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Chemical Amendments of Dryland Saline–Sodic Soils Did Not Enhance Productivity and Soil Health in Fields without Effective Drainage

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ABSTRACT

A common restoration treatment for saline–sodic soils involves improving soil drainage, applying soil amendments (e.g., $CaSO_4$, $CaCl_2$, or elemental S), and leaching with water that has a relatively low electrical conductivity. However, due to high subsoil bulk densities and low drainable porosities, these treatments many not be effective in glaciated dryland systems. A 3-yr field study conducted in three model systems determined the impact of chemical amendments (none, $CaCl_2$, $CaSO_4$, and elemental S) on plant growth, microbial composition, temporal changes in electrical conductivity (EC_e), and the relative sodium content (%Na). Chemical amendments (i) either reduced or did not increase maize (*Zea mays*), soybean (*Glycine max*), and sorghum (*Sorghum bicolor*) yields; (ii) did not increase water infiltration or microbial biomass as determined using the phospholipid-derived fatty acid (PLFA) technique; and (iii) did not reduce EC_e or %Na. These results were attributed to high bulk densities and low drainable porosities that reducing the drainage effectiveness in the model backslope and footslope soils, the presence of subsurface marine sediments that provided a source for sodium and other salts that could be transported through capillary action to the surface soil, high sulfate and gypsum contents in the surface soil, and relatively low microbial biomass values. The results suggests that an alternative multistep saline sodic soil restoration approach that involves increasing exchangeable Ca^{+2} through enhanced microbial and root respiration and increasing transpiration and soil drainage by seeding full season deep rooted perennial vegetation should be tested.

Core Ideas

- The amount of land impacted by salinity or sodicity is increasing worldwide.
- Precision conservation can be used to target corrective treatments to problem areas.
- Chemical amendments did not enhance soil health or plant productivity in northern Great Plains soils that did not have effective drainage systems.
- The application of chemical amendments as preventative treatment in tile drained North America northern Great Plains fields did not improve soil health (water infiltration and microbial diversity) and either reduced or did not increase crop yields.
- These results were partially attributed to high subsoil bulk densities and low drainable porosities.

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A GROWING WORLDWIDE agricultural salinity and sodicity problem can be attributed to many factors including rising sea and groundwater levels, seeps, and irrigating with water containing high concentrations of soluble salts (Shrivastava and Kumar, 2015). Each world region, has unique problems that may require the adoption of precision conservation techniques. In precision conservation, corrective treatments are targeted to problem areas. In South Dakota, which is within North American northern Great Plains (NGP), increasing precipitation when combined with changes in vegetation from perennial grasses to annual crops have raised water tables, created ponds, and converted dry basins to wetlands (Melillo et al., 2014; Schrag, 2011; Reistma et al., 2015). In addition, higher temperatures, along with raising water tables, are facilitating the capillary movement of water and associated salts from shallow aquifers to the surface soil. The net result is an increasing salinity and sodicity problem (Cannon and Wentz, 2000; Solomon et al., 2007; Kharel, 2016; USEPA, 2016; USGS, 2018)

In precision conservation, the first step in preventing or minimizing the expansion of saline and sodic problem areas is to identify areas at risk. However, complications arise because a wide range of approach are used to chemically analyze and interpret soil laboratory results. The US Salinity Laboratory Staff (1954) chemically analyzed saturated paste extracts to determine the soil solution electrical conductivity (EC) and the relative amount of sodium in the soil. Salinity and sodicity characterization was based on the EC of the saturate paste extract (EC_e) and the sodium adsorption ratio (SAR) (calculated from the $mmol_c$ of Na, Ca, and Mg in the saturate paste extract) values. However, because the saturation paste methods was expensive, many commercial laboratories determine EC using a predetermined amount of soil or water. In the NGP, as opposed to determining EC_e many laboratories use a 1:1 solution to

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Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; $EC_{1:1}$, EC 1:1 solution to soil ratio; EC_e, EC of the saturate paste extract; ESP, exchangeable sodium percent; ESR, exchangeable sodium ratio; %NA, relative sodium content; NGR, northern Great Plains; PLFA, phospholipid-derived fatty acid; SAR, sodium adsorption ratio.

soil ratio ($EC_{1:1}$), which is approximately double the EC_e value (Matthees et al., 2017).

A second complication is that the technique to assess sodium risks varies from region to region. Some regions use %Na, whereas others use SAR, exchangeable sodium percentage (ESP), or the exchangeable sodium ratio (ESR). The SAR value is calculated from the Na, Mg^{+2}, and Ca^{+2} in the saturated paste; and the %Na is 100× the $cmol_c$ of sodium divided by the sum of the $cmol_c$ of K, Mg^{+2}, Ca^{+2}, and Na extracted by ammonium acetate. The denominator in this calculation is often referred to as the effective cation exchange capacity.

To compare results from studies using different short cuts or analysis approaches (Robbins, 1993; Rashidi and Seilsepour, 2011; Elbashier et al., 2016), a clear understanding of the methods and associated units are needed. The SAR is calculated with the equation, $SAR = \frac{Na^{+}}{\sqrt{\frac{(Ca+Mg)}{2}}}$, where the units for Na^+, Ca^+, and Mg are $mmol_c\ L^{-1}$, and the ESP value is defined as $ESP = 100 \times cmol_c\ Na \times CEC^{-1}$. Confusion about saline/sodic soils classification is complicated further by the use of the term ESR. The relationship among these terms (ESR, ESP, CEC, SAR, and %Na) are soil specific and have been defined by Harron et al. (1983) with the following equation:

$$ESP = \left[100 \times \frac{[0.0076 + 0.0058 \times SAR]}{[1 + (0.0076 + 0.0058 \times SAR)]}\right].$$

$$ESR = -0.0126 + 0.01475 \times SAR$$

$$ESR = \frac{ExNa}{CEC - ExNa}$$

where *ExNa* is the amount of sodium on the exchange sites. For soils in the NGP, the relationship between many of these terms have been determined. For example, DeSutter et al. (2015) reported that $SAR = 1.04 \times \%Na - 0.35$ ($r^2 = 0.92^{**}$), whereas Matthees et al. (2017) reported that in South Dakota the relationship between EC_e and $EC_{1:1}$ was $EC_e = 1.14 + 1.91 \times EC_{1:1}$ ($r^2 = 0.82^{**}$).

The final complication is inconsistency in the interpretation of values, obtained by a myriad of methods. In the United States, soils with SAR values greater than 13 are characterized as sodic and soils with EC_e values greater than 4 dS m^{-1} are characterized as saline. However, other areas of the world use different values (Sumner et al., 1998; Rengasamy, 2006; Isbell, 2016). In South Dakota, soils with a %Na value of 4 are at the tipping point of sustainability (Carlson et al., 2016).

The chemical restoration process in saline/sodic soils is based on the exchange of Ca^{2+} for Na^+, the use of chemical amendments to maintain the soil EC above the dispersion threshold, followed by the subsequent downward transport of Na^+ with percolating water (Carlson et al., 2013, 2016). The soil amendments recommended include gypsum, $CaCl_2$, and elemental S. Unfortunately, gypsum may not be effective in soils already containing high concentrations of gypsum or sulfate, which is often the case in NGP soils. The application of $CaCl_2$ also may be problematic and result in Cl^- toxicity to some plants (Tavakkoli et al., 2010). For example, the application of 1 Mg of $CaCl_2$ ha^{-1} can increase the chloride concentration to over 300 mg kg^{-1} in the surface 15 cm, which may be harmful for many plants. An alternative approach might include the solubilization of Ca^{+2} by increasing microbial activity or root respiration.

It is surprising that few salinity and sodicity studies have been conducted in the field over multiple years, used undisturbed soil columns, investigated chemical management other than gypsum, or determined the impact of a single or a combination of treatments on crops. A problem in the NGP is that tile-drainage can be ineffective due to high soil bulk densities and that many soils have very low drainable porosities (saturation point-field capacity). A second problem is that salinity and sodicity problem are generally localized in low elevation areas with irregular shapes (Fig. 1) and often do not have a natural water outlet.

Many current saline/sodic restoration practices are based on findings from columns repacked with dried soil that were milled to pass through a 2-mm sieve (Jury et al., 1979; Chi et al., 2012; Elmajdoub and Marschner, 2015; He et al., 2013, 2015). For example, Jury et al. (1979) assessed changes in ESP as water percolated through large columns (122 cm diam. × 150 cm deep) filled with disturbed surface soil. McIntyre (1979) used air-dried ground soil packed into soil columns. They reported that there was a relationship between hydraulic conductivity and ESP. Gharaibeh et al. (2009) reported that based on data collected from packed soil columns filled with sandy clay loam soil, that the recommended restoration practices for southern Jordan soils was the application of 20 Mg gypsum ha^{-1} followed by leaching with three to four pore volumes of water. In air-dried ground Spanish soil, Amezketa et al. (2005) reported that gypsum prevented surface crusts.

While the above studies suggest that chemical amendments and leaching with water will help restore saline/sodic soil function, fundamental differences between laboratory and field conditions affect the transferability of laboratory findings to the field. For example, packed soil columns may not have equivalent bulk densities as undisturbed soil, and the water flow mechanisms may differ (Kharel et al., 2018). In addition, in soil column leaching studies, mass balance dictates that soluble anions and cations decrease as water leaves the column (Clay et al., 2004). However, in the field, water can flow in multiple directions (Ilyas et al., 1996) and if drainage is slow, soils can become saturated, thus not removing any of the dissolved salts.

Once the extent and magnitude of the salinity–sodicity problem are defined, producers have numerous questions about prevention, restoration, and costs associated with restoration (Oster et al., 1999; Carlson et al., 2013, 2016; Rahimi et al., 2000; He et al., 2013, 2015, 2018). However, in dryland systems, there is a paucity of research to answer these questions. Hence, this study examined the impact of chemical amendments (none, $CaCl_2$, $CaSO_4$, and elemental S) on plant growth, microbial composition, temporal changes in soil EC_e, and the relative sodium content (%Na) in three model landscape positions located in the North American NGP.

MATERIALS AND METHODS

Experimental Design

This experiment contained laboratory and field components. In the laboratory, Br^- was used to track water flow characteristics in undisturbed soil columns treated with chemical

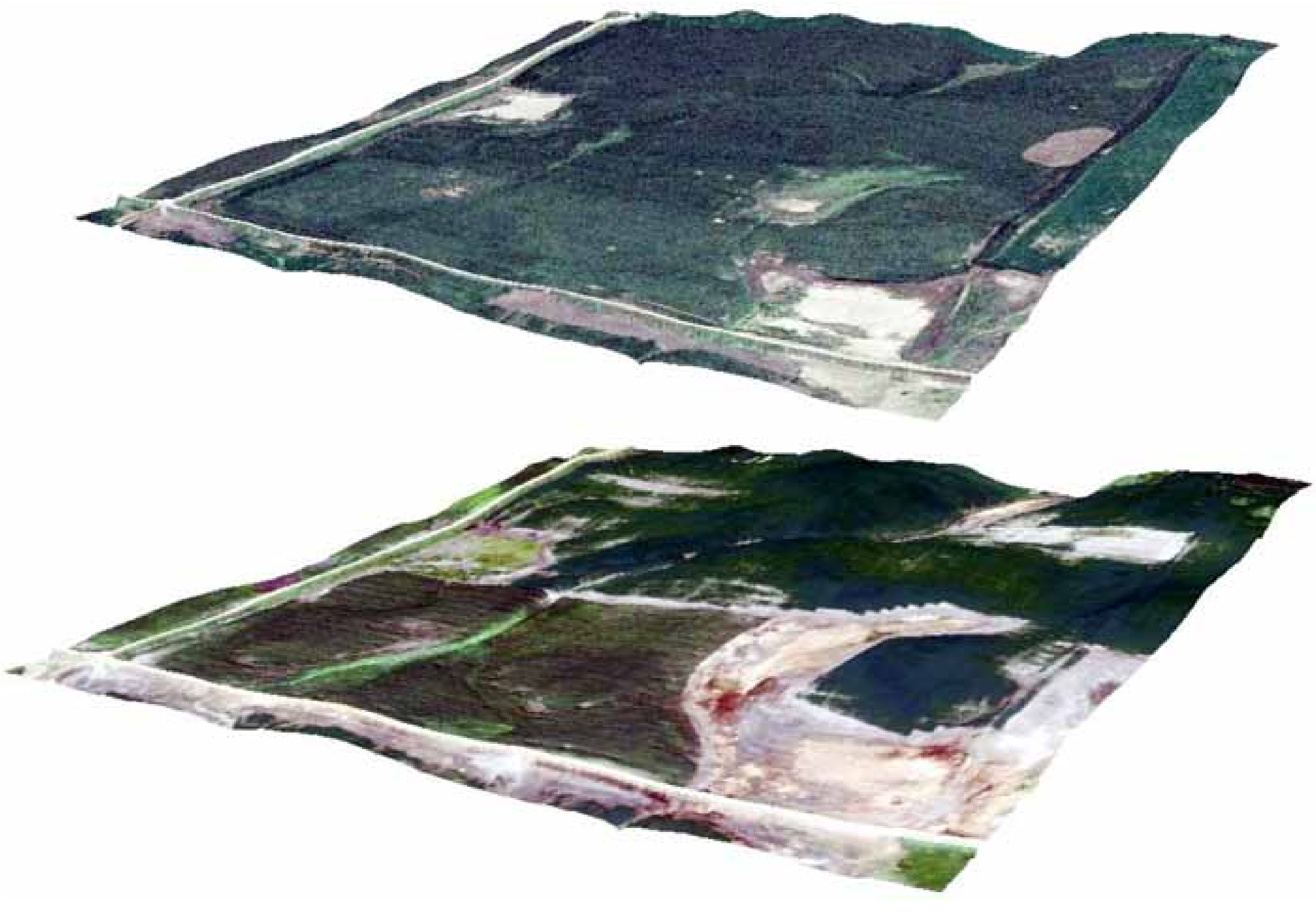

Fig. 1. Natural color aerial image (blue, green, and red) of the Pierpont research site (model toeslope position) on 8 Aug. 2004 (Top) and 13 Aug. 2010 (Bottom). The white areas in the image represent areas that have higher salt concentrations.

amendments (Clay et al., 2004; Kharel, 2016; Kharel et al., 2018). This research showed that soil EC_e decreased with profile washing. However, slower than expected EC_e decreases were attributed to bypass water flow that occurred in the undisturbed soil columns. The second study assessed the effectiveness of the chemical treatments on plant and soil health in the field. Findings from this study are reported in this paper.

The research design was a randomized complete block. The common treatment was four chemical amendments ($CaCl_2$, gypsum [$CaSO_4{\cdot}2H_2O$], elemental S, and no treatment) that were applied to three model landscape positions (model backslope, footslope, and toeslope). Of these soil amendments, $CaCl_2$ was the most water soluble and elemental sulfur requires microbial oxidation. These model landscape positions were previously utilized by Kharel et al. (2018) and they were dependent on different NGP landscape positions having different chemical and physical characteristics (Clay et al., 2001; Noorbakhsh et al., 2008). The model backslope and footslope positions had tile drainage. However, due the chemical and physical characteristics of the soil in the model toeslope position, tile drainage was not installed.

In the NPG, many fields contain areas requiring treatment and areas not requiring treatment. Spatial analysis shows that salinity and sodicity problems contain spatial structure and soils with the highest EC_e and SAR values are often found in toe slope areas (He et al., 2018). A hypothesis associated with this paper, is that a chemical amendment applied uniformly across a field can be used to manage this problem. Associated with this hypothesis is that chemical amendments that are applied to areas not requiring treatment will improve soil and plant health. At the model toeslope and footslope positions, the soil amendments were based on the sites chemical characteristics. However, because the model backslope position did not require chemical amendments, treatment were applied to determine the impact of a preventative treatment on soil health and productivity.

The varieties planted at all sites were based on discussions between the local agronomist and producer and it was in their best interest to select appropriate cultivars. Prior to conducting this research we tested 27 region-specific, publically available maize hybrids for salinity tolerance. Of the hybrids tested, none had higher salinity tolerance than the others. The lack of differences were attributed to all of the cultivars having relatively high drought tolerance, which is often linked to salinity tolerance. Similar results have been conducted in sorghum (*Sorghum bicolor* L.; Sun et al., 2014). To the best of our knowledge, the local commercially available cultivars are not marketed based on salinity tolerance.

The chemical characteristics of samples collected from the research sites are provided in Table 1 and the physical properties for the dominant soil series for the three model landscape positions are provided in Table 2. The data in Table 2 was obtained from the archived soil pedon database (USDA National Cooperative Soil Survey, 2018). Table 3 contains growing season rainfall and evapotranspiration data from the sites.

Prior to the application of the soil amendments, soil samples were collected from the surface 15 cm in the fall of 2012.

Table 1. The initial pH_e, EC_e, %Na, sulfate, total N, total C, inorganic C, and gypsum for the surface soil (0–15 cm) from the model backslope (Redfield), footslope (White Lake), and toeslope (Pierpont) positions. The chemical analysis for pH_e and EC_e were determined on a saturated paste. The %Na was the ratio between the amount of sodium and the sum of the cations (Ca, Mg, K, and Na) extracted by ammonium acetate. Total N and C were determined by combustion. The 95% CI are provided.

	Saturated paste				
Site	pH_e	EC_e	%Na	Sulfate	Total N
		dS m^{-1}		mg kg^{-1}	g kg^{-1}
Backslope	7.67 ± 0.21	4.14 ± 1.52	1.9 ± 0.70	271–400	2.3
Footslope	6.80 ± 1.19	6.79 ± 1.11	11.8 ± 2.9	320–3146	2.3
Toeslope	7.49	12.2 ± 1.22	17 ± 7.63	1181–3017	1.6

Site	Total C	Inorganic carbon	Gypsum	Avg. saturated water infiltration	Median water infiltration
	g kg^{-1}	g kg^{-1}	g kg^{-1}	mm h^{-1}	mm h^{-1}
Backslope	24.8	1.7	0.5 ± 0.48	215 ± 89	81.5
Footslope	23.5	1.7	0.2 ± 0.22	107 ± 78	57
Toeslope	18	0.3	0.5 ± 0.08	134 ± 135	0

Samples were dried, ground, and analyzed for pH_e, EC_e, Na^+, Ca^{+2}, Mg^{+2}, sulfate, total N, total C, inorganic C, and gypsum (Table 1; Page, 1982; Rhoades, 1982; Combs and Nathan, 2011). The chemical treatment rates for the foot and toe slope soils were determined following calculations discussed in Kharel et al. (2018) and Carlson et al. (2016).

In the model backslope (Redfield) position, gypsum, calcium chloride, and elemental S treatments were applied on 11 June 2013 at rates of 5.0, 4.3, and 0.92 Mg ha^{-1}, respectively. For the model footslope (White Lake) position, gypsum, calcium chloride, and elemental S treatments were applied on 20 June 2013 at rates of 5.0, 4.3, and 0.92 Mg ha^{-1}, respectively. In the toeslope (Pierpont) position, gypsum, calcium chloride, and elemental S treatments were applied in April 2014 at rates of 8.7, 7.5, and 1.6 Mg ha^{-1}, respectively. In all plots, the surface amendments were incorporated into the surface 15-cm using a rototiller.

Model Backslope Position

The soil mapping unit at Redfield was a Harmony (55%) (fine, smectitic, frigid, Pachic Argiudolls)–Aberdeen (35%) (fine, smectitic, frigid Glossic Natrudolls). Even though soils in this mapping unit were moderately well drained with little risk of flooding, tile drainage had been installed at this site (>120 cm). The distance between adjacent tile lines was approximately 15 m. This site was located in Spink County SD at 44°40'33″ N, 98°57'31″ W.

The soil structure in the Harmony and Aberdeen soils is weak medium and fine granular in the surface horizon. In the Aberdeen soil, the drainable porosity (water at field capacity subtracted from the saturation point) ranges from 0.02 to 0.136 g cm^{-3} in the B and C horizons (Table 2). Ground water depth measurements indicted that the depth to the water table decreased with time. The ground water depth at a nearby groundwater monitoring site (SD DENR 84A), showed that the depth of the water table was 1 m in 2012. The April to October rainfalls and evapotranspiration information for this site are provide in Table 3.

In 2013, maize, which is a moderately saline tolerant plant (Carlson et al., 2016) was seeded on 27 May 2013 following the application of the chemical amendments. The row spacing was 76 cm and the density was 74,000 seeds ha^{-1}. At physiological maturity (black layer), grain yield, stover yield, and surviving plants were measured. Based on these values, the yield per plant and harvest indexes were calculated by dividing the dry grain weight by the dry grain + stover weights. For maize, the N and P rates were approximately 120 kg N ha^{-1} and 50 kg P ha^{-1}.

Soybeans (maturity group 1.2) were seeded on 7 June 2014 and 5 June 2015 at a row spacing of 50 cm and a density of 370,000 seeds ha^{-1}. Fertilizer was not applied to soybeans. The selection of the soybean maturity group was consistent with Mourtzinis and Conley (2017). Soybean is classified as a moderately saline tolerant plant (Carlson et al., 2016). Soybeans were machine harvested following maturity in October, and grain subsamples were collected and analyzed for oil and protein using an Infratec 1229 Whole Grain Analyzer (Foss Tecator AB).

Model Footslope Position

The soil mapping unit at White Lake was a Houdek (fine-loamy, mixed, superactive, mesic Typic Argiustolls)-Ethan (fine-loamy, mixed, superactive, mesic Typic Calciustolls) (Soil Survey Staff, 2017). Soil horizon information for these soils are available in Table 2. This site is located in Aurora County, SD at 43°40'32″N, 98°45'50″W. For these soils, the surface soil structure is weak fine granular that is slightly hard, friable, and slightly sticky and plastic. The soil structure in the B-horizon ranges from medium prismatic to moderate medium and fine subangular blocky. Soil pedon information for the Ethan soil indicates that the bulk densities ranged from 1.52 to 1.67 g cm^{-3} (Table 2). These bulk densities were high enough to slow root penetration and water movement. Observations showed that the water table depth was relatively close to the soil surface.

In the model footslope position, the depth of the tile drainage was >120 cm and the distance between adjacent tile lines was approximately 15 m. When the experiment was initiated, sampling ports were installed on the tile drainage system. However, due to the lack of water flow, we were unable to collect water samples from the tile lines. These results were attributed to low drainable porosity (Tables 1, 2)

In 2013, sorghum (*Sorghum bicolor*) was seeded following the application of the soil amendments at 76 cm row spacing on 2 June 2013 at a density of 70,000 seeds ha^{-1}. The late planting date was the result of high soil moisture. Sorghum is a moderately saline sensitive plant (Carlson et al., 2016), and it was hand harvested following physiological maturity (black layer). On a subsample, the grain and stover dry weights were determined, and the harvest index (dry grain/dry grain + dry stover) calculated.

Table 2. Bulk density and drainable porosity from the soil horizons in model pedons from the soil series located at the study sites. The data provided were summarized from 3, 4, 3, 1, 2, and 1 pedons collected from the Harmany, Aberdeen, Houdek, Ethan, Nahon, and Exline soils, respectively.†

Backslope	Redfield	Unit	Horizon							
Harmany			A1	A2	AB	Bw	BK	C1	C2	
	Depth (cm)	cm	18	28	46	56	102	152	203	
	Bulk density	g cm^{-3}	1.27	1.32	1.56	1.54	1.48	1.33	1.34	
	WC sat point	g cm^{-3}	0.52	0.49	0.4	0.41	0.43	0.48	0.48	
	Drainable porosities	g cm^{-3}	0.18	0.19	0.12	0.13	0.13	0.14	0.15	
			Horizon							
Aberdeen			Ap	E	Btn1	Btn2	Bk1	Bk2	C1	C2
	Depth (cm)	cm	18	28	46	56	76	102	152	203
	Bulk density	g cm^{-3}	1.2	1.38	1.65	1.56	1.39	1.3	1.29	1.3
	WC sat point	g cm^{-3}	0.54	0.45	0.36	0.4	0.47	0.5	0.5	0.5
	Drainable porosities	g cm^{-3}	0.147	0.142	0.02	0.052	0.136	0.05	0.07	0.06
Footslope			Horizon							
Houdek	White Lake		Ap	AB	Bt	Bk	Bky	C		
	Depth (cm)	cm	20	36	47	63	104	152		
	Bd (g cm^{-3})	g cm^{-3}	1.25	1.3	1.4	1.4	1.5	1.6		
	WC sat point	g cm^{-3}	0.52	0.5	0.46	0.46	0.42	0.39		
	Drainable porosities	g cm^{-3}	0.24	0.26	0.21	0.16	0.12	0.13		
			Horizon							
Ethon			Ap	Bk1	Bk2	Bk3	C			
	Depth (cm)	cm	20	41	64	86	203			
	Bulk density	g cm^{-3}	1.62	1.52	1.67	1.54	1.6			
	WC sat point	g cm^{-3}	0.38	0.42	0.36	0.41	0.38			
	Drainable porosities	g cm^{-3}								
Toeslope			Horizon							
Nahon	Pierpont		Ap	E	Bt1	Bt2	Bky1	Bky2	C1	C2
	Depth (cm)	cm	15	23	35	50	63	94	142	170
	Bulk density	g cm^{-3}	1.4	1.47	1.74	1.56	1.43	1.37	1.36	1.45
	WC sat point	g cm^{-3}	0.46	0.43	0.33	0.4	0.45	0.47	0.48	0.44
	Drainable porosities	g cm^{-3}	0.148	0.176	0.037	0.13	0.16	0.18	0.1	0
			Horizon							
Exline	Horizon		Ap	E	Bt1	Bt2	Bky	C1	C2	
	Depth (cm)	cm	20	30	56	106	117	152	203	
	Bulk density	g cm^{-3}	1.18	1.21	1.74	1.69	1.38	1.26	1.32	
	WC sat point	g cm^{-3}	0.55	0.53	0.33	0.35	0.47	0.52	0.49	
	Drainable porosities	g cm^{-3}	12.4	20	0	0	0.077	0.035	0	

† Bd, bulk density; WC sat point, water content at the saturation point; A1, A2, AB, Bw, Bk, C1, C2, Ap, E, Bt1, Bt2, Bk1, Bk2 Bky1, and Bky2 are all soil horizons.

During harvest, the number of surviving plants in a 5.25 m^2 area were determined. Fertilizer was not applied to sorghum.

In 2014, the crop failed due to high soil moisture and results from 2014 are not included in this paper. In 2015, soybean was seeded on 6 June 2015 at a row spacing of 50 cm and a density of 370,000 seeds ha^{-1}. Fertilizer was not applied to soybeans. The treatments were machine harvested from a 12-m^2 area following maturity. The soybean grains were analyzed for oil and protein content using Infratec 1229 Whole Grain Analyzer (Foss Tecator AB). The April to October rainfalls and evapotranspiration information for this site are provide in Table 3,

Model Toe Slope Position

The soil mapping unit at Pierpont was a Nahon (fine, smectitic frigid Calcic Natrudolls)-Aberdeen-Exline (fine, smectitic, frigid Glossic Natrudolls and fine, smectitic, frigid Leptic Natrudolls). This site was located in Day County South Dakota at 45°30'34″N, 97°53'50″W.

These soils have slow water permeability with variable depths to the natric horizon (Table 2). The slopes ranged from 0 to 2%, and soil structure in the Ap horizon was weak fine granular, whereas the E horizon contained a weak medium platy soil structure (Soil Survey Staff. 2014). A nearby South Dakota Department Environmental Natural Resources groundwater monitoring site (DA-78H) showed that the depth to the water table decreased 3 m from 1981 to 2012. The rising water table was consistent with observations in the region (Kibria et al., 2016). Due to high soil water contents and the soils chemical characteristics, tile drainage was not installed at this site (Table 1). The B horizon soil bulk densities ranged from 1.37 to 1.74 g cm^{-3}, and high soil moisture contents routinely delays or prevents seeding.

In 2014, soybean (maturity rating 1.2) was seeded on 22 May 2014 at a row spacing of 50 cm and density of approximately of 370,000 seeds ha^{-1}. However, due to poor drainage this crop failed, and the findings from 2014 were not included in this paper. In 2015, maize, with a maturity rating of 88 d, was seeded on 8 June 2015 at a row spacing of 76 cm and a density of 76,000 plant ha^{-1}. Fertilizer was not applied to this site. Following physiological maturity (black layer), the number of plants that survived to harvest in a 5.25 m^2 area were counted, and the aboveground biomass was separated into grain and stover. Grain yields, at 15.5% moisture and harvest indexes were calculated. The April to October rainfalls and evapotranspiration information for this site are provide in Table 3.

Chemical, Physical, and Biological Soil Health Measurements

Chemical Assessment

Approximately 0 (2013), 1 (2014) and 2 (2015) years after the application of the chemical amendments, soil samples from the 0- to 15-cm soil depth were collected from the model backslope and footslope positions. In the toeslope postion, samples were collected in April 2014 (zero) and 1 yr after the chemical amendment application (April 2015). In addition, soil samples from the surface 15 cm were collected in June 2016 after the completion of the study. These samples were analyzed for %Na. Each sample consisted of 10 subsamples that were collected with a 1.9 cm diameter soil probe. Soil samples were dried at 40°C, ground, sieved (<2 mm), stored in plastic bags, and analyzed for pH$_e$, EC$_e$, and ammonium acetate extractable Ca^{2+}, Mg^{2+}, K^+, and Na^+ (Warncke and Brown, 2011). Selected samples were analyzed to determine the SAR. The strong correlation between SAR and %Na confirmed the findings of DeSutter et al. (2015) and indicated that SAR and %Na were almost identical. Inorganic C was determined in a two-step process where organic matter was removed (Combs and Nathan, 2011), followed by combustion at 1000°C to determine total remaining C. Gypsum was determined following precipitation with acetone (US Salinity Laboratory Staff, 1954), and SO_4-S was determined following Combs et al. (2001).

Physical Assessment

Saturated hydraulic conductivity was measured on 12 June 2014, 18 June 2014, and 15 Nov. 2015 in the backslope, footslope, and toeslope soils using a double ring infiltrometer. The inside ring had a 12 cm radius. The ring was driven into the soil to a depth of 4 cm and the soil was saturated with water. Approximately 24 h later, saturated hydraulic conductivity measurements were conducted for 60 min (Reynolds and Elrick, 1990). For these measurements, the water height above the soil surface was maintained at 10 cm by added water every 5 min to replenish the amount of water that infiltrated into the soil. The saturated hydraulic conductivity was the ratio between the amount water added to maintain the water height at 10 cm and the time interval.

Biological Assessment

Soil samples from the surface (15 cm for this analysis) were collected 1 yr after the chemical amendments were applied. Soil samples (0 to 15 cm) from the backslope (Redfield) and footslope (White Lake) landscape positions were collected on 12 June and 16 June 2014, respectively, whereas at the toeslope position (Pierpont) samples were collected on 9 Sept. 2015. All samples were collected adjacent to growing plants. The sampling method followed Bligh and Dyer (1959) as modified by Petersen et al. (2002). The samples were analyzed for microbial diversity using the PLFA method (Ibekwe and Kennedy, 1998; Pritchett et al., 2011, Cogger et al., 2013; Reese et al., 2014).

Data Analysis

In the backslope (Redfield) the experiment contained two replications within a block and nine blocks, respectively. In the footslope (White Lake) position, the experiment contained four blocks with three replications within a block, whereas in the toeslope position (Pierpont), the experiment contained four blocks with two replications within a block. The area of each plot was 9 × 9 m for the backslope and 9 × 6 m for the footslope and toeslope positions. During the statistical analysis, blocks were treated as random effects and chemical amendments were treated as fixed effects. In the analysis of variance, each site year was analyzed separately for multiple reasons including (i) that the landscape positions were not replicated, (ii) the chemical amendments were different at the different sites, (iii) the initial conditions were different at the different sites, (iv) the crops that were seeded were not replicated across sites, (v) the variable climatic conditions produced failed crops at some sites but not others, and (vi) treatments and experimental protocols were site specific.

Analysis of variance and the least significance difference (LSD, $p < 0.10$) were used to determine differences among the means. In the text, the term statistically significant was not specified because the statement different implies that the differences were significant. The yield losses per unit increase in EC$_e$ were determined by converting the yield values to a relative yield (observed yield/maximum yield) that ranged from 0 to 1 (Clay et al., 2017). The relative yield was the grain weight at the appropriate moisture content (15.5% maize and 13% for sorghum and soybeans) divided by the county average.

RESULTS AND DISCUSSION

Model Backslope Position

In the model backslope position, the %Na value at the beginning of the experiment was 1.9 (Table 1). In June 2016, this value had not changed and it was 2. Based on these values, chemical amendments would not be recommended. However, to assess the impact of a broadcast application of a preventative treatment, chemical amendments were applied to this tile-drained soil. In 2013, the chemical amendments did not influence maize yields or stover production (Table 4), and the measured yields were generally greater than the county average. The harvest index values ranged from 0.53 to 0.63, which were consistent with maize grown in the region (Kim et al., 2008). Even though the grain yields per hectare were not influenced by chemical amendments, the yield per plant was highest when chemical amendments were not applied.

In 2014, soybean yields in the untreated control treatment (none) were 84% of the county average, whereas the soybean yields in the $CaCl_2$ treatment were 49% of the county average, which was the lowest yield of all of the treatments. The yield decrease highlights the importance of field testing prior to implementation and suggests that broadcast application of $CaCl_2$ as a preventative treatment may produce adverse impacts on crop growth. The yield decreases in $CaCl_2$ treatment were attributed to the application of $CaCl_2$, which were calculated to increase the Cl^- concentration (>1300 mg kg^{-1}) in the surface 15 cm.

In 2015, the soybean yields were higher than those measured in 2014 and ranged from 87 to 114% of the county average. Even though the chemical treatments did not influence yield in 2015, the lowest numeric yields were observed in the $CaCl_2$ and gypsum treatments. Soybean oil contents were reduced by the $CaCl_2$ treatment. Across years, the gypsum treatment did not increase the yields relative to the untreated control soil. Others have reported different results (Caires et al., 2011; Chi et al., 2012; Rasouli et al., 2013). The lack of yield response to gypsum was attributed to high sulfate and gypsum concentrations that reduced the effectiveness of the chemical amendment. In this model landscape position, the gypsum treatment was calculated to have increased soil gypsum contents from 97 to 102 Mg ha^{-1} (Table 1).

Model Footslope Position

Based on the %Na value of 16.0 and EC_e value of 6.8 in 2013, management guidelines generally recommend drainage along with the application of an appropriate soil amendments (Carlson et al., 2016). Both treatments were imposed at this site. At this site, the initial soil EC_e was 6.8 dS m^{-1}, which theoretically should provide some protection from soil dispersion (He et al., 2013). However, this is not guaranteed because EC_e in surface soils can rapidly decrease as percolating water removes soluble cations and anions (Carlson et al., 2016).

In 2013, the yield per plant was reduced ($p < 0.1$) by $CaCl_2$ and gypsum (Table 5), and a crop was not harvested from the site in 2014 due to high soil water contents. In 2015, soybean yields ranged from 59 to 78% of the county average and the soil amendments did not influence yield, protein, or oil content. The lack of positive benefits from gypsum were expected given that the soil contained both gypsum and high sulfate concentration (ranged from 320 to 3146 mg SO_3–S kg^{-1}). In this model landscape position, the gypsum application was estimated to increase the total amount of gypsum in the surface soil from 39 to 44 Mg ha^{-1}.

Table 3. The growing season (Apr. to Oct.) rainfall, evapotranspiration (maize, Apr. to Oct.), and 25-yr annual rainfall (Jan. to Dec.) for the study sites.

Backslope	2013	2014	2015
Growing season rainfall, cm	60	46	81
25 yr annual rainfall avg, cm	60	60	60
Growing season evapotranspiration, cm		53.3	56.4
Crop	Maize	Soybean	Soybean
Footslope	**2013**	**2014**	**2015**
Growing season rainfall, cm	51	46	64
25 yr annual rainfall avg, cm	60	60	60
Growing season evapotranspiration, cm		51.6	56.4
Crop	Sorghum	Failed	Soybean
Toeslope	**2013**	**2014**	**2015**
Growing season rainfall, cm	54.5	50.3	50.8
25 yr annual rainfall avg, cm	66	66	66
Growing season evapotranspiration, cm	47.8	51.6	57.2
Crop		Failed	Maize

Table 4. Maize and soybean grain and aboveground biomass yields, harvest index, and yield per plant at the model backslope position (Redfield) as impacted by the chemical amendments in 2013, 2014, and 2015. Due to chemical analysis, the soil amendments were considered as a preventative treatment. County averages were obtained from NASS (2018). ND, not determined.

Backslope 2013	Maize yield	Stover	Total aboveground biomass	Plant ha^{-1}	Harvest index	g plant^{-1}
Surface amendment	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	×1000		
None	12.03	6.22	16.4	50.6	0.62	203
$CaCl_2$	10.43	5.30	14.1	52.6	0.63	165
Gypsum	11.18	5.85	15.2	49.8	0.62	188
Elemental sulfur	9.85	5.48	13.8	50.7	0.53	157
County avg	8.32					
p-value	0.151	0.26	0.092	0.8	0.137	0.0283
LSD (0.10)	ND	ND	1.85	ND	ND	28.9
2014	**Soybean yield**		**Seed protein**	**Seed oil**		
Surface amendment	Mg ha^{-1}		g kg^{-1}	g kg^{-1}		
None	2.39		314	184		
$CaCl_2$	1.39		290	18		
Gypsum	2.71		3.2	186		
Elemental sulfur	2.62		3	186		
County avg	2.85					
p-value	<0.01		0.24	< 0.01		
LSD (0.10)	0.447			0.222		
2015	**Soybean yield**		**Seed protein**	**Seed oil**		
Surface amendment	kg/ha		%	%		
None	2.82		347	206		
$CaCl_2$	2.44		351	202		
Gypsum	2.41		348	206		
Elemental sulfur	2.58		342	207		
County avg	2.78					
p-value	0.503		0.02	< 0.01		
LSD (0.10)			0.225	0.450		

Table 5. Sorghum and Soybean yields, harvest index, and yield per plant in the model footslope position (White Lake) as impacted by the chemical amendments in 2013, 2014, and 2015. ND, not determined.

Footslope 2013 Surface amendments	Sorghum yield	Stover	Harvest index	Harvest population	Individual plant
	Mg ha^{-1}	Mg ha^{-1}		×1000 ha^{-1}	g plant^{-1}
None	6.02	2.37	0.732	57.1	106.7
$CaCl_2$	5.10	3.71	0.575	58.1	74.7
Gypsum	5.15	1.85	0.602	62.9	76.4
Elemental sulfur	6.32	2.96	0.658	66.2	96.7
County avg	5.96				
p-value	0.54	0.55	0.019	0.66	0.097
LSD (0.10)	ND	ND	0.085	ND	24.8
2014	Crop failed				
2015 Surface amendments	Soybean yield		Seed protein	oil	
	Mg/ha		g kg^{-1}	g kg^{-1}	
None	1.56		313	210	
$CaCl_2$	1.81		330	211	
Gypsum	2.05		300	214	
Elemental sulfur	1.91		309	213	
County avg	2.63				
p-value	0.68		0.8	0.45	
LSD (0.10)	ND		ND	ND	

Model Toeslope Position

In the model toeslope position, the %Na was 17.5 and the EC_e at the initiation of the experiment was 12.2 dS m^{-1} (Table 1). Based on this analysis, a general restoration recommendation would include applying chemical amendments, installing tile drainage, and leaching with water having low concentrations of soluble salts. At this site, tile drainage was not installed and good quality water was provided by rainfall. Soils from this site were poorly drained with a median saturated hydraulic conductivity of zero.

The model toeslope position had lower yields than either the footslope or backslope soils. The failure to produce a crop in 2014 was attributed to the combined impacts of rainfall and poor drainage. In 2015, maize yields ranged from 1000 to 2400 kg ha^{-1}, which were about 80% lower than the county average (Table 6). At this site, gypsum did not increase maize yields relative to the untreated control. The lack of treatment differences were attributed to the soil containing gypsum (Table 1). Based on the initial soil gypsum concentration, the gypsum treatment increased the amount of gypsum in the surface 15-cm from 97 to106 Mg ha^{-1}.

Electrical Conductivity Impact on Maize and Soybeans Yields

A linear regression analysis between relative soybean yields in the backslope (Redfield) and footslope (White Lake) positions and EC_e ($RY = 115.8–3.98×EC_e$; $r^2 = 0.424, p < 0.01$) indicates that yields declined 4% for each dS m^{-1} increase in EC_e A regression analysis between relative maize yields in the model backslope (Redfield) and toeslope positions (Pierpont), suggests that an increase in the EC_e by 1 dS m^{-1} would reduce maize yield 11.9% ($RY = 177.9–11.9 × EC_e$; $r^2 = 0.54, p < 0.01$). This yield reduction is almost identical to Carlson et al. (2016) where maize yields were predicted to decrease 12% with each dS/m increase above an EC_e value of 1.7 dS m^{-1}.

Impacts on Soil Health

Chemical Assessment: Spatial and Temporal Changes in Electrical Conductivity of the Saturate Paste Extract and Relative Sodium Content

The chemical amendments did not influence %Na 1 yr after their application (Table 7). However, temporal changes during the study were detected. In the model backslope position, EC_e increased from 4.14 ± 1.52 dS m^{-1} in 2013 to 6.65 ± 1.13 dS m^{-1} in 2014

Table 6. Maize yields in the model toeslope position (Pierpont) in 2015 as impacted by the chemical amendments. ND, not determined.

Toeslope 2014	Crop failed					
2015 Surface amendments	Corn yield	Stover	Biomass	Plants ha^{-1}	Harvest index	Individual plant
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	×1000		g plant^{-1}
None	2.04	1.44	3.56	62.2	0.49	28.5
$CaCl_2$	2.4	1.65	3.68	57.9	0.41	38.0
Gypsum	1.3	1.22	2.31	45.4	0.31	22.0
Elemental sulfur	1.04	1.38	2.26	62.4	0.39	14.9
County avg	10.035					
p-value	0.087	0.765	0.31	0.085	0.076	0.058
LSD (0.10)	0.966	ND	ND	ND	0.116	13.9

Table 7. The EC_e and %Na from the surface soil (0–15cm) 1 yr after the chemical amendments were applied to model backslope, footstope, and toeslope soils. The backslope and footslope soils samples were collected in 2014 and the toeslope soils samples were collected in 2015.

Location	Treatment	EC_e	%Na
		dS m^{-1}	
Backslope (Redfield)	None	7.16	3.00
	$CaCl_2$	6.74	2.93
	Gypsum	5.84	3.03
	Elemental S	6.51	3.24
	Phosphorus	0.305	0.966
Footslope (White Lake)	None	12.58	12.0
	$CaCl_2$	14.58	14.4
	Gypsum	15.11	16.0
	Elemental S	12.78	13.9
	Phosphorus	0.81	0.79
Toeslope (Pierpont)	None	13.8	21.2
	$CaCl_2$		
	Gypsum	10.8	21.3
	Elemental S	11.7	22.8
	Phosphorus	0.0318	0.610
	LSD (0.10)	2.22	

(Tables 1, 7), whereas %Na remained relatively low and was 1.9 ± 0.7 in 2013, 3.26 ± 1.04 in 2015, and 2.0 ± 0.48 in June 2016.

In the model footslope (White Lake) position, EC_e increased from 6.79 ± 1.11 dS m^{-1} in 2013 to 13.8 ± 2.8 in 2014. This increase was attributed to the capillary movement of cations and anions in the groundwater to the soil surface and it occurred even though tile drainage had been installed at the site. The %Na was 11.8 ± 2.9 in 2013, 19.3 ± 1.7 in 2015, and 10.9 ± 2.42 in 2016. These findings show that EC_e and %Na in the surface 15 cm were highly variable.

In the model toeslope soil, EC_e remained relatively constant and was 12.2 ± 1.22 in 2014 and 11.9 ± 0.87 dS m^{-1} in 2015. However, the %Na remained at a relatively high level and was 17.0 ± 7.63 in 2014, 21.0 ± 1.74 in 2015, and 20.3 ± 2.46 in 2016. These findings show that at this position, EC_e and %Na were highly variable.

Physical Assessment: Soil Water Flow

The differential crop failure across landscape positions were attributed to a combination of factors including slow water flow, and high moisture contents and EC_e values. Saturated water flow was measured to assess the impact of the imposed treatments on drainage. The mean saturated hydraulic conductivities for the three model landscape positions were numerically similar and were 215 ± 89 mm h^{-1} in the backslope, 107 ± 78 mm h^{-1} in the footslope, and 134 ± 135 mm h^{-1} in the toeslope (Table 1). However, the median flow rates decreased as you moved down slope and were 81.5, 57, and 0 mm h^{-1} in the model backslope, footslope, and toeslope positions, respectively. Median water flow rates were less than the mean values because water movement in many columns was very low. For example, in the toeslope position, over 50% of measurement did not have measureable water movement.

The field saturated water hydraulic conductivity values were much higher (50×) than those reported for the undisturbed soil columns from the backslope and footslope landscape position (Kharel et al., 2018). In Kharel et al. (2018) the hydraulic conductivity rates for the first 10 cm of percolating water in the none, $CaCl_2$, gypsum, and H_2SO_4 treatments were 4.60 ± 3.15, 6.67 ± 7.06, 5.70 ± 3.10, and 5.32 ± 4.05 mm h^{-1}, respectively. Differences between the field (Table 1) and soil column study highlight the importance of plants in rebuilding the soil structure. Roots provide water channels and release CO_2 that lower pH and solubilize Ca^{+2} (Qadir et al., 2001a, 2001b).

Biological Assessment: Microbial Community

In our experiment, the PLFA analysis was used to calculate microbial biomass and the relative amount fungi and bacteris in the soil (Willers et al., 2015). At the three landscape positions, microbial biomass ranged from 145 ± 21.4 μg C (g soil)$^{-1}$ in the backslope to 278 ± 25.7 μg C (g soil)$^{-1}$ in the toesloe. In studies that used a similar analysis approach, these values were lower than those reported by Cogger et al. (2013) on a Mollisol located in Washington state (386 to 626 μg C [g soil]$^{-1}$) and an antibiotic treated Alfisol located in Missouri (247 to 354 μg C [g soil]$^{-1}$). In Mollisols located in South Dakota, unpublished data from Trail City and Andover had slightly higher microbial biomass values of 346 ± 85 and 296 ± 135 μg C (g soil)$^{-1}$, respectively (Reese et al., 2014). In subsequent unpublished research conducted in South Dakota in 2017, CO_2 respiration was 82% less in a high EC_e soil (20 dS m^{-1}) than a low EC_e soil (0.3 dS m^{-1}).

In the model landscapes positions, the soil microbial community were primary bacteria, and in the backsloe, footslope, and toeslope the bacteria to fungi ratios were 0.147 ± 0.023, 0.082 ± 0.018, and 0.177 ± 0.0285, respectively. These values are much lower than a 0.434 reported by Cogger et al. (2013) for unfertilized soil, and they suggest that a critical component of saline and sodic soil restoration, may include steps that involve rebuilding the diversity and activity of the soil microbial community.

At the different model landscape positions, the chemical amendments 1 yr after application had minimal impacts on the % bacteria or % fungi (Table 8). However, there were several notable exceptions. In the backslope position, the $CaCl_2$ and gypsum treatments reduced microbial biomass-C, and in the footslope, elemental S decreased the percent bacteria. Others have reported that chemical amendments can impact the microbial community structure (Dose et al., 2015).

Across the model landscape positions, the % mycorrhizae fungi were negatively correlated ($r = -0.245, p < 0.05$) to EC_e (Table 9). These findings could be attributed to multiple factors including (i) a negative correlation between relative yield and EC_e (maize $r = -0.73, p < 0.01$; soybean $r = -0.65, p < 0.01$), (ii) a positive correlations between EC_e and pH ($r = 0.359$, $p < 0.01$), and (iii) a positive correlation between EC_e and %Na ($r = 0.605, p < 0.01$). Others have suggested that the adverse impacts of salinity on plants can be mitigated by maintaining high organic carbon availability (Elmajdoub and Marschner, 2015).

Many of the soil biological characteristics including % bacteria, % fungal, % gram positive, % aerobic, and % mycorrhizae fungi were negatively correlated to soil pH, whereas ratio between the sum of the all saturated fatty acids and sum of mono unsaturated fatty acids was positively correlated to pH. These results suggest that soil pH had multiple impacts on the microbial composition and one possible explanation for the observed

Table 8. The impact of chemical remediation on phospholipid-derived fatty acid-derived microbial biomass, bacteria to fungi ratios, and total bacteria, total fungi, aerobic and anaerobic bacteria-C per biomass-C in the three model hillslope positions. For the three landscape positions, samples were collected in 2014.

Location	Surface amendments	Microbial biomass	Bacteria	Fungi	Bacteria/fungi
		μg C(g soil)$^{-1}$	Bact-C (MB-C)$^{-1}$	Fung-C(MB-C)$^{-1}$	
Backslope	None	162	0.133	0.0240	7.83
(Redfield)	$CaCl_2$	129	0.124	0.0246	7.71
	Gypsum	128	0.129	0.0257	6.68
	Sulfur	161	0.140	0.0386	5.51
	p	0.021	0.504	0.8340	0.52
	LSD(0.10)	43.2			
Footslope	None	187	0.162	0.0126	15.4
(White Lake)	$CaCl_2$	202	0.164	0.0229	10.1
	Gypsum	237	0.168	0.0215	13.9
	Sulfur	190	0.148	0.0249	10.9
	p	0.429	0.081	0.126	0.88
	LSD (0.10)		0.167		
Toeslope	None	278	0.133	0.0247	5.61
Pierpont	$CaCl_2$	301	0.132	0.0205	6.91
	Gypsum	234	0.141	0.0293	4.83
	Sulfur	233	0.126	0.0205	5.57
	p	0.44	0.470	0.753	0.373

results was that there was a feedback loop between root respiration, microbial respiration, pH, and exchangeable Ca. This loop could involve plant and microbial respiration releasing CO_2 into the soil atmosphere, which lowered the pH and solubilized Ca, resulting in a more favorable environment for soil microorganisms and plants. Others have reported that pH can have complex impacts on the soil microbial community structure (Kaur et al., 2005; Alexander, 1977; Högberg et al., 2006; Bååth and Anderson, 2003; Aciego Pietri and Brookes, 2008).

SUMMARY

Climate variability is decreasing the depth to the water table in many areas in the North American NGP. Shallow ground water depths when combined with increasing temperatures and subsurface marine sediments has resulted a growing salinity and sodicity problem. Within the timeframe of this experiment, installing tile drainage and treating the soil with gypsum did not produce positive responses. The standard restoration management recommendation of washing the salts out of the soil profile was not effective in this study. These results were attributed to low hydraulic conductivities, high bulk densities, and low drainable porosity. Different results would be expected in soils with different characteristics. In a relatively level irrigated field, it may be possible to pond water on the soil surface to facilitate exchange and replacement. However, in these fields, the producer collaborators did not seriously consider this option.

In the field studies, high soil bulk densities, low saturated water hydraulic conductivity, and low drainable porosities limited ability to wash the salts out of the field soil. To determine the amount of water required to the soils high salt concentrations, profile washing was conducted in the laboratory (Kharel et al., 2018). This work showed that the chemical amendments were not effective at promoting Na^+ leaching and ability to wash the salts out of the soil profile was reduced by bypass flow. The lack of effectiveness of the gypsum was attributed to the soils containing gypsum. Subsequent work suggested that the elemental S may have not been effective because these soils may have very low microbial activity.

Table 9. Correlation coefficients (*r*) between the sum of bases; %Na; pH, EC_e, and microbial biomass; % bacteria; % fungi; B/F ratio; % gram negative; % gram positive bacteria; % mycorrhizae fungi; the ratio between the saturated and monosaturated fatty acids (saturated/monosaturated ratio); and the sum of the momosaturated fatty acids as measured by phospholipid-derived fatty acid analysis in soil samples collected 1 yr after chemical application. Correlation coefficients greater 0.223 or less than –0.223 are significant at the 5% level. Correlation coefficients greater 0.291 or less than –0.291 are significant at the 1% level.

	Chemical characteristic			
Soil biology characteristic	Sum bases	%Na	EC_e	pH
Microbial biomass	–0.1257	0.5695	0.0865	0.2042
% Bacteria	–0.2153	–0.0487	–0.1843	–0.4305
% Fungi	–0.2169	–0.1246	–0.2172	–0.4549
Bacteria/Fungi	–0.1849	–0.0441	–0.2198	–0.0426
% g negative	–0.0444	0.0475	–0.0732	–0.2298
% g positive	–0.2841	–0.1458	–0.2021	–0.4081
% Aerobe	–0.2154	–0.0511	–0.1854	–0.4313
% Anaerobe	–0.0444	0.0454	–0.0744	–0.2302
% Mycorrhizae fungi	–0.2179	–0.2459	–0.2398	–0.4950
Sat fatty acid to monounsaturated fatty acid	0.0774	0.0891	0.0051	0.2734

Unfortunately, as shown in this paper, restoration can be slow and the magnitude and extent of the problem can expand with time. Where possible, findings from this study suggests that precision saline sodic management should be implemented and managers need to create long-term restoration management plans. In these soils, a restoration plan might take advantage of a hypothesized feedback loop between root respiration, microbial respiration, pH, and exchangeable Ca^{+2}.

This study demonstrates that growing crops are sensitive to EC_e and that adding some chemical amendments to saline/sodic soils may simultaneously reduce microbial biomass and slow plant growth. Across the model hillslope positions, salinity and sodicity management was confounded by spatial and temporal changes that can increase EC_e or %Na values. The use of the chemical amendments either reduced or did not increase grain yields. Without a yield increase, the application of 10 Mg ha^{-1} of gypsum at a cost of over US$100 per Mg^{-1} is cost prohibitive.

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