr, z is height in cm where the soil surface is at a 5 cm height, and h is matric potential of tensiometer in cm H_2O (Schindler et al., 2010). The water retention curve was calculated by

$$\Psi_{m,t_i} = \frac{h_{t_i,z=1.25} + h_{t_i,z=3.75}}{2} \tag{23}$$

$$\theta_{t_i} = M_{t_i} - M_{OD}D_b \tag{24}$$

where Ψ_m is the average matric soil water potential in cm H_2O at the i^{th} time h, D_b is the soil bulk density in g cm^{-3}, M_t is mass in g at the i^{th} time, and M_{OD} is the soil mass in g at oven-dry conditions (Schindler et al., 2010). The Hyprop Data Evaluation Software was used to calculate the water retention and conductivity curves (UMS Gmbh). Once the upper tensiometers lowest soil water potential was reached (approximately -1,000 cm H_2O) and cavitation occurred, the soil columns were cut into 1.25 cm depth increments and oven-dry soil water contents and 1:1 suspension EC values determined in which mean water contents vs depth for each soil is shown in (Figure A) and the relative 1:1 suspension EC vs depth for each solution EC treatment is shown in (Figure B).

Model Selection and Inverse Parameterization

Inverse modeling of soil hydraulic parameters was performed across the range of salt solution treatments and soil textures as described in the previous sections to evaluate how salt solution composition affects soil hydrologic properties. The measured water retention and hydraulic conductivity data was fitted to the van Genuchten water retention model and the Durner dual porosity model using the HYDRUS-1D codes (van Genuchten et al., 2005; Durner, 1994; van Genuchten, 1980). However, both models were initially parameterized using the RETC code with the hydraulic conductivity and retention data obtained from all methods (van Genuchten et al., 2005). The optimized model parameters were determined where the RETC code served as a reasonability close initial guess with further optimization using the Levenberg-Marquardt nonlinear minimization of the objective function in HYDRUS-1D (Marquardt, 1963).

The van Genuchten model is described as

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = S_e = \frac{1}{[1 + (\alpha|h|^{n})]^{m}} \tag{25}$$

$$m = 1 - \frac{1}{n} \tag{26}$$

where θ is the volumetric soil water content (at pressure head -cm H_20) in cm^3 cm^{-3}, θ_s is volumetric water content at saturation in cm^3 cm^{-3}, θ_r is the residual volumetric water content in cm^3 cm^{-3}, S_e is the relative saturation, h is the pressure head in -cm H_2O, and *α* and *n* are fitted parameters corresponding to the inverse of the soil air entry point 1/cmH_2O matric potential and the slope of the water retention curve, respectively. The Durner dual porosity model is described as

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = S_e = \sum_{i=1}^{k} \omega_i^* \left[\frac{1}{1 + (\alpha_i|h|^{n_i})}\right]^{mi} \tag{27}$$

$$m_i = 1 + \frac{1}{n_{€}} \tag{28}$$

where ω_i* is a weighing factor of the ith pore region, α_i is the inverse of the air entry point in 1/cmH_2O matric potential of the ith pore region and n_i is the slope of the ith pore region (Durner, 1994). The unsaturated hydraulic conductivity as a function of relative saturation, K(S_e) in cm d^{-1}, was determined by Mualem’s model, using the fitted water retention models m parameter and the measured saturated hydraulic conductivity, as

$$K(S_e) = K(s)\, {S_e}^{\lambda} \left[1 - \left(1 - {S_e}^{1/m}\right)^{m}\right]^2 \tag{29}$$

where $K(S_e)$ is in cm d^{-1}, S_e is the relative saturation state, and λ is a fitted tortuosity parameter (van Genuchten, 1980; Mualem, 1976). The unsaturated hydraulic conductivity using Mualem's model was also determined using the dual porosity water retention parameters as

$$\mathrm{K}(\mathrm{S_e}) = \mathrm{K_s} \frac{(w_1 \mathrm{S}_{\mathrm{e}_1} + w_2 \mathrm{S}_{\mathrm{e}_2})^{l} \left\{ w_1 \alpha_1 \left[1 - \left(1 - \mathrm{S}_{\mathrm{e}_1}^{1/m_1} \right)^{m_1} \right] + w_2 \alpha_2 \left[1 - \left(1 - \mathrm{S}_{\mathrm{e}_2}^{1/m_2} \right)^{m_2} \right] \right\}^2}{(w_1 \alpha_1 + w_2 \alpha_2)^2} \quad (30)$$

where w_1 and w_2 are weighting factors, l is pore connectivity factor, and α_i and m_i are fitting parameters for each overlapping pore region of the dual porosity equation (Durner, 1994; Mualem, 1976). An average saturated hydraulic conductivity from zero to one pore volume of discharge using the constant head method as well as the saturated volumetric water content from the evaporation columns were used in the inverse modeling.

The evaporation experiments were inverse parameterized in HYDRUS-1D (Simunek et al., 2008). The governing equation used was Richards's equation

$$\mathrm{C(h)} \frac{\mathrm{dh}}{\mathrm{dt}} = \frac{\mathrm{d}}{\mathrm{dz}} \left[\mathrm{K(h)} \frac{\mathrm{dh}}{\mathrm{dz}} - \mathrm{K(h)} \right] \quad (31)$$

where C is the water capacity function in cm^{-1} (Richards, 1931). Water retention points from the WP4 dew point potentiometer, the pressure plates and cookers, and the tensiometer readings over time from the HYPROP evaporation units was used to find inverse solution and optimize model parameters. The bottom boundary was defined as a no flux boundary condition and the surface boundary was set as an atmospheric boundary condition. Evaporation was calculated as $E = \Delta V_w / (A^* \Delta t)$; where E is evaporation in cm h^{-1}, V_w is volume of water change in cm^3, A is the cross sectional area of the soil surface in cm^2, and t is time in h. The inverse simulated data was run with the van Genuchten and Durner dual porosity models. The hydrologic parameters for the inverse simulations were then compared across salt solution treatments to see how salt solution composition affects hydraulic parameters across a range of soil textures.

Statistical Analysis and Water Retention Method Comparison

The effects of solution EC, solution SAR, soil type, and their interactions on soil hydraulic parameters were evaluated using a mixed model analysis of variance (ANOVA) in (SAS® 2002). The initial evaluation showed that soil type contributed to more than 90% of the mixed models variance while many interactions were significant. Therefore, the model was also ran to test the effects of solution EC and SAR on hydraulic properties for each soil individually. Means were determined by least squares and separated using Tukeys at the 0.05 significance level. Upon inspection of the soil water retention data, there appeared to be consistent variation between methods. Therefore, we evaluated fitted hydraulic parameters of the van Genuchten model and model errors when data from the following methods were used: Hyprop + pressure plates (HPP), Hyprop + WP4 dewpoint potentiometer (HDP), Hyprop + dewpoint potentiometer pressure plate (HDPPP), and dewpoint meter + pressure plate (DPPP) using the RETC code (van Genuchten et al., 2005).

Results and Discussion

Water Retention and Hydraulic Conductivity Parameters

Soil water retention and hydraulic conductivity parameters for the van Genuchten and dual porosity models were significantly affected by soil type (Tables 17 and 18). Additionally, all parameters, except for the residual water content θ_r and the slope shape factors N_1 and N_2, were significantly affected by either solution EC, solution SAR, or their two and three way interactions with soil type (Tables 17 and 18). When the residual water content θ_r and slope shape factors N_1 and N_2 were reanalyzed for each soil individually, the 2:1 or 1:2 Fargo:Serden mix significantly varied among solution EC or SAR levels. However, no consistent trend existed among these differences across the solution EC and SAR gradients.

As expected, soil type or soil mixes were significant and contributed the most to the statistical model's total variance for all of the soil water retention and hydraulic conductivity model parameters (i.e., 11 to 95 %). The only exceptions were the dual porosity models. second pore regime's inverse of the air-entry value (α_2) and the pore regime weighting factor (ω_i) in which the three way interaction (i.e., soil texture by solution EC by solution SAR) and the two way interaction of soil type by solution SAR, respectively, contributed the most to the statistic model's total variance (i.e., 39 and 25%, respectively).

Table 17. Analysis of variance summary of soil type and solution composition effects on van Genuchten soil water retention and Mualem hydraulic conductivity model parameters.

Source of variance	θ_r	θ_S	α	N	λ	K_{sat}
	-----------------------	-----------------------	-----------------------	P-value	-----------------------	-----------------------
Soil	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
EC	0.17	0.04	<0.01	0.05	0.02	<0.0001
SAR	0.91	0.29	0.14	0.89	0.26	0.05
Soil*EC	0.10	0.01	0.02	0.03	0.09	<0.01
Soil*SAR	0.92	0.01	0.50	0.51	0.02	0.89
EC*SAR	0.31	0.03	0.08	0.25	0.25	0.60
Soil*EC*SAR	0.26	< 0.01	0.08	0.40	0.12	0.61

Soil = Fargo, 2:1 Fargo:Serden, 1:2 Fargo:Serden, and Portwing soil and soil mixes; EC = solution EC level; SAR = solution SAR level; θ_r = residual soil water content; θ_S = saturated soil water content; α = inverse of the air-entry value; N = shape parameter for the soil water retention curve slope, λ = tortuosity factor; K_{sat} = saturated hydraulic conductivity.

Table 18. Analysis of variance summary of soil type and solution composition effects on dual porosity soil water retention and Mualem hydraulic conductivity model parameters.

Source of variance	θ_r	θ_S	α_1	N_1	l	K_{sat}	ω_i	α_2	N_2
	-----------------------	-----------------------	-----------------------	-----------------------	P-value	-----------------------	-----------------------	-----------------------	-----------------------
Soil	<0.01	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.14	0.03	<0.01
EC	0.58	0.04	0.99	0.55	0.42	<0.0001	0.86	0.90	0.45
SAR	0.92	0.29	0.05	0.41	0.37	0.05	0.29	0.42	0.56
Soil*EC	0.54	0.01	0.34	0.53	0.42	<0.01	0.79	0.44	0.88
Soil*SAR	0.12	0.01	0.30	0.16	0.96	0.89	<0.01	0.41	0.20
EC*SAR	0.19	0.03	0.61	0.22	0.95	0.60	0.09	0.05	0.17
Soil*EC*SAR	0.32	< 0.01	0.76	0.35	0.10	0.61	0.43	0.04	0.95

Soil = Fargo, 2:1 Fargo:Serden, 1:2 Fargo:Serden, and Portwing soil and soil mixes; EC = solution EC level; SAR = solution SAR level; θ_r = residual soil water content; θ_S = saturated soil water content; $\alpha_{1,2}$ = air-entry values for pore regimes 1 and 2, respectively; $N_{1,2}$ = shape parameters for the soil water retention curve slope for pore regimes 1 and 2, respectively, l = pore connectivity factor among pore regime 1 and 2; K_{sat} = saturated hydraulic conductivity; ω_i = weighting factor among pore regimes 1 and 2

Table 19. Mean van Genuchten and Mualem fitting parameters for each soil type and across solution compositions from inverse parameter estimation in HYDRUS-1D code.

Soil	θ_r	θ_S	α	N	λ	K_{sat}	R^2
	$cm^3\ cm^{-3}$	$cm^3\ cm^{-3}$	cm^{-1}			$cm\ h^{-1}$	
Fargo	0.120b	0.647a	0.0274c	1.27c	-2.78b	0.73c	0.988
2:1 Fargo:Serden mix	0.161a	0.644a	0.0363b	1.41b	-0.90a	1.68b	0.989
1:2 Fargo:Serden mix	0.138b	0.573b	0.0460b	1.63a	0.28a	9.51a	0.987
Portwing	0.088c	0.574b	0.0571a	1.25a	-3.52b	1.79b	0.994

The θ_s and K_{sat} parameters were not fitted and are the same for the van Genuchten and dual porosity models.
Different letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.

Table 20. Mean dual porosity and Mualem fitting parameters for each soil type and across solution compositions from inverse parameter optimization in HYDRUS 1-D code.

Soil	θ_r	θ_S	α_1	N_1	l	K_{sat}	w_i	α_2	N_2	R^2
	$cm^3\ cm^{-3}$	$cm^3\ cm^{-3}$	cm^{-1}			$cm\ h^{-1}$		cm^{-1}		
Fargo	0.104a	0.647a	0.027b	1.77c	-0.80b	0.73c	0.535a	0.007a	1.60a	0.992
2:1 Fargo:Serden mix	0.041b	0.644a	0.028b	2.46b	-0.22b	1.68b	0.548a	0.010a	1.27b	0.997
1:2 Fargo:Serden mix	0.063b	0.573b	0.022b	4.25a	1.48a	9.51a	0.512a	0.018a	1.29b	0.998
Portwing	0.063b	0.574b	0.046a	1.75c	-2.06c	1.79b	0.491a	0.011a	1.45ab	0.994

The θ_s and K_{sat} parameters were not fitted and are the same for the van Genuchten and dual porosity models.
Different letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.

The fitted residual water content θ_r for the van Genuchten model was greatest for the 2:1 Fargo:Serden soil mix followed by the 1:2 Fargo:Serden soil mix and Fargo soil, which were similar (Table 19). This was unexpected since the Fargo soil should have substantially greater specific surface area than the Fargo:Serden soil mixes and would be expected to retain more water at low soil water potentials. We hypothesize that this effect on θ_r may be due to the Serden sand grains creating more space between the silty clay aggregates in the Fargo:Serden soil than in the Fargo soil; thus allowing more space for expansion. This may result in allowing more water to enter the silty clay aggregates as compared to if the aggregates were neighbored by other expanding aggregates upon saturation. The Portwing soil had the lowest θ_r and was 1.83 times less than the 2:1 Fargo:Serden soil mix even though they were similar in soil texture (i.e., clay loams) and smectite content. The lower θ_r was likely due to the Portwing soil having 2.4 to 6.0 times less organic matter than the Fargo soil and Fargo:Serden soil mixes. In contrast to the van Genuchten model, the dual porosity model θ_r for the Fargo soil was significantly greater than the Fargo:Serden soil mixes and the Portwing soil which were all similar (Table 20). This trend was expected due to differences in soil texture. The goodness of fit (R^2) was slightly greater for the dual porosity model at 0.992 to 0.997 than the van Genuchten model at 0.987 to 0.994. However, the plotted water retention curves as a function of soil water potentials did not display an obvious bimodal pore size distribution (Figure 4). This may suggest that the dual porosity model over parameterizes our dataset even though bimodal pore distributions among the mixed sand grains and silty clay microaggregates could be expected in the Fargo:Serden mixes.

The measured saturated water content θ_s was highest and similar for the Fargo soil and 2:1 Fargo:Serden soil mix and lowest and similar for the 1:2 Fargo:Serden soil mix and Portwing soil (Table 19). However, the θ_s of each soil type was not affected by solution EC and SAR the same (Tables 17 and 18). The Fargo soil was not significantly affected by solution EC and SAR. Whereas, the 2:1 Fargo:Serden soil mix was affected by solution EC but not solution SAR. Additionally, the 1:2 Fargo:Serden soil mix and the Portwing soil were affected by the interaction of solution EC and SAR levels. In general, θ_s increased as solution EC increased. Similarly, θ_s increased as solution SAR increased in the Portwing soil; whereas, the θ_s tended to decrease as solution SAR increased in the Fargo derived soil and soil mixes.

The fitted α parameter for the van Genuchten model was significantly higher for the Portwing soil than the Fargo derived soil and soil mixes (Table 19). The Fargo:Serden soil mixes has similar α parameters and were both significantly higher than the Fargo soil. In general, α parameter decreased with clay content in the Fargo derived soil and soil mixes (Table 19). Solution EC affected the α parameter differently among soil types with the α parameter significantly increased as solution EC increased to 2 dS m^{-1} for the Fargo soil and 2:1 Fargo:Serden mix. In contrast, the α parameter decreased for the Fargo soil above EC 4 dS m^{-1}. In the dual porosity model, the α_1 parameter was significantly affected by soil type and SAR level. In contrast, the α_2 parameter was significantly affected by the three way interaction of soil type, solution EC, and solution SAR (Table 18). Although, this effect was limited to the 1:2 Fargo:Serden soil mix (i.e., the coarsest soil) and no effect for the soils with higher clay contents. The α_2 parameters were 1.2 to 4.2 times less than the α_1 parameters which means that the air-entry value of the second pore regime occurs at lower soil water potentials than the first pore regime (Table 20). These differences in α parameters among the two pore regimes are greater for soils with higher clay content in the Fargo derived soil and soil mixes. Although the difference between α_1 and α_2 is greatest in the Portwing soil. This indicates that solution SAR affects the soil air-entry value ranging from at least -20 to -140 cm H_2O soil matric potentials; whereas, the solution EC affect is limited to soil air-entry values less than -66 cm H_2O soil matric potentials for coarse textured soils only. For the 1:2 Fargo:Serden soil mix, the α_2 parameter significantly increased and then decreased as solution EC exceeded 2 and 4 dS m^{-1}, respectively, when solution SAR was zero. When solution SAR was 20, this increase followed by a decrease in the α_2 parameter occurred as solution EC exceeded 0.5 and 2 dS m^{-1}, respectively. The fitted N parameter(s) (i.e., the water retention slope shape factor) were significantly affected by soil type for both the van Genuchten and dual porosity models (Tables 19 and 20). However, solution EC and SAR did not affect the N parameter except in the van Genuchten model where the N parameter changed with solution EC for the Portwing soil but not for the Fargo derived soil and soil mixes (Table 17). In the Portwing soil, the N parameter significantly decreased from 1.26 to 1.22 as solution EC increased between 1 and 2 dS m^{-1} and no further decreases from 2 to 8 dS m^{-1}. The fitted ω_i parameter (the weighting factor between pore regime 1 and 2 in the dual porosity model) was significantly affected by solution SAR across all soil types and significantly affected by solution EC only for the 1:2 Fargo:Serden soil mix (Table 20). Solution SAR slightly, but significantly, decreased ω_i from 0.54 to 0.51 as SAR level changed from zero to 20. Solution EC significantly increased ω_i in the 1:2 Fargo:Serden soil mix (i.e. the coarsest soil) from 0.48 to 0.59 for solution EC levels of 4 and 8 dS m^{-1}, respectively. Despite these few differences in ω_i, the pore regime weighting factor of the dual porosity model was not substantially impacted by soil types and solution compositions used in this study. dual porosity model was not substantially impacted by soil types and solution compositions used in this study.

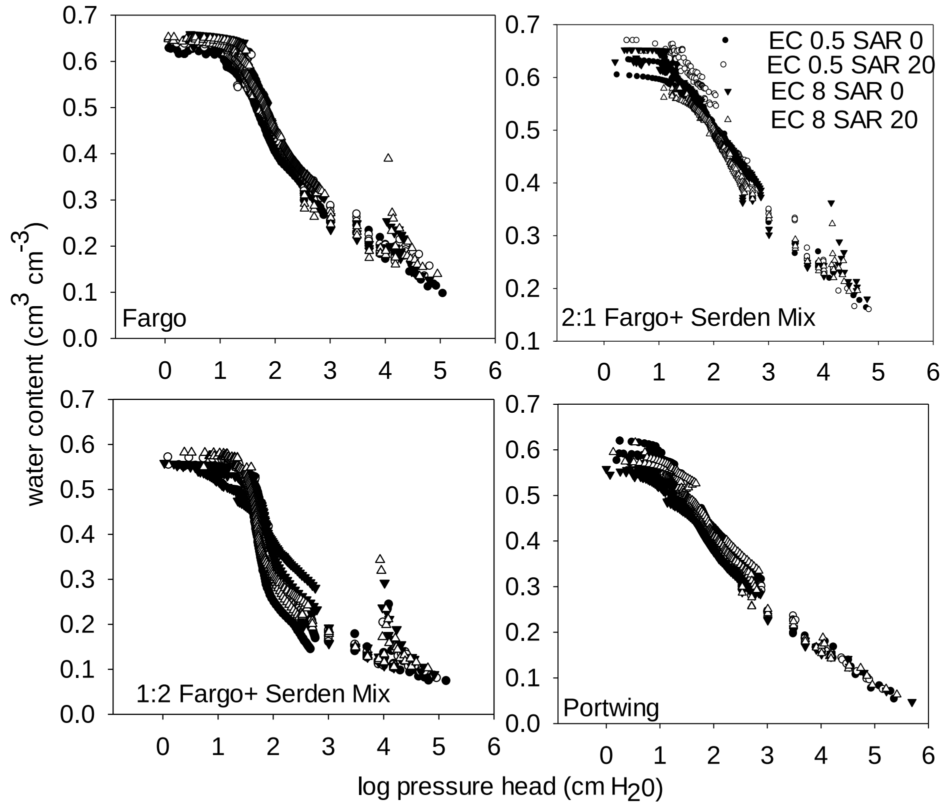

Figure 4. Water content vs log pressure head in cm H_2O for Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix and Portwing soil for EC 0.5 dS m^{-1} by SAR 0, EC 0.5 dS m^{-1} by SAR 20, EC 8 dS m^{-1} by SAR 0 and EC 8 dS m^{-1} by SAR 20 treatments.

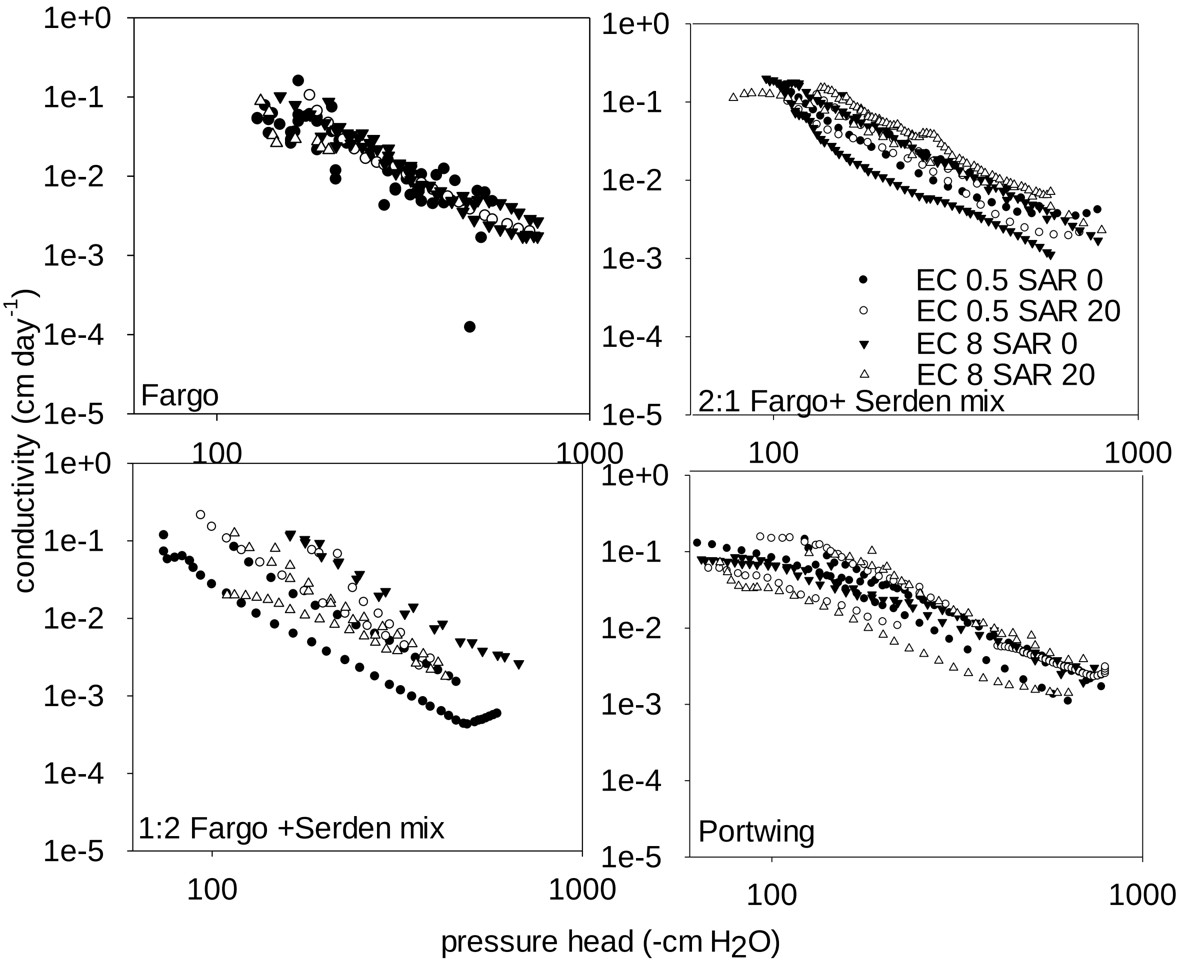

Figure 5. Measured conductivity vs pressure head in cm H_2O from evaporation experiments for Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix and Portwing soil for EC 0.5 dS m^{-1} by SAR 0, EC 0.5 dS m^{-1} by SAR 20, EC 8 dS m^{-1} by SAR 0 and EC 8 dS m^{-1} by SAR 20 treatments .

Other studies report an increase in soil water retention near saturation to soil water matric potentials at or less than -336 cm H_2O as an infiltrating solution increases in SAR or decreases in EC levels (He et al., 2015; Curtain et al., 1994). In our study, the largest differences in soil water retention occurred in the Fargo soil (i.e., the finest textured soil) with the smallest differences in the 1:2 Fargo:Serden soil mix (i.e., the coarsest soil) when using the pressure plate method to potentials as low as 5100 cm

H_2O as EC decreased and SAR increased. The Hyprop soil evaporation unit showed very small differences in soil water retention when soil matric potentials were at or larger than -100 cm H_2O as solution SAR increased and EC levels decreased with no differences at lower soil water matric potentials. In general, there was a small decrease in soil pore sizes as the EC level of saturating waters decreased and SAR levels increased. Other studies also have observed a decrease in soil pore sizes as infiltrating solution EC decreased and SAR increased (Yang et al., 2014; Jayawardane and Beattie, 1978).

For parameters related to hydraulic conductivity, small differences were observed between the measured K(h) data based on solution composition. Larger differences were observed among soil types, as expected (Figure 5). The N, λ, and K_s parameters all impact the hydraulic conductivity curve as a function of soil water potential (Durner, 1994). The fitted λ (tortuosity factor) parameter significantly decreased as solution EC Increased for all soils (Table 19). Additionally, the λ parameter was twice as large when solution SAR increased from zero to 20 in the Fargo soil; although no differences were observed in the other soil and soil mixes. The measured K_s parameter consistently increased as solution EC increased for the Fargo derived soil and soil mixes but not in the Portwing soil (Table 17). The K_s increased by 4.1, 2.0, and 1.3 times for the Fargo, 2:1 Fargo:Serden, and 1:2 Fargo:Serden soil and soil mixes, respectively, as the solution EC changed from 0.5 to 8 dS m^{-1}. In contrast, K_s decreased by 10% across all soils when solution SAR changed from zero to 20 (Table 17). Similar to our study using simulated sodium and calcium dominated solutions as saturating waters, several studies have reported that increasing SAR and decreasing EC levels of surface infiltrating waters will decrease saturated hydraulic conductivity (Crescimanno et al., 1995; Curtain et al., 1994).

Differences in the log-log plotted unsaturated hydraulic conductivity curves [K(h)] as a function of soil water potentials were not distinct or clear due to the variability among soil column replications (Figure 5). In general, the variability among soil columns increased as clay content increased with the degree of variability among soil columns also scaling with K(h) and soil water matric potential (Figure 5). Other researchers have reported differences among hydraulic conductivities of soils with high SAR and low EC levels compared to low SAR and high EC levels by as much as two orders of magnitude with these differences decreasing as the soil becomes drier when using the soil water diffusivity method (Chaudhari and Somawanshi, 2003; Malik et al., 1992 and Gupta and Verma, 1985). The large differences are due to the high gradient of water content within the wetting front and low soil water diffusivity values at high SAR and low EC levels (Chaudhari and Somawanshi, 2003; Malik et al., 1992). Soil water diffusivities derived from our fitted van Genuchten parameters were consistently lower when solution EC was low and SAR was high (i.e., 0.5 dS m^{-1} and 20) as compared to when solution EC was high and SAR was low (i.e., 8 dS m^{-1} and zero; Figure 6). Differences in differential soil water capacity (i.e., the first derivative of the soil water retention curve) showed a similar pattern, with the peak in differential soil water capacity shifting to smaller pore sizes as solution EC was decreased or as solution SAR was increased. However, the differential soil water capacity was similar at soil water potentials less than or equal to -100 cm H_2O. These differences in the differential soil water capacity were greater for fine textured soils and decreased as sand content increased and smectite percentage of bulk soil decreased. These observations are similar to those in a study of Australian soils where salt solutions of low EC and high SAR created a large decrease in mean pore size on a red brown clay loam (Alfisol soil order) but no differences were observed on highly weathered kranozem soil (i.e., equivalent to an Oxisol) (Jayawardane and Beattie, 1978).

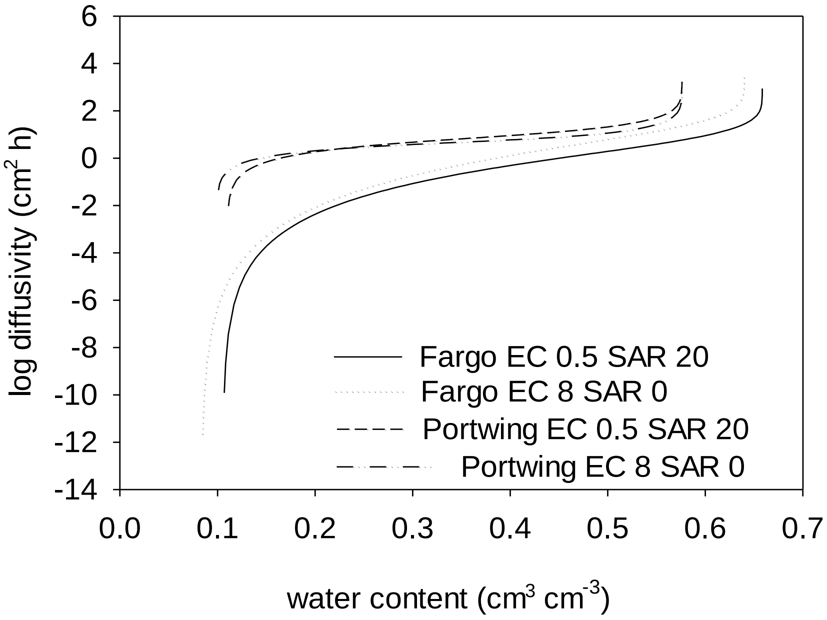

Figure 6. Soil water diffusivity vs water content values from average van Genuchten fitting parameters for Fargo Soil and Portwing soil for EC 0.5 dS m^{-1} by SAR 20 treatment and EC 8 dS m^{-1} by SAR 0 treatment.

Water Retention Method Comparison

Variations in the water retention data existed between the measurement methods (i.e., pressure plates/cookers, Hyprop evaporation units, and WP4 dew point potentiometer; Table 21). In general, data from the Hyprop and pressure plate water retention methods appeared to agree well for soils treated with solutions of low EC levels regardless of the solution SAR level (Table 21). However, in the Fargo and

Portwing soils, the pressure plates produced lower soil water retention at a given soil water potential as compared to the Hyprop evaporation unit. This trend was also observed in the two Fargo:Serden soil mixes when solution SAR was zero and solution EC became high (Figure 7). No differences in water retention at a given soil matric potential were observed between pressure plates and dew point potentiometer when solution EC was low (Figure 7). However, large differences in water retention occurred at matric potentials greater than -4.5 log(cm H_2O) when solution EC was high which was likely due to errors in predicting the osmotic soil water potential (Figure 7). This trend was observed for the Fargo soil and Fargo:Serden mixes with differences becoming greater as clay content decreased. In contrast, very little if any differences among the pressure plates and the dew point potentiometer were evident in the Portwing soil (Figure 7).

Due to these inconsistences, soil water retention data from each method was used together in various combinations and fitted with the van Genuchten model. Determine how each water retention method would attribute to variation in van Genuchten fitting parameters. The soil type, method combinations, and soil by method combinations interaction were significantly (p value < 0.002) for all θ_r, α, and N parameters. The method combinations included 1) the pressure plates data with the Hyprop evaporation data (HPP), 2) Hyprop data with the dew point potentiometer data (HDP), 3) Hyprop data with the pressure plates and dew point potentiometer data (HDPPP), and 4) the dew point potentiometer data and pressure plates data (DPPP; Table 21; Figure 7). The fitted residual soil water content, θ_r, did not differ when solution EC and SAR levels were at their lowest. However, when either solution EC or SAR values increased in the Fargo:Serden soil mixes and the Portwing soil, the θ_r was substantially and consistently lower in the DPPP combination as compared to the combinations that included the Hyprop evaporation data (Table 7). In contrast, the θ_r in the all soils was larger in the HPP combination as compared to the combinations with the Hyprop evaporation data when groundwater solution EC was 4 dS m^{-1} or less (Table 7). Similarly, the inverse of the air-entry point, α parameter, was consistently different between the DPPP method combination and method combinations that included the Hyprop evaporation data. However, there is no consistent pattern in these differences with the DPPP derived α parameter being 0.7 to 13 times that of the combinations that included the Hyprop evaporation data (Table 21). The shape factors of the water retention curve's slope, N parameter, was not sensitive to method combinations with the range of percent coefficient of variations being 0.4 to 19% for any given soil type and solution composition level.

Table 21. An example in variation between fitting parameters for different water retention combinations for soil treatment combinations placed in Figure 3 with soil type, method combination, EC dS m^{-1} of saturating water, SAR, θ_r in cm^3 cm^{-3}, θ_s in cm^3 cm^{-3}, α in cm^{-1}, N, and R^2 values

Soil	Method†	EC	SAR	θ_r	θ_s	α	N	R^2
Fargo	HPP	0.5	0	0.078	0.624	0.023	1.22	0.98
Fargo	HDP	0.5	0	0.001	0.624	0.025	1.18	0.98
Fargo	HDPPP	0.5	0	0.047	0.624	0.023	1.20	0.99
Fargo	DPPP	0.5	0	0.001	0.624	0.079	1.19	0.97
Fargo	HPP	2	20	0.001	0.637	0.054	1.15	0.98
Fargo	HDP	2	20	0.001	0.637	0.058	1.15	0.99
Fargo	HDPPP	2	20	0.001	0.637	0.056	1.15	0.99
Fargo	DPPP	2	20	0.056	0.637	0.037	1.19	0.95
Fargo	HPP	8	0	0.040	0.640	0.028	1.20	0.98
Fargo	HDP	8	0	0.118	0.640	0.031	1.22	0.98
Fargo	HDPPP	8	0	0.115	0.640	0.027	1.24	0.98
Fargo	DPPP	8	0	0.128	0.640	0.088	1.22	0.98
Portwing	HPP	0.5	0	0.001	0.597	0.053	1.20	0.98
Portwing	HDP	0.5	0	0.001	0.597	0.055	1.19	0.98
Portwing	HDPPP	0.5	0	0.001	0.597	0.048	1.20	0.98
Portwing	DPPP	0.5	0	0.001	0.597	0.079	1.20	0.97
Portwing	HPP	8	0	0.061	0.554	0.046	1.25	0.99
Portwing	HDP	8	0	0.007	0.554	0.049	1.21	0.99
Portwing	HDPPP	8	0	0.015	0.554	0.049	1.22	0.99
Portwing	DPPP	8	0	0.001	0.554	0.063	1.20	0.97
1:2 Fargo:Serden mix	HPP	0.5	20	0.138	0.576	0.018	2.01	0.96
1:2 Fargo:Serden mix	HDP	0.5	20	0.130	0.576	0.018	1.99	0.96
1:2 Fargo:Serden mix	HDPPP	0.5	20	0.130	0.576	0.019	1.95	0.97
1:2 Fargo:Serden mix	DPPP	0.5	20	0.001	0.576	0.254	1.20	0.96

† HPP is Hyprop and pressure plate methods, HDP is hyprop and dewpoint meter method, HDPPP is all methods combined together, and DPPP is dewpoint meter and pressure plate methods.

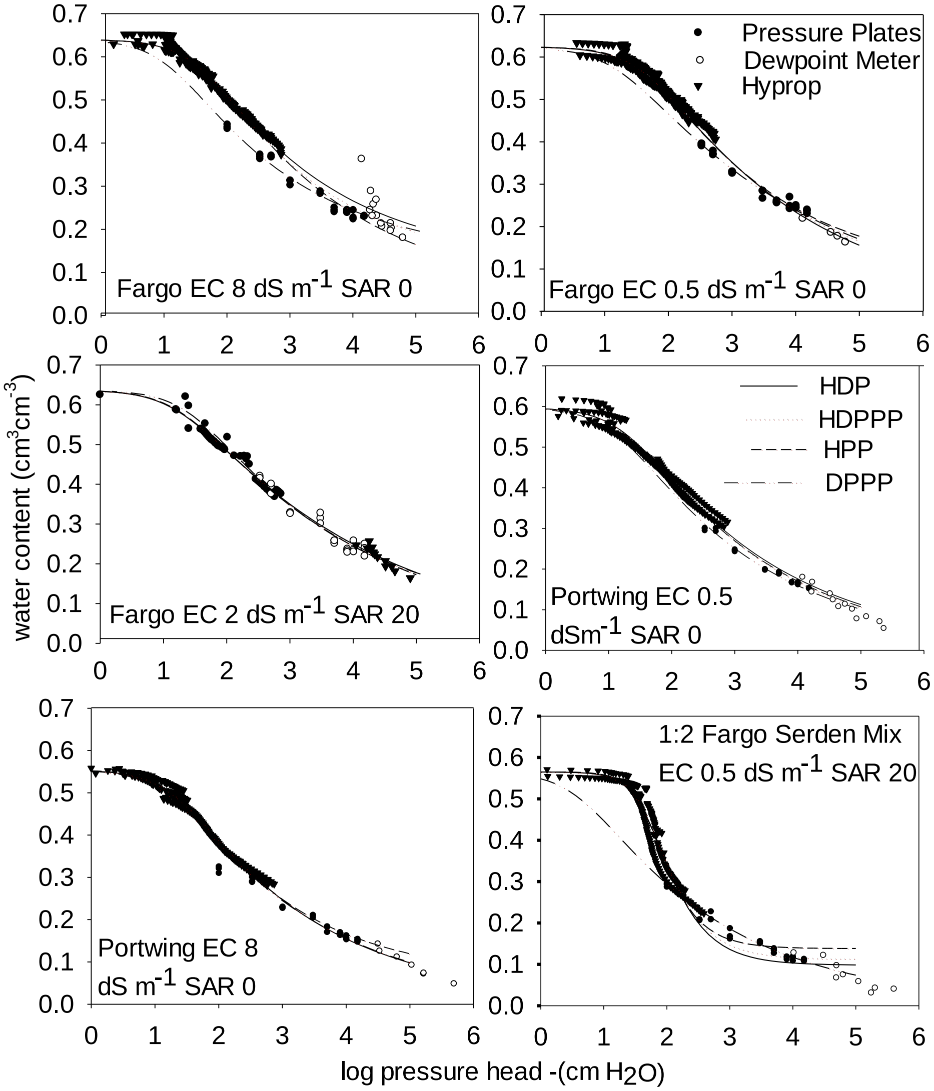

Figure 7. Examples of water retention method combinations put into the van Genuchten equation and how good they fit the measured soil water retention data. HDP is Hyprop and dewpoint meter combined together, HDPPP is all methods combined together, HPP is Hyprop and pressure plates and DPPP is dewpoint meter and pressure plates.

In general, the fitted water retention curves for each method combination were very similar to each other when soils were saturated with solutions of low EC levels (Figure 7). Additionally, the fitted water retention curves among method combinations did not differ in the Portwing soil for any solution EC and SAR level combination (Figure

7). This may be due to the Portwing soil having a wide range of soil pore sizes in combination with low soil organic matter contents (i.e., 0.9%). In contrast, the coarse textured 1:2 Fargo:Serden soil mix had a narrow range of soil pore sizes with a majority of pores draining at soil water potentials greater than -336 cm H_2O. Here, water retention curves were substantially different between DPPP and combinations that included the Hyprop evaporation data (Figure 7). The largest differences appeared as the water retention curves approached saturation (Figure 7).

Water retention methods appear to produce some variation among the model fitted water retention curves with the pressure plate method estimating less water retained for the Fargo soil at solution SAR levels of zero and for the coarse textured Fargo:Serden soil mixes when solution EC values were high (Figure 7). Other studies have observed that the variation within method replicates were greater than the variance produced among the different methods (Schindler et al., 2012). This trend was not observed in our dataset, but was instead the exact opposite with replicates within a method being less variable than data generated among methods (Figure 7). The Hyprop evaporation method had the least variation among sample replicates. The variation that did occur within replicates for the Hyprop method was most abundant near saturation in textures between sand and clay from Germany and Brazil at soil water potentials greater than -100 cm H_2O. This was also observed in a study conducted on sand, silt and silt loam soil textures in Germany (Schelle et al., 2013). In that study in some cases, the Hyprop evaporation method estimated greater soil water retention as compared to other standard methods (i.e., hanging water column and pressure plates, which gave similar results). They attributed these differences to the Hyprop's larger sample size and unsteady state conditions (Schelle et al., 2013). Other studies suggest that dispersion may be responsible for inaccuracies when using the pressure plate method (Creswell et al., 2008). This may have been the case in our study as the pressure plate's method showed less water retention for soils treated with solutions of SAR 0 as compared to SAR 20; whereas, no differences were observed among these treatments using the Hyprop (Creswell et al., 2008). Other papers have consistently found pressure plates overestimate water retained compared to a dew point potentiometer due to the long time requirement for soil samples to reach equilibrium, poor soil contact with the pressure plates, and due to soil shrinkage (Cresswell et al., 2008; Gee et al., 2002). However, this was not observed in our study (Table 21; Figure 7).

For soils saturated with low solution EC and SAR values, the Hyprop evaporation method created only a slightly deviation among measured and fitted water retention curves on the dry end and thus decreasing the θ_r parameter (Table 21). By adding the dew point potentiometer data to the pressure plate data, the θ_r decreased with exception for soil treated with solution of high EC values. The high salt solutions may have created an overestimate of water retention due to the need for longer sample equilibration times in the dew point potentiometer. This decrease in θ_r was observed in research on a silt loam soils from Washington and on soils of varying textures and mineralogy from Italy where a decrease in θ_r was evident by adding dew point potentiometer data to data generated from pressure plates and hanging water columns (Solone et al., 2012; Bitteli and Flury, 2009). The N parameters in our study did not change by adding dew point potentiometer data to Hyprop data or by combining all three methods together. The insensitivity of the N parameter to method type differs from that reported by Solone et al. (2012) where they observed an increase in the N parameter when data from a dew point potentiometer was added to data from the pressure plate method (Solone et al., 2012). Based on these findings, soil water retention measured on the pressure plates in our study appeared to closely approach steady state conditions.

Conclusions

Saturating soils with waters of varying EC and SAR combinations such as the upward rise of salt-bearing ground waters caused some slight changes in soil hydrologic properties with most occurring at greater than -100 cm H_2O matric potential. There were small differences in θ_s, α, N, K_{sat}, l, w_i, and λ van Genuchten and Durner dual porosity water retention parameters coupled with Mualem conductivity model with impacts differing depending upon soil texture and bulk smectite percent. When the soils are within the range of potentials during normal field conditions, there was little differences in soil hydrologic properties from saline and sodic ground water application except when water potentials were close to 0 (i.e. saturated water contents). However, the impacts of saline and or sodic ground waters may increase over time if soil sodium levels increase or electrical conductivity of waters are decreased by management practices. The van Genuchten and Durner dual porosity models both provided a good fitting to the water retention and conductivity values which can determine water potential and conductivity at any water content. These parameters can be used to predict salt and water transport of a given soil solution when applying irrigation waters or with climatic conditions for a given area in a program such as Hydrus. To determine water retention fitting parameter changes from capillary rise of saline or sodic waters, the changes would be soil dependent with saturated conductivity parameter having largest changes occurring based on findings in this study.

The retention data appeared to have some consistent variation between methods but only slight variation occurred with van Genuchten fitting parameters for the solution treatments on the various soils which were used as long as combinations were combined with Hyprop method. The van Genuchten function appeared to fit the data well for low EC levels and high SAR levels of saturating waters. As the sand content of the soil mixes increased the differences between fitting parameters between method combinations increased. The pressure plates used in this study appeared to resemble steady state condition for soils which were used. The evaporation method in combination with standard water retention methods appear to fit to the shape of the van Genuchten model well for a majority of soils which were used except for when the soil contains high salt concentrations or sand percentage increases in Fargo:Serden mixes. Across a majority of the potentials measured there were no differences in conductivity and water retention values except during wet conditions > assumed potential of field capacity

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GENERAL CONCLUSIONS

Saline and sodic simulated groundwaters created some differences in soil shrinkage and hydrologic properties of the soils which were analyzed. Soil shrinkage for oven dry conditions appeared to increase as EC decreased in smectite dominant soils as clay percentage increased over 25%. Fargo soil having 53% clay having an average COLE of 0.211 mm mm^{-1} at solution EC of 8 dS m^{-1} and 0.230 mm mm^{-1} at solution EC of 0.5 dS m^{-1}. As solution SAR increased from 0 to 20, average COLE increased from 0.180 mm mm^{-1} to 0.200 mm mm^{-1}, respectively, when clay percentage of soils was above 35%. The relative soil length decreased from 0.96 to 0.82 mm mm^{-1} as gravimetric water content at saturation increased from 0.43 to 0.76 g g^{-1} and as bulk smectite percentage of the soil increased from 8.8 to 29.1%. Once clay content exceeded 30% the slopes of the soil normal shrinkage range and residual shrinkage range were similar. Solution composition at the salt levels used in our study created minimally impacts on soil shrinkage curve parameters as a function of soil water content. Empirical regression models were developed to predict oven dry shrinkage of the soils in which the parameters appeared to be most sensitive to clay content, with RMSE values of 0.020 mm mm^{-1}, and only slightly influenced by salt solutions. However, further evaluation of soil shrinkage across solution composition is needed due to the non-linearity of clay content and solution composition effects. The soil shrinkage at the sodicity and salinity levels of the solutions used in this study likely were not high enough to induce sodic conditions based on the NRCS classification. However, these levels did create up to a 10% difference on soil shrinkage which may create differences in soil hydrology at the landscape level.

The simulated capillary rise of sodium and calcium solutions in different ratios increased soil EC_e to levels slightly higher than the solution EC when the solution EC was below 4 dS m^{-1} and slightly less than the solution EC when the solution EC was higher than 2 dS m^{-1}. The SAR_e of the soil increased to between 0.8 and 1.4 for the solution EC and SAR combination of 0.5 dS m^{-1} and 20, respectively, whereas SAR_e of the soil increased to between 5.3 and 7.4 for the solution EC and SAR combination of 8 dS m^{-1} and 20, respectively. Initial saturated hydraulic conductivity was lowest for the smectite dominant silty clay soil at 0.32 cm h^{-1} with a solution of EC 0.5 dS m^{-1} and SAR 20; as compared to a saturated hydraulic conductivity at 1.96 cm h^{-1} following saturation with a solution of EC 8 dS m^{-1} and SAR 0. The differences in the slope of the saturated hydraulic conductivity curve as a function of leachate pore volume was greatest among soils following saturation with a solution of SAR 20 vs a solution of SAR 0 on the mixed clay mineralogy clay loam soil (i.e., 0.56 vs. 0.29 cm pore volume h^{-1}, respectively) and least for the smectite dominant sandy loam soil (i.e., 0.08 vs. 0.03 cm pore volume h^{-1}, respectively). Empirical functions were created to predict the saturated hydraulic conductivity curve's slope and initial value. These functions provided bias of 0.14 to 0.73 cm h^{-1} for the initial saturated hydraulic conductivity estimation at zero leachate volume and a bias of 0.008 to 0.043 cm pore volume h^{-1} for slope parameter of conductivity vs pore volume.

Saline and sodic solutions affected soil hydrologic properties with most of the impact occurring at matric potentials > -100 cm H_2O. In general, these reflected as an increase in water retention and a decrease in hydraulic conductivity as solution EC decreased and solution SAR increased. There was a 30% decrease in saturated hydraulic conductivity and a 25% decrease in α (i.e., the inverse of the air entry point) between EC 8 dS m^{-1} and EC 0.5 dS m^{-1} of saturating waters averaged across all soils. The van Genuchten parameters exhibited the largest differences among solution EC and SAR values as compared to the Durners dual porosity water retention models coupled with the Mualem hydraulic conductivity model. The water retention measurement methods appeared to have variation between method combinations. The van Genuchten fitting parameters were different only when the Hyprop evaporation method was included or excluded from the WP4 dew point potentiometer and pressure plate method data for soils with high sand content and high EC levels of saturating solutions. The residual water contents were 0.14 and 0.05 cm^3 cm^{-3} and the α parameters were 0.021 and 3.02 cm H_2O^{-1} when the Hyprop evaluation method was included and excluded, respectively, with the WP4 dew point potentiometer and pressure plate data for the sandy loam soil.

The smecitite-dominant silty clay soil was the most sensitive to saline and sodic ground waters; whereas, the sandy loam showed no differences after saline and sodic solutions saturated soil columns. The silty clay soil had a 9% increase in soil COLE and a 75% decrease in saturated hydraulic conductivity when it was saturated with solutions of EC 0.5 dS m^{-1} as compared to solutions of EC 8 dS m^{-1}. In contrast, the sandy loam soil had a 0% increase in COLE and a 0% decrease in saturated hydraulic conductivity when it was saturated with solutions of EC 0.5 dS m^{-1} as compared to solutions of EC 8 dS m^{-1}. Across SAR levels the silty clay soil had an 11% increase in COLE and a 27% decrease in saturated hydraulic conductivity when it was saturated with solutions of SAR 20 as compared to solutions of SAR 0. Whereas the sandy loam soil had a 13%

increase in COLE and a 13% decrease in saturated hydraulic conductivity when it was saturated with solutions of SAR 20 as compared to solutions of SAR 0. Soil SAR_e levels as low as 0.7, which were created by saturating solutions of EC 0.5 dS m^{-1} and SAR 20, were enough to decrease some soil's relative saturated hydraulic conductivities below 25% (i.e., the percent decrease in saturated hydraulic conductivities used as a criteria in classify waters as being or not being sodic).

Each soil used in this study, had a different solution EC and SAR threshold where soil shrinkage and hydraulic properties were significantly affected. These thresholds and their degree of influence on soil physical properties increase as the soil's percent smectite increases. Each individual soil had its own level of solution composition where significant differences in parameters occurred meaning sodic conditions in a sandy loam textured soil will not occur until higher SAR levels are achieved as compared to a smectite clay dominant silty clay textured soil. Most of the affects of solution levels obtained from simulation of salt bearing capillary fringe occurred at water potentials which would exist after rain events or snow melt which would raise matric potentials >-100 cm H_2O

APPENDIX A

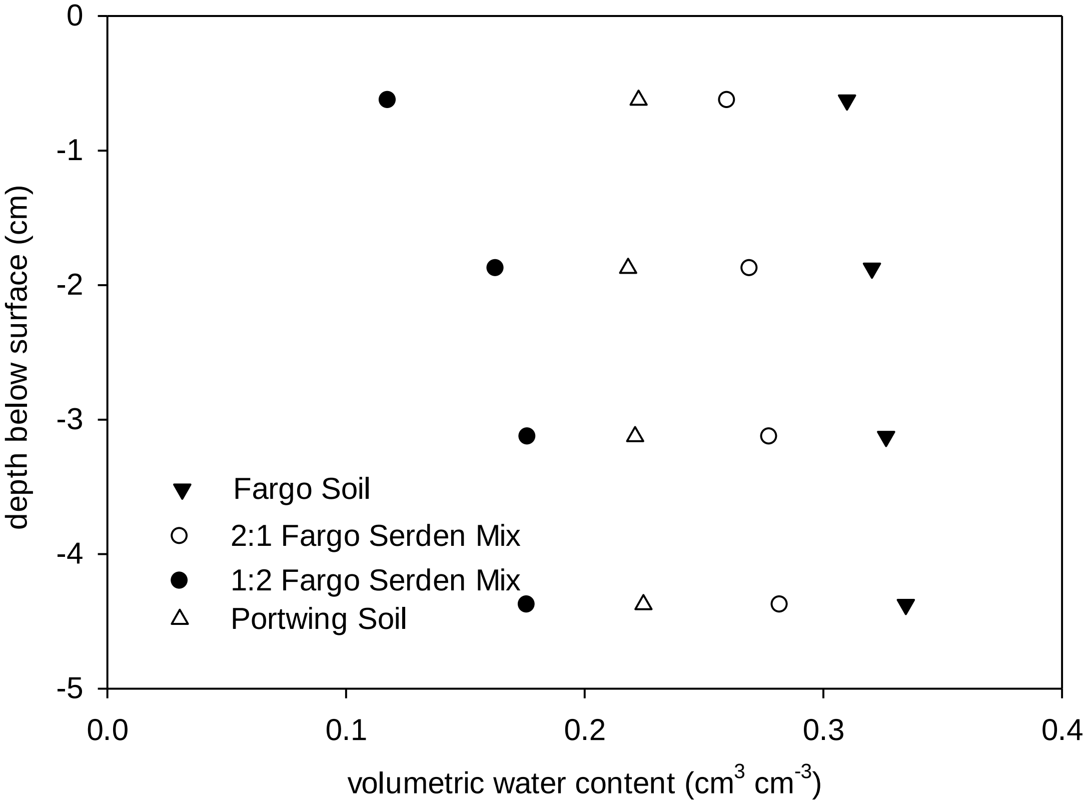

Figure A.1. Mean volumetric soil water contents vs soil depth at the termination of the evaporation experiments for the 1:2 Fargo:Serden mix, 2:1 Fargo:Serden mix, Fargo and Portwing soils. Water contents are average values across all EC and SAR levels.

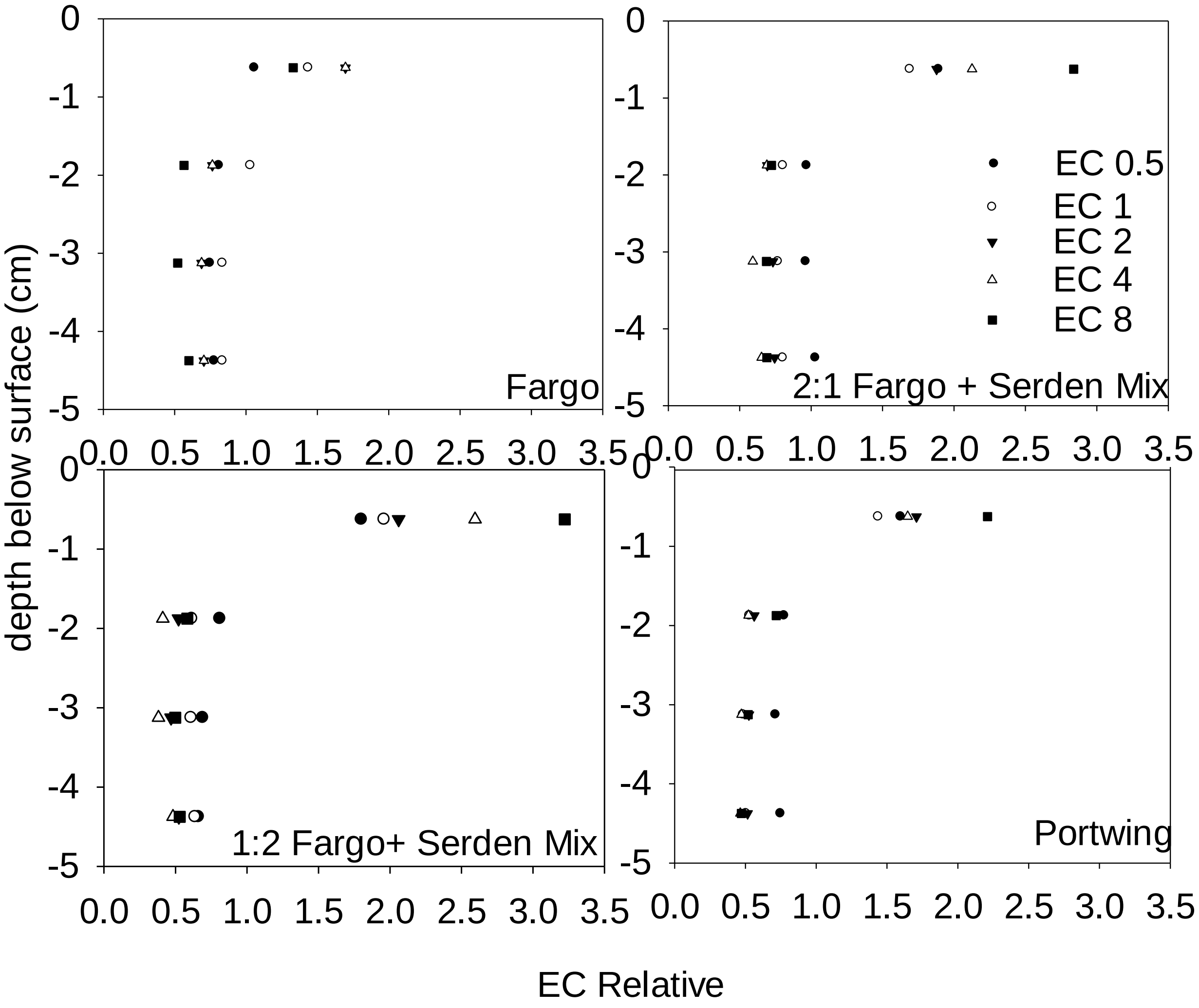

Figure A.2. Average 1:1 soil EC values relative to initial conditions vs soil depth at the termination of the evaporation experiments for Fargo soil, 2:1 and 1:2 Fargo:Serden mixes, and Portwing soils at solution EC levels of 0.5 dS m^{-1}, 1 dS m^{-1}, 2 dS m^{-1}, 4 dS m^{-1} and 8 dS m^{-1}. The 1:1 soil:water suspensions were measured after soil cores were cut into four sections at 1.25 cm increments below surface of evaporation experiments after the tensiometers cavitated. Measured EC values of 1:1 suspension for a given solution treatment were divided by measured 1:1 suspension of samples equilibrated in chapter 2.

APPENDIX B

Table B.1. Average saturated hydraulic conductivity for Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing soils. The solution EC 8 dS m^{-1} treatment at SAR levels of 0, 6, 12 and 20 was applied until saturated hydraulic conductivity reached steady state then followed by the infiltration of solution EC 0.5 dS m^{-1} treatment at same SAR level until steady state saturated hydraulic conductivity was reached or became negligible such as has been done in many previous salinity studies (i.e., Frenkel et al., 1978; McNeal et al.,1968).

Solution EC	Solution SAR	Fargo	2:1 Fargo:Serden mix	1:2 Fargo:Serden mix	Portwing	All soils
dS m^{-1}		------------------------------------- cm h^{-1} -------------------------------------				
0.5	0	10.3bB†	22.0aA	22.9bcA	3.12aC	14.6b
0.5	6	4.35cB	5.75cB	21.5cA	0.64bcC	8.06c
0.5	12	0.12cC	0.29dC	15.3dA	0.79bcC	4.12d
0.5	20	0.07cA	0.14dA	1.36eA	0.40cA	0.49e
8	0	15.0aB	25.5aA	23.5bcA	3.29aC	16.8ab
8	6	16.7aB	16.0bB	24.0bcA	2.25abC	14.7b
8	12	14.5abC	22.0aB	29.0abA	3.38aD	17.2a
8	20	15.0aB	15.5bB	27.0abA	2.53aC	15.0ab

†Different lower case letters within a column are significantly different using Tukey pairwise analysis at the 0.05 level.

Different capital letters within a row are significantly different using Tukey pairwise analysis at the 0.05 level.

Table B.2. EC_e and SAR_e levels for Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix, and Portwing soils measured by saturated paste extract. The solution EC 8 dS m^{-1} treatment at SAR levels of 0, 6, 12 and 20 was applied until saturated hydraulic conductivity reached steady state then followed by the infiltration of solution EC 0.5 dS m^{-1} treatment at same SAR level until steady state saturated hydraulic conductivity was reached or became negligible such as has been done in many previous salinity studies (i.e., Frenkel et al., 1978; McNeal et al., 1968).

Solution SAR	Fargo	2:1 Fargo:Serdenmix	1:2 Fargo:Serden mix	Portwing
	---------------------- EC_e (dS m^{-1}) ----------------------			
0	0.71	0.64	0.75	0.36
6	0.84	0.60	0.47	0.52
12	0.86	0.74	0.80	0.53
20	1.23	1.29	0.94	0.51
	------------------------- SAR_e -------------------------			
0	0.27	0.31	0.25	0.28
6	2.55	2.88	3.50	3.08
12	6.66	5.90	5.65	6.79
20	12.03	8.47	8.24	6.36

APPENDIX C

Table C.1. Fitting parameters for Fargo, 2:1 Fargo:Serden mix, 1:2 Fargo:Serden mix and Portwing soils shrinkage characteristic curve in Figure 1 within Chapter 1 using Equation 8 where l_{dry} is relative soil rod length in mm mm^{-1}, a, b and c are empirical fitting parameters and Θg_s g g^{-1} is the initial soil moisture content of the soil rods.

Soil	EC	SAR	L_{dry}	a	b	c	Θ_{gs}	R^2
	dS m^{-1}		mm mm^{-1}				g g^{-1}	
Fargo	0.5	0	0.845	0.467	0.601	1	0.656	0.982
Fargo	0.5	20	0.805	0.472	0.593	1	0.657	0.981
Fargo	8	0	0.836	0.292	0.449	1	0.831	0.993
Fargo	8	20	0.812	0.422	0.580	1	0.712	0.999
2:1 Fargo:Serden mix	0.5	0	0.859	0.385	0.489	1	0.463	0.971
2:1 Fargo:Serden mix	0.5	20	0.853	0.461	0.568	1	0.493	0.973
2:1 Fargo:Serden mix	8	0	0.872	0.427	0.582	1	0.487	0.986
2:1 Fargo:Serden mix	8	20	0.871	0.511	0.638	1	0.459	0.960
1:2 Fargo:Serden mix	0.5	0	0.97	0.0579	0.269	1	0.411	0.363
1:2 Fargo:Serden mix	0.5	20	0.959	0.0454	0.161	1	0.451	0.187
1:2 Fargo:Serden mix	8	0	0.969	0.0675	0.360	1	0.461	0.687
1:2 Fargo:Serden mix	8	20	0.965	0.087	0.406	1	0.431	0.629
Portwing	0.5	0	0.863	0.435	0.518	1	0.449	0.992
Portwing	0.5	20	0.854	0.469	0.510	1	0.437	0.991
Portwing	8	0	0.868	0.488	0.561	1	0.433	0.956
Portwing	8	20	0.848	0.411	0.469	1	0.469	0.965