doi:10.2489/jswc.2022.00131

Increased rainfall may place saline/sodic soils on the tipping point of sustainability

M.E. Budak, D.E. Clay, S.A. Clay, C.L. Reese, S. Westhoff, L.E. Howe, R.K. Owen, G. Birru, Y. He, and Z. Wang

Abstract: Increased rainfall is increasing the risk of the capillary movement of sodium (Na^+) and other salts from buried marine sediments to the soil surface in the North American northern Great Plains. These salts reduce productivity and resilience while increasing their effect on the environment. Understanding the interactions among management, climate, cropping system, and soil is the first step toward implementing effective management plans. Unfortunately, while much work has been conducted, little is known about the effective management of semiarid dryland saline/sodic soils. This study determined the influence of soil depth on hydraulic conductivity and changes in soil Na^+ (mg Na^+ kg^{-1} soil) to electrical conductivity ($EC_{1:1}$) (dS m^{-1}) ratio following high spring rainfall in 2019 in three soils. The soil parent materials were Glaciolacrustrine underlaid at a depth of approximately 15 m by marine sediments that contained Na^+ and other salts. The landscape positions included in the study were a well-drained shoulder, moderately well-drained backslope, and a poorly drained toeslope soil. Based on the soil classification, shoulder and backslope subsoils were not predicted to be salt affected, while the toeslope soil was predicted to contain a natric soil horizon. Rainfall in 2018, 2019, and 2020 was 46, 76, and 37 cm, respectively, and soil cores were collected prior to and following the 2019 high rainfall. Soil cores were separated into the 0 to 7.5, 50 to 57.5, 82.5 to 90, 92.5 to 100, and 105 to 112.5 cm segments. Samples from 2018 were analyzed for soil $EC_{1:1}$, pH, ammonium acetate extractable cations, soil particle size, available water at field capacity, drainable porosity, soil bulk density, and saturated hydraulic conductivity. Samples from 2019 were analyzed for $EC_{1:1}$ and ammonium acetate extractable Na^+. Across the sampling sites, shoulder and backslope soils had higher saturated hydraulic conductivities than the toeslope soils. Saturated hydraulic conductivities were negatively correlated to pH ($r = -0.55$, $p < 0.01$), the Na^+ to $EC_{1:1}$ ratio ($r = -0.66$, $p < 0.01$), extractable Na^+ ($r = -0.56$, $p < 0.01$), and sand content ($r = -0.66$, $p < 0.01$), and positively correlated to the silt content ($r = 0.65$, $p < 0.01$). A comparison between the saturated hydraulic conductivity and the Na^+ to $EC_{1:1}$ ratio suggests that saturated conductivities approached 0 cm h^{-1} when the Na^+ (mg Na^+ kg^{-1}) to $EC_{1:1}$ (dS m^{-1}) ratio exceeded 600. The 2019 high rainfall increased the risk of soil dispersion in the lower soil depths (>82.5 cm). For example, in the shoulder soil at the 105 to 112.5 cm depth, $EC_{1:1}$ decreased 0.936 ± 0.254 dS m^{-1} from 2018 to 2019, whereas the exchangeable Na^+ increased 688 ± 283 mg kg^{-1} soil. Our findings suggest that a climate change-induced shift in rainfall patterns can increase salinity and sodicity risks in northern Great Plains subsurface soils. Salinity and sodicity risks are expanding into zones not previously identified as at risk, and improving or maintaining the productivity of these soils requires careful planning.

Key words: drainage classification—northern Great Plains—precision conservation

The amount of land affected by salinity and sodicity is expanding worldwide, and interactions among soil, climate, and management produce unique problems that require the development and testing of new remediation techniques. For example, in the North American northern Great Plains (NGP) region, spring rainfall has raised water tables, increased yield variability, and contributed to the salinity and sodicity problem (Fiedler et al. 2022; Melillo et al. 2014; Birru et al. 2019). Long-term climate predictions suggest that weather changes are not temporary and may continue through 2090 (Almazroui et al. 2021).

In the NGP, the growing salinity and sodicity problem is attributed to the capillary movement of salts from underlying marine sediments to the soil surface. Different mechanisms are observed in different environments. For example, in the Chinese Songnen Plains, the growing salinity and sodicity problem is attributed to overgrazing, freeze-thaw action, and wind conveyance (Wang et al. 2009), whereas in marine environments, salinity and sodicity expansion is driven by saltwater intrusion (Mahmuduzzsaman et al. 2014). In these soil systems, remediation techniques that have been developed for irrigated system may have limited effectiveness (Birru et al. 2019). In addition, Fiedler et al. (2021) showed that that the application of nitrogen (N) fertilizer to NGP saline/sodic soils can result in very high nitrous oxide (N_2O) emissions. Thus, a better understanding of the mechanisms and the complex relationships

Received August 30, 2021; Revised November 22, 2021; Accepted November 24, 2021.

Mehmet Emin Budak is a research engineer, Soil, Fertilizer and Water Resources Central Research Institute, Ankara, Turkey. **David E. Clay** is a distinguished professor of soil science, South Dakota State University, Brookings, South Dakota. **Sharon A. Clay** is a distinguished professor in the Agronomy, Horticulture, and Plant Science Department, South Dakota State University, Brookings, South Dakota. **Cheryl L. Reese** is a senior lecturer, South Dakota State University, Brookings, South Dakota. **Shaina Westhoff** is a research associate, South Dakota State University, Brookings, South Dakota. **Lance E. Howe** is a Major Land Resource Areas (MLRA) soil survey office leader, USDA Natural Resources Conservation Service (NRCS), Redfield Soil Survey Office, Redfield, South Dakota. **Rachel K. Owen** is an adjunct professor, School of Natural Resources, University of Missouri, Columbia, Missouri. **Girma Birru** is a research agronomist, Agroecosystem Management Research Unit, USDA Agricultural Research Service (ARS), Lincoln, Nebraska. **Yangbo He** is an associate professor, Key Laboratory of Arable Land Conservation, Ministry of Agriculture and Rural Affairs, Huazhong Agricultural University, Wuhan, Hubei, China. **Zhichun Wang** is a professor of soil salinity and sodicity, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, China.

among the soil characteristics, management, and climate are needed to improve economic and environmental sustainability in semiarid dryland systems (Ruark et al. 2009).

A classical management approach to improve productivity in salt-affected soils is to install tile drainage (Franzen 2019). However, in the northern Great Plains, installing tile drainage can have positive and negative effects on plant and soil health (Hundal et al. 1976; Hopkins et al. 2012; Kharel et al. 2018). One of the positive effects is higher yields resulting from earlier planting in areas with water saturated soils (Scherer et al. 2015). However, short-term gains may come at the expense of long-term sustainability if the soil contains high concentration of sodium (Na^+) (Hopkins et al. 2012; Cihacek et al. 2020). In these soils, drainage failure can result from Na^+ increasing soil dispersion and reducing drainable porosity. Cihacek et al. (2020) noted that drainage failure risks can be reduced by consulting the US Web Soil Survey and determining the soil Na^+ adsorption ratio (SAR_e) prior to installation. However, (1) salinity and sodicity problems are often not predicted by available soil maps, (2) the collection and chemical analysis of soil samples a meter deep in the soil is expensive, and (3) the Web Soil Survey does not provide information on how tile-drainage when combined with high rainfall will affect the risk of dispersion.

The classical approach to assess salinity and sodicity is to determine the electrical conductivity (EC_e) and the calcium (Ca^{+2}), magnesium (Mg^{+2}), and Na^+ concentrations in a saturated paste extract (Cihacek et al. 2020). These values are then used to calculate the SAR using equation 1:

$$SAR_e = \frac{mmol_c Na/L}{\left[\dfrac{\dfrac{mmol_c Ca}{L} + \dfrac{mmol_c Mg}{L}}{2}\right]^{0.5}} . \quad (1)$$

Cihacek et al. (2020) suggested that if the SAR_e value is <6 then artificial drainage might not be limited by Na^+, and if it is >10 then artificial drainage might not be appropriate. The primary disadvantages of Cihacek et al. (2020) were that the Web Soil Survey does not provide an exhaustive list of salt effected soils and it does not make predictions on how climate change affects the soil characteristics. In addition, SAR_e are not determined in many standard soil tests; this recommendation does not consider EC, which tends to counteract the effect of Na^+ on clay flocculation; and information on the SAR value at the tipping point between stable and unstable soil aggregates is not available (He et al. 2013, 2015). Therefore, to resolve these crucial issues, the objective was to determine the influence of soil depth on hydraulic conductivity and changes in the soils $EC_{1:1}$ and exchangeable Na^+ following a high rainfall event in three soils across a landscape.

Materials and Methods

Related Work Associated with the Study Site. The experiment discussed in this paper is linked to several related papers that investigated the effect of chemical amendments on soil productivity (Birru et al. 2019), and the effect of applying N fertilizer to saline sodic soils on greenhouse gas emissions (Fiedler et al. 2021). Fiedler et al. (2022) provides annual crop yield information for 2018, 2019, and 2020 at a nearby site with similar soils and landscape positions.

Characteristics of the Study Site. The experimental site was located near Stratford, South Dakota, at the latitude and longitude coordinates of 45°16'24.55" N and 97°50'13.34" W, respectively. The Köppen climate regime was on the border between three Köppen climate regimes Dwa, Dwb, and Bsk. The soil parent materials were quaternary late Wisconsin, Late Dakota Silts underlaid by the Na^+ containing Pierre shale at approximately 15 m, and the landscape positions included in the study were a well-drained shoulder, moderately well-drained backslope, and a poorly drained toeslope soil.

No-tillage had been practiced in the experimental field for at least 10 years, and the crop rotation was corn (*Zea mays* L.) followed by soybeans (*Glycine max* [L.] Merr). The study site is underlain by Glaciolacrustrine and marine sediments deposited during the Cretaceous and Paleogene periods (George 1978). The marine sediments are impermeable to water and a source for Na^+ and other salts that can be transported to the surface soil through capillary action. The depth of ground water was obtained at South Dakota observation well SP-77C, which is located at 44°54'51.1416" N latitude and –98°1'25.0032" W longitude. This field was separated into three landscape positions (shoulder slope, back slope, and toeslope). Based on the USDA Natural Resources Conservation Service (NRCS) Web Soil Survey, the shoulder and backslope soils were not expected to have a Na^+ affected subsoil, whereas the toeslope soil was expected to have a natric soil horizon.

Shoulder Soils. Soils in the shoulder areas were well-drained (Soil Survey Staff 2018), and the soil-mapping unit was a Great Bend (fine-silty, mixed, superactive, frigid Calcic Hapludolls)-Beotia silt loam (fine loamy, mixed, super active, Typic Argiustolls). The soil chemical and physical characteristics are provided in table 1. The Great Bend soil series is typically higher in the landscape than the Beotia soil series, and both soils were not expected to contain natric horizons. The Great Bend and Beotia soils have a land capability class value of 2e with slopes of 2% to 6%. When the soil cores were collected, the soil horizons were determined. The soil horizons in these cores were Ap (0 to 10 cm), Bw (10 to 18 cm), Bkz1 (18 to 36 cm), Bkz (36 to 69 cm), C1 (69 to 84 cm), and C2 (84 to 122 cm). The k and z subscription means that there is an accumulation of carbons (C) and salts that are more soluble than gypsum, respectively. The soil structure depended on the horizon, and in the Ap horizon, the soil structure was weak fine granular, whereas in the Bw horizon the structure was a weak medium subangular blocky (Soil Survey Staff 2018). Saturated hydraulic conductivity is considered moderately high, and subsurface drainage was not installed.

Backslope Soils. The backslope soils were moderately well-drained and had slopes that ranged from 0% to 2%. Selected chemical and physical characteristics are provided in table 1 and the soil mapping unit was a Beotia (fine, smectitic, frigid, Pachic Argiudolls). When the soil cores were collected, the soil horizons were identified, and they included the Ap (0 to 20 cm), Bw (20 to 33 cm), Bkz1 (33 to 48 cm), Bkz2 (48 to 76 cm), Cz1 (76 to 110 cm), and Cz2 (110 to 132 cm) horizons. The soil structure in the Ap horizon was a weak fine granular, whereas in the Bkz1 horizon the soil structure was a weak to moderate blocky (Soil Survey Staff 2018). In the backslope, a subsurface tile line was installed in the fall of 2017 at a depth of 1.05 m. The spacing between the tile lines was 12 m.

Toeslope Soils. Soils in toeslope were characterized as poorly drained and had slopes between 0% to 2%. Soils in this mapping unit were the Harmony (fine, smectitic, frigid Pachic Argiudolls) and Aberdeen (fine, smectitic, glossic Udic Natriborolls) series. The Harmony and Aberdeen soils have a land capability class value of 2s. Based on their descriptions, the Harmony soil does not contain a natric horizon while the Aberdeen soil contains a natric horizon. Based on the cores that were collected, the soil horizons were the Ap (0 to 13 cm), ABkz (13 to 28 cm), Bk1 (28 to 53 cm), Bk2 (53 to 81 cm), and C (81 to 122 cm). The soil structure depended on the soil horizon, and the Ap horizon had a weak medium and fine granular structure, whereas the ABkz horizon had an angular block structure (Soil Survey Staff 2018). In this soil, subsurface drainage had been installed in the fall of 2017 at a depth of 1.05 m, and the distance between adjacent tile lines was 12 m.

Soil Core Collection and Analysis. Soil cores were collected at similar locations with a 7.5 cm diameter to a depth of 120 cm. In November of 2018, November of 2019, and June of 2020, soil cores were collected from four locations in the three landscape positions. The soil samples collected in 2018 were analyzed for their physical and chemical properties, whereas samples collected in 2019 were only analyzed for their chemical properties. Samples from 2020 were analyzed for bulk density (Richards 1965). Soil cores for chemical analysis were separated into five depth increments (0 to 7.5, 50 to 57.5, 82.5 to 90, 92.5 to 100, and 105 to 112.5 cm), dried (40°C), ground to pass through a 2 mm sieve, and analyzed for soil $pH_{1:1}$, $EC_{1:1}$, and ammonium acetate extractable Ca^{+2}, Mg^{+2}, and Na^{+} concentrations following Warncke and Brown (2015). The sum of bases or apparent cation exchange capacity (CEC_a) was calculated with equation 2:

$$\text{sum of bases} = \text{cmol}_c\ Na^+/\text{kg} + \text{cmol}_c\ Mg^{+2}/\text{kg} + \text{cmol}_c\ Ca^{+2}/\text{kg} + \text{cmol}_c\ K^+/\text{kg}. \quad (2)$$

The $\%Na^+$ was calculated using equation 3:

$$\%Na = 100 \times \frac{cmol_cNa/kg}{\frac{cmol_cNa}{kg}+\frac{cmol_cCa}{kg}+\frac{cmol_cK}{kg}+\frac{cmol_cMg}{kg}}, \quad (3)$$

where Na^+, Ca^{+2}, Mg^{+2}, and potassium (K^+) are extracted with ammonium acetate. Previous work showed that at low $\%Na^+$ values, the $\%Na^+$ and SAR_e are similar (DeSutter et al. 2015).

The amount of water retained in the soil at field capacity (–33 kPa), or water holding capacity, was determined on a ceramic plate, and the soil texture was determined using the hydrometer method after the soil organic matter (SOM) was removed using 30% hydrogen peroxide (H_2O_2) (Gee and Bauder 1986). Based on the bulk density and the measured soil water content at –33 kPa, drainable porosity was calculated as the difference between the saturation point and water content at –33 kPa bar.

Saturated hydraulic conductivity (Ksat) was measured on undisturbed soil samples collected in 2018 on the 0 to 7.5, 50 to 57.5, 82.5 to 90, 92.5 to 100, and 105 to 112.5 cm soil depths. Each sample had a height and diameter of 7.5 cm. The columns were prepared by placing them on a layer of cheesecloth and washed sand. To prevent water from flowing between the plastic column and the soil, the edge was sealed with molten paraffin wax (Weber et al. 1986). The columns were conditioned for the measurement by saturating them for 24 hours with water with an EC < 0.004 dS m^{-1} and total organic C < 20 *ug* L^{-1} (Reynolds and Elrick 1990). During Ksat measurements, the height of the ponded water was maintained at 2.3 cm above the top of the soil surface by adding water every five minutes to replace water that had infiltrated into the soil. Evaporation was prevented by covering the columns with aluminum foil.

Statistical Analysis. The mean value and associated standard deviation for $EC_{1:1}$, Na^+, Na^+ to $EC_{1:1}$ ratio, and hydraulic conductivities were determined for each landscape position and soil depth. Correlation analysis was used to compare the physical and chemical measurements in soil samples collected in 2018. In addition to these values, the change in the $EC_{1:1}$, Na^+, and the Na^+ to $EC_{1:1}$ ratio from 2018 to 2019 were determined for the three landscape positions and five soil depths. Confidence intervals (95%) for the measured values were determined. For the correlation analysis, the significant *r* values at the 0.01 and the 0.05 level are provided.

Results and Discussion

Climatic Conditions. The precipitation in 2017, 2018, 2019, and 2020 was 37, 46, 76, and 37 cm, respectively. Inspection of the field in 2019 showed that the toeslope soils were water saturated, which contributed to a rise in the water table. For example, at a nearby groundwater monitoring system, the water table rose from 3.79 m below the soil surface on June 26, 2018, to 1.76 m below the soil surface on June 18, 2019. In 2020, the water table receded to 3.3 m below the soil surface. The high rainfall data when combined with the rising water tables suggest that water percolated through the soil in 2019.

Initial Soil Conditions. Across the three landscape positions, sand contents varied from 220 to 556 g kg^{-1} (table 1), whereas clay contents ranged from 74 to 339 g kg^{-1}. Like soil textures, the bulk densities and CEC_a were variable, and the dominant cations within the CEC_a were 18.5 $cmol_c$ Ca^{+2} kg^{-1} and 8.5 $cmol_c$ Mg^{+2} kg^{-1}.

In the shoulder, $EC_{1:1}$, Na^+, $\%Na^+$, and the ratio between Na^+ to $EC_{1:1}$ were lower in the 0 to 7.5 cm depth than the other soil depths. Even though the shoulder soil did not have a natric horizon, subsurface soil samples had $\%Na^+$ value > 10 ($cmol_c$ Na^+ kg^{-1}) ($cmol_c$ kg^{-1})$^{-1}$. Work done by DeSutter et al. (2015) suggests that SAR_e is approximately equal to $\%Na^+$ and, therefore, this value was used to assess sodicity risk. The drainable porosities for the five soil depths ranged from 0.15 to 0.26 cm^3 cm^{-3}, and hydraulic conductivities ranged from 36 to 138 mm h^{-1}. In the backslope position, $EC_{1:1}$, Na^+, the Na^+ to $EC_{1:1}$ ratio, and hydraulic conductivities were lower in the 0 to 7.5 cm depth than all other soil depths. Despite the soil not containing a natric horizon, the subsoils had $\%Na^+$ values > 10 ($cmol_c$ Na^+ kg^{-1}) ($cmol_c$ kg^{-1})$^{-1}$. In this soil, the drainable porosity for the five soil depths ranged from 0.13 to 0.20 cm^3 cm^{-3}, and hydraulic conductivities ranged from 8 to 85 mm h^{-1}.

In the toeslope position, $EC_{1:1}$ was higher in the 0 to 7.5 cm soil depth than the other soil depths. These soils also had relatively high sand and exchangeable Na^+ concentrations, and it was identified by Cihacek et al. (2020) as potentially having a Na^+ effected subsoil. In the five soil depths, $\%Na^+$ ranged from 47 to 63 $cmol_c$ Na^+ (CEC_a)$^{-1}$, and drainable porosity ranged from 0.16 to 0.20 cm^3 cm^{-3}. The saturated hydraulic conductivities were near zero for all soil depths.

Relationship between the Soil Chemical and Physical Measurement. Across all soil depths and landscape positions, many of the physical and chemical measurements

Table 1

The sand, clay, pH, electrical conductivity ($EC_{1:1}$), apparent cation exchange capacity (CEC_a) sodium (Na^+), %Na^+, Na^+/EC ratio, hydraulic conductivity (con.), and drainable porosities of soil samples collected from five soil depths and three landscape positions in 2018. The standard deviations (sd) are provided adjacent to the means. For the means and standard deviations, *n* is 4. The standard deviations of the mean (sd_x) across depths are also provided. The *n* for these calculations was 20.

Landscape position	Soil depth (cm)	Mapping unit	Sand (g kg^{-1})	Clay (g kg^{-1})	$pH_{1:1}$	$EC_{1:1}$ (dS m^{-1}) Mean/sd	CEC_a ($cmol_c$ kg^{-1}) Mean/sd	Na^+ (mg kg^{-1}) Mean/sd	%Na^+ (%) Mean/sd	$Na^+/EC_{1:1}$ (ppm/EC) Mean/sd	Hydraulic con. (mm h^{-1}) Mean/sd	Drainable porosities (cm^3 cm^{-3}) Mean/sd
Shoulder	0 to 7.5	Great Bend	35.3	23.1	8.2	0.37/0.05	22.7/3.2	28.0/6.55	0.53/0.06	73.9/7.88	75.8/3.70	0.2/0.06
Shoulder	50 to 57.5	Beotia	22.0	22.3	8.2	3.48/0.42	27.5/1.9	1,524/517	23.9/7.2	429/105	138/6.00	0.15/0.08
Shoulder	82.5 to 90	silt loam	21.8	16.3	8.3	3.35/0.27	26.1/2.52	1,582/73.4	26.4/2.8	472/26.5	100/20.8	0.21/0.06
Shoulder	92.5 to 100		27.6	15.1	8.3	3.13/0.43	25.2/2.52	2,328/284	40.1/2.0	746/30.4	36.2/5.05	0.2/0.05
Shoulder	105 to 112.5		24.1	14.6	8.3	3.2/0.11	25.8/1.24	1,541/147	25.9/1.4	481/31.4	51.4/5.7	0.26/0.07
	sd_x		1.2	0.9	0.04	0.27	0.53	175	3.0	50.1	8.6	0.018
Backslope	0 to 7.5	Beotia	40.0	20.4	8.2	1.11/0.78	20.3/00.73	285/204	6.22/4.42	233/41.5	8.8/1.34	0.19/0.17
Backslope	50 to 57.5	silt loam	31.2	326.3	8.3	4.92/0.78	30.5/3.6	3,590/727	50.7/13.0	722/64.1	85.4/10.1	0.14/0.08
Backslope	82.5 to 90		26.4	19.5	8.2	4.14/0.09	51.5/10.5	2,043/106	17.5/6.0	493/15.6	28.7/4.04	0.13/0.004
Backslope	92.5 to 100		31.6	17.3	8.1	3.79/0.56	44.6/5.51	2,599/122	25.5/4.8	699/123	33.2/2.96	0.16/0.08
Backslope	105 to 112.5		50.9	7.4	8.1	3.05/0.38	29.1/1.42	1,431/201	21.2/2.53	487/121	56.7/3.11	0.2/0.05
	sd_x		2.48	1.61	0.03	0.32	2.33	265	3.96	43.2	0.06	0.02
Toeslope	0 to 7.5	Harmony	51.7	17.2	8.1	4.55/0.89	40.3/6.2	3,370/1,000	47.3/14.0	729/74	0/0	0.16/0.21
Toeslope	50 to 57.5	silt loam	41.5	22.4	8.9	3.85/1.19	32.9/0.9	4,444/1,463	62.3/20.5	1,152/136	0/0	0.2/0.11
Toeslope	82.5 to 90		36.4	33.9	8.9	2.89/0.14	29.2/0.8	3,417/137	47.9/1.93	1,180/72	0/0	0.18/0.11
Toeslope	92.5 to 100		47.6	17.8	8.9	3.16/0.30	31.2/1.1	3,734/604	52.4/8.47	1,175/85.5	0.0	0.19/0.19
Toeslope	105 to 112.5		55.7	13.4	8.9	3.23/0.37	29.3/1.6	2,860/57.9	54.1/0.81	1,205/138	0/0	0.15/0.17
	sd_x		1.63	1.82	0.00	0.195	1.88	188.	2.66	46.29	0.00	0.02

were correlated to each other (table 2). These relationships provided insights into the interactions between the soil physical and chemical processes. For example, the amount of Na^+ extracted with 1 M ammonium acetate was positively correlated to the %Na^+, the Na^+ to $EC_{1:1}$ ratio, sand, and bulk density, and negatively correlated to silt content, gravimetric water at –33 kPa, drainable porosity, pore space, and hydraulic conductivity. The volumetric amount of water at field capacity (–33 kPa) was negatively correlated to pH, clay content, bulk density, and pore space. Strong relationships between many of the factors were expected because the calculated values were derived from other measurements using the same data. For example, drainable porosity was calculated from the bulk density and volumetric amount of water at field capacity (–33 kPa). Drainable porosity is the maximum amount of water that can be removed by tile drainage and it is the difference between the water contents at 0 and –33 kPa. He et al. (2015) showed that drainable porosity may be reduced by high Na^+ concentrations. Saturated hydraulic conductivity, which is the rate that water moves through a water saturated soil, was positively correlated to the soil's silt content and negatively correlated to $pH_{1:1}$, CEC_a, Na^+, $Na^+/EC_{1:1}$, and sand content. A high saturated conductivity indicates that in a saturated soil, water moves rapidly from the surface to the subsurface or from soil to a tile drain. For comparative purposes, Garcia-Gutierrez et al. (2018) reported that the average hydraulic conductivity of 345 sandy clay soils and 78 clay loam soils was 27.2 and 12.6 mm h^{-1}, respectively. The surface soil hydraulic conductivities, which were 75.8, 8.8, and 0 mm h^{-1} in the shoulder, backslope, and toeslope, respectively were consistent with Birru et al. (2019) where the median hydraulic conductivities were 81.5, 57, and 0 mm h^{-1} for the saline/sodic soils located in the model backslope, footslope, and toeslope positions, respectively. The negative relationship between Ksat and sand content was surprising because water generally moves rapidly though course textured soils. However, this is not always the case. For example, more rounded sands generally have higher hydraulic conductivities than angular sand grains (Cabalar and Akbulut 2016), and small amounts of clay, silt, and Na^+ can greatly reduce the soil hydraulic conductivity (Dungan et al. 2007; Levy et al. 2005). The negative relationship between hydraulic conductivity and the Na^+ to $EC_{1:1}$ ratio suggests that Na^+ contributed to a decrease in the flow of water through the soil. This decrease could have resulted from soil dispersion (Frenkel et al. 1978) and/or increased amount of water held at field capacity, which in turn reduced drainable porosity (He et al. 2015).

The soil $EC_{1:1}$ value was not correlated to hydraulic conductivity but was positively correlated to CEC_a and the Na^+ concentration. The strong relationship between the CEC_a and $EC_{1:1}$ was expected because increasing the number of dissolved cations or anions in a soil solution increases the solution's ability to transmit an electrical charge (US Salinity Laboratory 1954). The types of ions in the soil solution affect both soil structural stability and the net effect on the EC_e. To demonstrate this effect, we compared samples from the Chinese Songnen basin (Wang et al. 2009) with those from the NGP (Wang et al. 2009; Owen 2015). Owen (2015) reported that the equation relating EC_e and total cations ($mmol_c$ L^{-1}) was total cations = EC_e × 13.5. Chang et al. (1983) in research conducted in Alberta, Canada, had a similar relationship and reported that the

Table 2

Correlation coefficients between pH, ammonium acetate sum of bases (CEC_a) electrical conductivity ($EC_{1:1}$), sodium (Na^+), %Na^+, Na^+/EC ratio, sand, clay, silt, bulk density (BD), pore space (PS), water content (wc) at field capacity (g g^{-1}), water content at field capacity (g cm^{-3}), hydraulic conductivity, and drainable porosity (DP) in samples collected from the subsurface soil samples collected across the three landscape positions in 2018. Correlation values greater than 0.288 or less than −0.288 are significant at the 0.05 level. Correlation values greater than 0.372 or less than −0.372 are significant at the 0.01 level.

	pH	CEC_a	$EC_{1:1}$	Na^+ (mg kg^{-1})	%Na^+or Na^+/ CEC_a	Na^+/ $EC_{1:1}$	Sand (g k^{-1}g)	Clay (g k^{-1}g)	Silt (g k^{-1}g)	BD (g cm^{-3})	PS (cm^3 cm^{-3})	wc (g g^{-1})	wc (g cm^{-3})	DP
CEC_a	−0.083													
EC	0.053	0.531												
Na^+	0.649	0.340	0.683											
Na^+/CEC	0.164	−0.011	0.663	0.525										
Na^+/EC	0.826	0.202	0.379	0.882	0.386									
Sand	0.381	0.177	0.059	0.445	−0.218	0.474								
Clay	0.350	−0.143	−0.134	0.078	0.002	0.144	−0.316							
Silt	−0.592	−0.096	0.018	−0.498	0.221	−0.566	−0.831	−0.265						
BD	0.610	0.153	0.298	0.580	0.304	0.632	0.144	0.195	−0.260					
PS	−0.610	−0.153	−0.298	−0.580	−0.304	−0.632	−0.144	−0.195	0.260	−1.000				
wc (g g^{-1})	−0.498	0.029	−0.259	−0.410	−0.515	−0.502	−0.018	0.162	−0.076	−0.466	0.466			
wc (g cm^{-3})	−0.065	0.180	0.000	0.034	−0.273	−0.035	0.053	0.323	−0.243	0.331	−0.331	0.673		
DP	−0.379	−0.196	−0.182	−0.395	−0.047	−0.401	−0.116	−0.326	0.309	−0.848	0.848	−0.068	−0.779	
Hydraul. cond.	−0.547	−0.298	−0.086	−0.564	0.121	−0.657	−0.664	0.037	0.653	−0.195	0.195	0.132	0.023	0.110

equation was total cations ($mmol_c$ L^{-1}) = EC_e × 13.9. However, in soil samples collected from the Chinese Songnen basin (Wang et al. 2009), the equation was total cations ($mmol_c$ L^{-1}) = EC_e × 10. This equation was identical to the US Salinity Lab Staff (1954).

Differences in the equations were attributed to differences in ions contained in the soil solution. For example, Songnen basin soils on average contained 3.87 $mmol_c$ L^{-1} of Mg^{+2} and 5.22 $mmol_c$ L^{-1} of Ca^{+2}, whereas in soils from the Redfield and Pierpont, South Dakota, sites (Owen 2015; Birru et al. 2019) on average contained 32.8 $mmol_c$ L^{-1} of Mg^{+2} and 15.5 $mmol_c$ L^{-1} of Ca^{+2}. These differences are important because ion composition also effects the soil structural stability (US Salinity Laboratory 1954), hydraulic conductivity, and slaking (Vyshpolsky et al. 2008; McNeal et al. 1968; Dontsova and Norton 2001). Replacing Ca^{+2} or Mg^{+2} with Na^+ can also affect clay dispersion and hydraulic conductivity. Frenkel et al. (1978) showed that bulk density, clay type and amount, EC, and exchangeable Na^+ concentrations interacted to affect dispersion, soil pore plugging, and hydraulic conductivity. Their analysis showed that kaolinitic soils were less sensitive to Na^+-induced dispersion than soils containing montmorillonite or vermiculite clays. He et al. (2013) had similar results and showed that soils containing high concentrations of smectites have a higher dispersion risk than soils with high illite concentrations. Based on these findings, salinity and sodicity remediation recommendations should consider clay mineralogy and composition. However, recommendations such as those reported by Cihacek et al. (2020), Franzen et al. (2019), and Carlson et al. (2013, 2016) do not consider these factors.

The interpretation of $EC_{1:1}$ and %Na^+ data relative to hydraulic conductivity is further complicated by complex relationships among climate, soil, and management. For example, the relationship between Na^+, $EC_{1:1}$, and hydraulic conductivity (figure 1) suggests that the tipping point between soils that maintain water flows and those that do not is the Na^+ (mg Na^+ kg^{-1}) to $EC_{1:1}$ (dS m^{-1}). In this example, the tipping point appeared to occur at a Na to $EC_{1:1}$ ratio of 600. He et al. (2013) had similar results and reported that small decreases in the soil EC can transform a flocculated clay into a dispersed clay. This transformation is attributed to Na^+ expanding and EC shrinking the diffuse double layer. In a second example, increases in the SAR, when combined with a decrease in the soil EC, can increase the amount of water held at field capacity. This increase has the potential to swell soil clays and clog soil pores (He et al. 2015).

Temporal Changes in Electrical Conductivity, Sodium, and Sodium/Electrical Conductivity Ratio. In the shoulder, $EC_{1:1}$ decreased or remained the same from 2018 to 2019 at all soil depths. However, Na^+ concentrations increased in the 105 to 112.5 cm zone (table 3). These results suggest Na^+ was either transported with percolating water from the surface to the subsurface or was transported up from zones below 112.5 cm. In the shoulder, Na^+ to $EC_{1:1}$ ratio increased from 2018 to 2019 in four out of the five soil depths. A decrease in $EC_{1:1}$ when combined with an increase in Na^+ can increase the risk of dispersion and simultaneously increase the water content at field capacity (He et al. 2013, 2015). For example, in the 105 to 112.5 cm soil zone, the Na^+ (mg Na^+ kg^{-1}) to $EC_{1:1}$ (dS m^{-1}) ratio was 493 ± 31 in 2018 and 998 ± 119 in 2019. In this example, the increase in the Na^+ to $EC_{1:1}$ ratio from 2018 to 2019 may have increased the risk of clay dispersion and drainage failure.

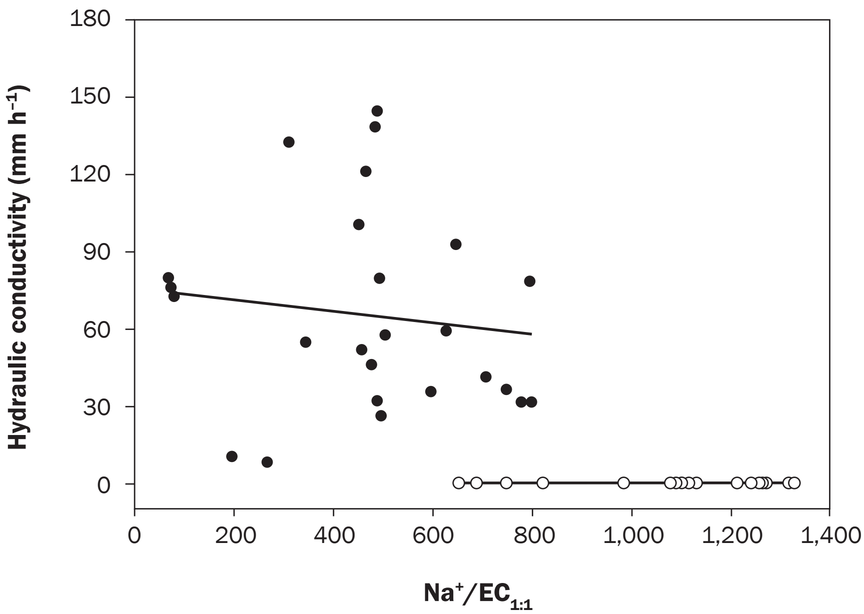
At the five soil depths in the backslope, $EC_{1:1}$ either decreased or remained the same in 2018 and 2019. Sodium decreased or remained the same at soil depths <57.5 cm and increased at soil depths >82.5 cm. Static or decreasing $EC_{1:1}$ when combined with an increasing Na^+ concentration resulted in an increase in the ratio between Na^+ (mg Na^+ kg^{-1}) and $EC_{1:1}$ (dS m^{-1}) in the 82.5 to 90 cm depth from 494 ± 15 in 2018 to 834 ± 49 in 2019. Again, this ratio was greater than the potential tipping point of 600.

In the toeslope, Na^+ either increased or were similar in 2018 and 2019 at all soil depths. Similar $EC_{1:1}$ when combined with higher Na^+ concentrations resulted in some

Journal of Soil and Water Conservation 77(4):418-425 www.swcs.org

Figure 1

Relationship between hydraulic conductivity (top) and sand and hydraulic conductivity and the sodium (Na^+)/electrical conductivity ($EC_{1:1}$) ratio (bottom) in samples collected from three landscape positions and five soil depths in 2018.



situations where the Na^+ to $EC_{1:1}$ ratio increased. For example, for the 105 to 112.5 cm soil depth the Na^+ (mg Na^+ kg^{-1}) to $EC_{1:1}$ (dS m^{-1}) ratio was 1,205 ± 135 in 2018 and 1,899 ± 317 in 2019.

Across the three landscape positions, the high spring rainfall influenced the $EC_{1:1}$ and the Na^+ concentration. Decreases in $EC_{1:1}$ when combined with increases in Na^+ can reduce the structural stability of the soil. Under these conditions, flocculated clay can be transformed into dispersed clays, which in turn can clog soil pores. When this occurs, hydraulic conductivities can rapidly decrease. Prior research suggests that small changes in EC can trigger this change (Frenkel et al. 1978; He et al. 2015). However, growing plants can help reduce this risk (Fiedler et al. 2022). At a nearby site that also experienced the high 2019 spring rainfall, Fiedler et al. (2022) reported on changes in the soil chemical properties during and after the 2019 rainfall. This related work showed that high spring rainfall reduced $EC_{1:1}$ (–0.83 ± 0.149 dS m^{-1}) and Na^+ (–656 ± 220) concentration in the surface soil in productive, transition, and saline/sodic soils. Additionally, Fiedler et al. (2022) also showed that plants accelerated these decreases.

Summary and Conclusions

This study investigated the effects of increasing rainfall on temporal changes in salinity and sodicity across a landscape. The soils in the shoulder area were well drained, whereas in the toeslope, the soils were poorly drained. Even though soils in two of the three landscape positions were not expected to have Na^+ enriched subsoil, all three soils contained had %Na^+ > 10 ($cmol_c$ Na^+ kg^{-1}) ($cmol_c$ kg^{-1}). Similar findings were observed by Birru et al. (2019) where salinity and sodicity problems were observed in the Harmony (fine, smectitic, frigid, Pachic Argiudolls) and Houdek (fine-loamy, mixed, superactive, mesic Typic Argiustolls) series. These findings suggest that the salinity and sodicity risks are expanding, and that while providing useful information, Web Soil Survey should not be the only information source considered when identifying salt effected soils.

A comparison between hydraulic conductivity and the ratio between Na^+ (mg Na^+ kg^{-1}) and $EC_{1:1}$ (dS m^{-1}) suggests that the tipping point between soils that conduct water and those with near zero hydraulic conductivity is approximately 600. These results are attributed to high Na^+ causing soil dispersion followed by the clogging of the soil pores, and/or increased swelling of the soil clays that reduces drainable porosity. Analysis of soil samples collected prior and following a large rainfall (76 cm) in 2019 showed that high rainfall may contribute to increasing the subsoil structure dispersion risk. If dispersion occurs, the tile-drainage system can fail.

From 2018 to 2019, the Na^+ (mg Na^+ kg^{-1}) to $EC_{1:1}$ (dS m^{-1}) increased above 600 in the 105 to 112.5 cm depth in the shoulder zone and the 82.5 to 90 cm depth in the backslope soil. Cihacek et al. (2020) summarized this problem and stated that "Once soils disperse due to subsurface drainage, attempting to remediate the soils to near their original internal drainage condition is extremely difficult and costly." For example, Sharma et al. (1974) conducted a long-term study in Illinois and reported that mixing a high amount of gypsum into the surface 90 cm when combined with tile drainage may increase annual crop yields in 13 to 15 years. The findings from Sharma et al. (1974) suggest that remediation is very slow and can require multiple decades. However, the use of gypsum in the NGP may not be effective because many of these soils may already contain gypsum (Birru et al. 2019).

Fiedler et al. (2022) evaluated an approach that did not rely on drainage or chemical amendments. In Fiedler et al. (2022), perennial grasses were dormant seeded in 2018 and 2019 into productive, transition, and saline/sodic soils. Across the three years of the study, perennial plants had similar or higher biomass production than corn, and soil health gradually improved. Given that saline/sodic soils are often found in riparian zones, restoring the productivity of these soils have the added benefits of reducing erosion and N_2O emissions (Fiedler et al. 2021). Fiedler et al. (2022) also showed that salinity and sodicity risks may increase during a drying cycle, with ions being re-transported to the surface soil with capillary water.

Changes in rainfall and temperatures are changing how we manage our soil resources worldwide (Almazroui et al. 2021). In the past, the conventional treatment for saline soils was tile drainage followed by leaching of the salts contained in the soil with water with a low EC. In saline/sodic soils, the soil would also be treated with gypsum. These treatments assume that outlets are available, that extra water exists for leaching salts out of the soil, and that the water and gypsum treatments are effective. Because these assumptions may not be valid, we need to rethink our solutions (Birru et al. 2019). This paper addresses

Table 3
The temporal changes (2019 to 2018) in the electrical conductivity ($EC_{1:1}$), ammonium acetate extractable sodium (Na^+), and the Na^+ to $EC_{1:1}$ ratio measured in five soil depths and three landscape positions. The 95% confidence interval (CI) for each soil depth and landscape position value are provided. A negative value indicates a decrease from 2018 to 2019.

		$EC_{1:1}$		Na^+		$Na^+/EC_{1:1}$	
Landscape	Soil depth	2019 to 2018	CI	2019 to 2018	CI	2019 to 2018	CI
Shoulder	0 to 7.5	−0.066	0.056	6.39	6.08	30.2	14.8
Shoulder	50 to 57.5	−0.839	0.900	−1,224	445	−302.2	40.22
Shoulder	82.5 to 90	−1.176	0.172	−40.96	289	324.8	142.6
Shoulder	92.5 to 100	−1.31	0.613	−353.8	938	349.2	288.7
Shoulder	105 to 112.5	−0.936	0.254	688.0	283	504.9	135
Backslope	0 to 7.5	−0.871	0.725	−182.6	213.3	−23.8	44.1
Backslope	50 to 57.5	−2.667	0.667	−2,582	650	−340.4	74.2
Backslope	82.5 to 90	−0.760	0.631	782.9	611	339.9	48.4
Backslope	92.5 to 100	−0.230	1.141	733.2	1,145	214.2	107.8
Backslope	105 to 112.5	0.841	1.401	2,354	841.7	495.7	112.2
Toeslope	0 to 7.5	2.981	2.461	3,655	3,671	548.3	184.1
Toeslope	50 to 57.5	−0.266	1.61	1,507	2,183	511.2	272.8
toeslope	82.5 to 90	0.174	0.423	1,862	278	542.1	135.9
Toeslope	92.5 to 100	0.011	0.722	2,691	508	881.8	233.9
Toeslope	105 to 112.5	−0.393	0.353	1,531	881	693.6	182.7

the management in dryland areas where climate change or management practices have elevated the water table resulting in the capillary movement of salts including Na^+ to the soil surface. Similar problems occur in many places including Canada, India, northwest Europe, China, and Australia (Steedevi and Reddy 2021; Craats et al. 2020; Wang et al. 2009). The growing salinity and sodicity problems in these areas lowers productivity and soil health and can increase greenhouse gas emissions (Fiedler et al. 2021). Findings between these and other studies suggest that remediation strategies are very complicated, and a common solution across locations is not available. The implication of this research is that improving the productivity of relatively shallow soils over marine sediments requires careful planning.

In conclusion, during a wet cycle, salts including Na^+ can be flushed from surface soils to subsurface soils. In the subsoil, these ions can increase the Na^+ to $EC_{1:1}$ ratio and reduce soil hydraulic conductivity. During a dry cycle, a related project on a similar soil showed that subsurface salts including Na^+ are transported to the surface soil through capillary movement. Our findings show that dryland systems are very different than irrigated systems, and that climate change when combined with mismanagement can reduce long-term productivity and water and air quality (Birru et al. 2019; Fiedler et al. 2022).

References

Almazroui, M., N.M. Islam, F. Saeed, S. Saeed, M. Ismail, M.A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martinez-Castro, T. Cavazos, R. Cerezo-Mota, M.K. Tippett, W.J. Gutowski Jr., E.J. Alfaro, H.G. Hidalgo, A. Vichot-Llano, J.D. Campbell, S. Kamil, I.U. Rashid, M.B. Sylla, T. Stephanson, M. Taylor, and M. Barlow. 2021. Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. Earth Systems and Environment 5:1-24. https://doi.org/10.1007/s41748-021-00199-5.

Birru, G.A., D.E. Clay, T.M. DeSutter, C.L. Reese, A.C. Kennedy, S.A. Clay, S.A. Bruggeman, R.K. Owen, and D.D. Malo. 2019. Chemical amendment of dryland saline-sodic soils did not enhance productivity and soil health in fields without effective drainage. Agronomy Journal 111:496-508.

Cabalar, A.F., and N. Akbulut. 2016. Evaluation of actual and estimated hydraulic conductivities of sands with different gradation and shape. SpringerPlus 5:820. doi:10.1186/s40064-016-2472-2.

Carlson, C.G., D.E. Clay, K. Reitsma, and R. Gelderman. 2013. Soybeans, salinity, and sodicity. Chapter 48. *In* iGrow Soybean: Best Management Practices, ed. D.E. Clay, C.G. Carlson, S.A. Clay, L. Wagner, D. Deneke, and C. Hay. Brookings, SD: South Dakota State University.

Carlson, C.G., D.E. Clay, D. Malo, J. Chang, C. Reese, R. Owen, T. Kharel, and G. Birru. 2016. Saline (salts) and sodium problems and their management in dryland corn production. *In* iGROW Corn: Best Management Practices, ed. D.E. Clay, C.G. Carlson, S.A. Clay, and E. Byamukama. Brookings, SD: South Dakota State University.

Chang, C., T.G. Sommerfeldt, J.M. Carefoot, and G.B. Schaalje. 1983. Relationships of electrical onductivity with total dissolved salts and cation concentration of sulfate-dominant soil extracts. Canadian Journal of Soil Sciemce 63:79-86. doi:10.4141/cjss83-008.

Cihacek, L.J., N. Kalwar, and T. Scherer. 2020. Evaluation of soils for suitability for tile drainage performance. Fargo ND: North Dakota State University SF1617.

DeSutter, T., D. Franzen, Y. He, A. Wick, J. Lee, B. Deutsch, and D.E. Clay. 2015. Relating sodium percentage to sodium adsorption ratio and its utility in the northern Great Plains. Soil Science Society of America Journal 79:1261-1264. doi:10.2136/sssaj2015.01.0010n.

Dontsova, K., and L.D. Norton. 2001. Effect of exchangeable Ca:Mg ratio on soil clay flocculation, infiltration, and erosion. Presented at Sustaining the Global Farm, 10th International Conservation Organization Meeting, West Lafayette, IN, May 24-29, 1999.

Dungan, R.S., B.D. Lee, P. Shouse, and J.D. Koff. 2007. Saturated hydraulic conductivities of soils bended with waste foundry sand. Soil Science 172:10.1097/SS.0b013e31812f4f72.

Garcia-Gutierrez, C., Y. Pachepsky, and M.A. Martin. 2018. Technical note: Saturated conductivities and textural heterogeneity of soil. Hydrology and Earth System Sciences 22:3923-3932.

Fiedler, D., S.A. Clay, S. Westhoff, C.L. Reese, S.A. Bruggeman, J. Moriles-Miller, L. Perkins, D.R. Joshi, S.-Y. Marzano, and D.E. Clay. 2022. Phytoremediation and rainfall combine to improve soil and plant health in a North America Northern Great Plains saline sodic soil. Journal of Soil and Water Conservation 77(4):381-388. https://doi.org/10.2489/jswc.2022.00112.

Fiedler, D.J., D.E. Clay, D.R. Joshi, A. Engel, S.Y Marzano, D. Jakubowski, D. Bhattarai, C.L. Reese, S.A. Bruggeman, and S.A. Clay. 2021. CO_2, and N_2O emissions and microbial community structure from fields that include salt-effected soils. Journal of Environmental Quality 50:567-579. DOI:10.1002/jeq2.20223.

Franzen, D., N. Kalwar, A. Wick, and T. DeSutter. 2019. Sodicity and remediation of sodic soils in North Dakota. North Dakota State University Extension Publication F1941. Fargo, ND: North Dakota State University Extension.

Frenkel, H., J.O. Goertzen, and J.D. Rhoades. 1978. Effect of clay type and content, exchangeable sodium percentage, electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Science Society of America 42:32-39.

Gee, G.W., and J.W. Bauder. 1986. Particle size analysis. *In* Methods of Soil Analysis Part 1. Physical and Mineralogical Methods, 2nd edition, ed. A. Klute, 383-411. Agronomy Monograph #9. Madison, WI: American Society of Agronomy.

George, P.R. 1978. The dryland salinity problem in North America. Journal of the Department of Agriculture, Western Australia 19:115–116.

He, Y., T.M. DeSutter, and D.E. Clay. 2013. Dispersion of pure clay minerals as influenced by calcium/magnesium ratios, sodium adsorption ratios, and electrical conductivity. Soil Science Society of America Journal 77:2014–2019. doi:10.2136/sssaj2013.05.0206n.

He, Y., T. DeSutter, F. Casey, D.E. Clay, D. Franzen, and D. Steele. 2015. Field capacity water as influence by Na and CE: Implications for subsurface drainage. Geoderma 245:83-88.

Hopkins, D., K. Chambers, A. Fraase, Y. He, K. Larson, L. Malum, L. Sande, J. Schulte, E. Sebesta, D. Strong, E. Viall, and R. Utter. 2012. Evaluating salinity and sodium levels on soils before drain tile installation: A case study. Soil Horizons 53:24-29.

Hundal, S.S., G.O. Schwab, and G.S. Taylor. 1976. Drainage system effects on physical properties of a lake-bed clay soil. Soil Science Society of America Journal 40:300-305.

Kharel, T.P., D.E. Clay, C. Reese, T. DeSutter, D.D. Malo, and S.A. Clay. 2018. Do precision chemical amendments applications impact sodium movement in dryland semi-arid saline-sodic soils? Agronomy Journal 110:1103-1110. doi:10.2134/agronj2017.07.0416.

Levy, G.J., D. Golstein, and A.I. Mamedov. 2005. Saturated hydraulic conductivity of semiarid soils: Combined effects of salinity, sodicity, and rate of wetting. Soil Science Society of America Journal 69:653-662.

Mahmuduzzsaman, Md., Z.U. Ahmed, A.K.M. Nuruzzaman, and F.R.S. Ahmed. 2014. Causes for salinity intrusion in coastal belt of Bangladesh. International Journal of Plant Research 4:8-13.

McNeal, B.L., D.A. Layfield, W.A. Norvell, W.A., and J.D. Rhodes. 1968. Factors influencing hydraulic conductivity of soils in the presence of mixed-salt solution. Soil Science Society of America Proceedings 32:187-190.

Melillo, J.M., T.C. Richmond, and G.W. Yohe. 2014. Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment. Washington, DC: US Global Change Research Program.

Owen, R.K. 2015. Spatial Variability of Saline and Sodic soils in the Black Glaciated Region of the Northern Great Plains. Master's thesis, South Dakota State University.

Reynolds, W.D., and D.E. Elrick. 1990. Ponded infiltration from a single ring. I. Analysis of steady flow. Soil Science Society of America Journal 54:1233-1241.

Richards, L.A. 1965. Physical condition of water in soil. *In* Method of Soil Analysis Part 1, ed. C.A. Black, 128-151. Agronomy Monograph #9. Madison, WI: American Society of Agronomy.

Ruark, M.D., J.C. Panuska, E.T. Cooley, and J. Pagel. 2009. Tile drainage in Wisconsin: Understanding and locating tile drainage systems. Madison WI: University of Wisconsin Extension GWQ054.

Scherer, T., G. Sand, H. Kandel, and C. Hay. 2015. Frequently asked questions about subsurface (tile) drainage. North Dakota State University Extension Publication AE1690. Fargo, ND: North Dakota State University Extension.

Sharma, A.K., J.B. Fehrenbacher, and B.A. Jones Jr. 1974. Effect of gypsum, soil disturbance and tile spacing on the amelioration of Huey silt loam, a natric soil in Illinois. Soil Science Society of America Proceedings 46:113-117.

Soil Survey Staff. 2018. Web Soil Survey. Washington, DC: USDA Natural Resources Conservation Service. http://websoilsurvey.Sc.egov.usda.gov/.

Steedevi, P.D., and D.V. Redduy. 2021. Influence of hydrological and hydrogeological factors on inland groundwater in a hard rock aquifer, south India. Journal of Earth System Science 130:215. https://doi.org/10.1007/s12040-021-01715-x.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. *In* Agricultural Handbook 60, ed. L. Richards. Riverside, CA: USDA.

van de Craats, D., S.E.A.T.M. van der Zee, C.S. Piet, A. vzn Asten, and P. Cornelissen. 2020. Soil sodicity originating from marginal groundwater. Vadone Zone Journal 19(1):e20010. https://doi.org/10.1002/vzj2.20010.

Vyshpolsky, F., M. Qadir, A. Karimov, K. Mukhamedjanov, U. Bekbaev, R. Paroda, A. Aw-Hassan, and F. Karajeh. 2008. Enhancing the productivity of high-magnesium soil and water resources in Central Asia through the application of phosphogypsum. Land Degradation Development 19:45-56. https://doi.org/10.1002/ldr.814.

Wang, L., K. Seki, T. Miyazaki, and Y. Ishihama. 2009. The causes of soil alkalinization in the Songnen Plain of Northeast China. Paddy and Water Environment 7:259–270.

Warncke, D., and J.R. Brown. 2015. Potassium and other basic cations. *In* Recommended Chemical Soil Test Procedures for the North Central Region. NCR Publication No.221 (Revised). Columbia, MO: Missouri Agricultural Experiment Station.

Weber, J.B., L.R. Swain, H.J. Strek, and J.L. Sartori. 1986. Herbicide mobility in soil leaching columns. *In* Research Methods in Weed Science, 3rd edition, ed N.D. Camper, 189-200. Champaign, IL: Southern Weed Science Society.