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Phytoremediation and high rainfall combine to improve soil and plant health in a North America Northern Great Plains saline sodic soil

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Abstract: Saline/sodic soils are often remediated by applying gypsum, improving drainage, and irrigating with high quality water. However, these management approaches may not be effective or feasible in dryland soils supersaturated with gypsum. A field study, conducted between 2017 and 2021, investigated the effect of phytoremediation on soil and plant health in a landscape containing productive, transition, and saline/sodic soils. Phytoremediation treatments–corn (*Zea mays*) and two perennial grass mixes (mix 1 slender wheatgrass [*Elymus trachycaulus*] and beardless wildrye [*Leymus triticoides*], and mix 2 slender wheatgrass, creeping meadow foxtail [*Alopecurus arundinaceus*], western wheatgrass [*Agropyron smithii*], and green wheatgrass [*Elymus Hoffmannii*])–were planted and compared with a no-plant control treatment across three soil zones. Perennial grasses were dormant seeded in the winter of 2017 and 2018, and corn was grown in 2018, 2019, and 2020. Soil samples (0 to 15 cm) were collected on July 24, 2018, July 23, 2019, July 24, 2020, and April 15, 2021. Across soil zones, corn production was 5,990 (grain + stover), 3,900 (stover only), and 6,150 (grain + stover) kg ha^{-1} in 2018, 2019, and 2020, respectively, whereas perennial grass biomass yields averaged 1,220, 9,065, and 7,375 kg ha^{-1} in 2018, 2019, and 2020, respectively. Due to high rainfall that occurred from the fall of 2018 through the summer of 2019, the depth to the water table decreased and the soil electrical conductivity ($EC_{1:1}$) (–0.83 ± 0.149 dS m^{-1}) and exchangeable sodium (Na^+) (–656 ± 220) decreased in all treatments. In addition, from 2018 to 2019, the risk of soil dispersion (lower $Na^+/EC_{1:1}$ ratio) was less in treatments with growing plants (p = 0.02) than plots without plants. With drier conditions from the fall of 2019 through the spring of 2021, the depth to groundwater increased, the $EC_{1:1}$ decreased in the transition soil but increased in the saline/sodic soil (p = 0.001), and the $Na^+/EC_{1:1}$ ratio increased in the productive and transition soils and was static or decreased in the saline/sodic soil (p = 0.001). In conclusion, this and related work showed that phytoremediation when combined with high natural rainfall reduced soil $EC_{1:1}$ and the exchangeable Na^+ in all soils; however, these benefits may be short lived, and as the water tables dropped in 2020, $EC_{1:1}$ increased in the saline/sodic zones. Laboratory and linked research from the study site also showed that fertilizing saline sodic soils can result in very high nitrous oxide (N_2O) emissions, and reseeding degraded soil to perennial plants provides soil cover that reduces the risk of erosion and provides habitat for wildlife.

Key words: electrical conductivity—erosion—soil health—sodium—Northern Great Plains

In the Northern Great Plains (NGP), increasing temperatures and spring rainfall are leading to rising water tables and the capillary transport of subsurface salts to the soil surface (George 1978; Eswaran and Zi-Tong 1991; Alberta Agriculture and Rural Development 2001; Shekhawat et al. 2006; Minhas et al. 2007; Gharaibeh et al. 2011; Schrag 2011; Hadrich 2012; Hopkins et al. 2012; Melillo et al. 2014; Carlson et al. 2015; Doyle et al. 2016; USEPA 2016; He et al. 2018; Birru et al. 2019; Eberhard et al. 2019; Fiedler et al. 2021). Salts transported to the soil surface can decrease seed germination and growth if their concentrations are high, whereas sodium (Na^+) can lead to soil dispersion. Salt risks are reported as the soil electrical conductivity (EC) and Na^+ risks are reported as the exchangeable Na^+ percentage (ESP). Sodium dispersion risks can be reduced by increasing the EC (He et al. 2013). Within a landscape, salts first appear in low elevations, and as time progresses, they move upslope (figure 1). This phenomenon is occurring on millions of hectares worldwide including in North Dakota, South Dakota, Montana, Minnesota, Canada, and Australia. In salt affected soil zones, crop yields and profits decrease as soil EC increases (Hadrich et al. 2012). For example, corn (*Zea mays* L.) is a moderately salt-sensitive plant, with grain yields starting to decrease at EC_e values > 1.7 dS m^{-1} and additional losses of 12% for each additional 1 dS m^{-1} increase in the soil EC_e (Carlson et al. 2015). In addition to low yields, these zones have very high nitrous oxide (N_2O-N) emissions, especially if nitrogen (N) is applied (Fiedler et al. 2021).

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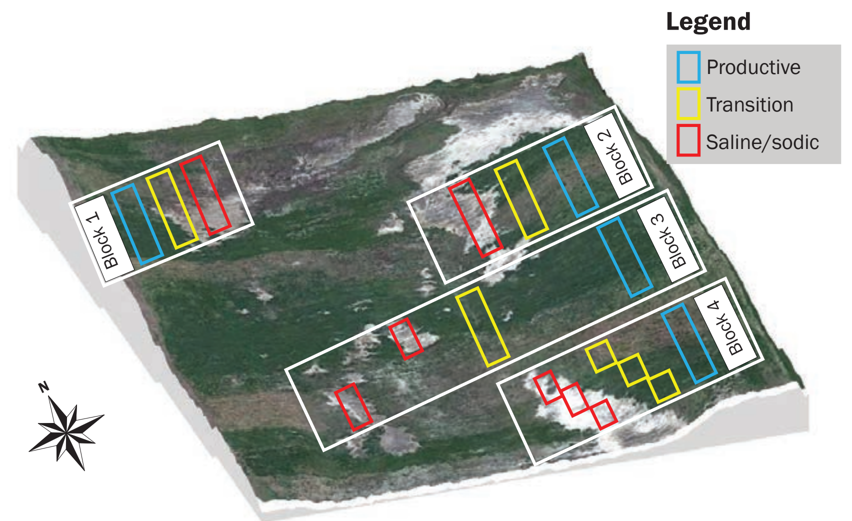
A common management approach used to restore the productivity of saline/sodic soils is to apply gypsum, improve drainage, and leach salts from the root zone with irrigation water (Franzen et al. 2006). However, in much of the NGP, this approach is unsuccessful for several reasons. First, most of the fields are not irrigated, so rainfall must be relied upon for leaching. While rainfall is increasing, it may not be enough to leach salts from the soil because the infiltration rates and drainable porosity may be very low and the source of the salts, marine sediments, may be close to the soil surface (Birru et al. 2019; Budak 2020). In addition, there are often no natural outlets for water drainage. Second, because many salt NGP affected soils already contain gypsum, adding more gypsum will not increase calcium (Ca^{+2}) concentrations. Similar problems can occur in soils that contain gypsic or petrogypic soil horizons (Boyadgiev 1974; Nachtergaele et al. 2009). The high cost and failure of the standard saline/sodic soil remediation technique has changed the question from "How much gypsum should be applied?" to "How can these fragile soils be stabilized?" (Parida and Das 2005; Grieve et al. 2012; Ammari et al. 2013; Ashraf et al. 2010; Jesus et al. 2015).

Phytoremediation has been hypothesized as a remediation method for high pH salt affected soils that contain calcium carbonate ($CaCO_3$) (Qadir and Oster 2002). Qadir and Oster (2002) hypothesized that roots exude acidic compounds and respire carbon dioxide (CO_2) that helps lower the soil pH, which in turn increases $CaCO_3$ solubility and the release of Ca^{+2} into the soil solution (Nye 1981; Marschner and Römheld 1983). The solubilized Ca^{+2} then replaces Na^+ on the exchange site, which allows Na^+ to be leached from the soil with percolating water. However, this mechanism does not consider the effect of other biological process, such as denitrification on soil pH. Alternative phytoremediation mechanisms are plant-induced increases in nutrient and water uptake, reduced evaporation, increased soil cover, and enhanced water infiltration.

To optimizes restoration, it is important to identify the dominant mechanisms and identify plants that can be established. For example, how much $CaCO_3$ needs to be present in the soil or are the hydrogen ions (H^+) and CO_2 emitted by plants sufficient to increase $CaCO_3$ solubility in well buffered soils? Much of the current literature explores salinity solutions in irrigated soils, but to the best of our knowledge there is scant information on phytoremediation in humid dryland soils of the NGP. The objective of this study was to investigate the impact of seeding perennial grasses on soil and plant health in NPG landscapes containing areas of barren saline/sodic soils interspersed in productive soils.

Figure 1

A Google Earth aerial image of the study site. The image is from June 4, 2019, superimposed on an elevation map. The location of blocks and productive, transition, and saline/sodic soils are shown. The experimental design was a randomized split-block. The phytoremediation treatments were applied as strips across the three soil zones. The dimensions were 177 by 218 m. The white areas have high soil moisture and are salt affected. The elevation change across the image is approximately 3 m.



Materials and Methods

Field Study. This is a second paper from these research plots. In the first study, Fiedler et al. (2021) reported that in 2019, N_2O emissions were 482% higher in unfertilized saline/sodic than productive soil, and that applying urea to the saline/sodic soil further increased emissions 268%.

The experiment was conducted in the James River watershed located in South Dakota at 44°42'9.6804" N latitude and 97°54'40.9" W longitude. The area's climate is on the border of three Köppen climate regimes, Dwa (warm continental climate/humid continental climate), Dwb (temperate continental climate/humid continental climate), and Bsk (cold semiarid climate). The 30-year average annual precipitation (1981 to 2010) is 60.4 cm, and the average annual temperature is 6.2°C (NOAA 2019). The field has upland positions on the eastern and western sides with an east-west depression (maximum depression 3 m) through the middle of the field (figure 1). Soil in the upland positions is a Forman-Cresbard loam (Soil Survey Staff 2018). The Forman series is characterized as a well-drained fine-loamy, mixed, superactive, frigid Calcic Argiudoll. This soil has an average saturated hydraulic conductivity value of 177 ± 39.4 mm h^{-1}. In this paper this zone is termed "productive."

The dominant soil in the depressional zone was a fine, smectitic, frigid, Glossic Natrudoll. The saturated hydraulic conductivity in this zone was approximately 0 mm h^{-1} and it is identified as "saline/sodic." Between the productive and saline/sodic soil zones is a transition area where the saturated hydraulic conductivity was 14.7 ± 10.4 mm h^{-1}. Soil in this zone was a Forman-Cresbard loam and it is identified as "transition." Selected soil characteristics for the three zones are provided in table 1.

The cation exchange capacity (CEC) of these three zones is 19.9 cmolc (kg soil)$^{-1}$ (Soil Survey Staff 2018). Common minerals in NGP glaciated soils are smectite, illite, and kaolinite. The depth of the water table was obtained at the South Dakota Department of the Environment and Natural Resources monitoring well SP-77C (figure 2) located at 44°54'51.16" N latitude and 98°1'24.96" W longitude.

Field Management. In the year prior to initiation of the experiment in 2018, crop

Table 1
Selected soil characteristics for the three soil zones at the study site. The sodium (Na^+) adsorption ratio (SAR) was estimated using the ratio between Na^+ extracted with ammonium acetate and the sum of bases extracted with ammonium acetate (DeSutter et al. 2015).

Soil zone	Soil depth (cm)	Porosity (cm^3 cm^{-3})	Bulk density (g cm^{-3})	$pH_{1:1}$	$EC_{1:1}$ (dS m^{-1})	Na^+ (Mg kg^{-1})	SAR	Organic matter (Mg kg^{-1})
Productive	0 to 15	0.56	1.16	7.4	0.39	72	1.79	2.37
	15 to 30	0.489	1.37	7.5	0.66	136	2.99	1.36
Transition	0 to 15	0.56	1.16	7.3	1.64	343	4.99	2.31
	15 to 30	0.48	1.37	7.5	1.83	327	6.01	1.24
Saline/sodic	0 to 15	0.48	1.37	7.7	3.87	1,680	22	2.16
	15 to 30	0.44	1.49	8	2.4	1,030	17	1.17

failure occurred, and the entire field had minimal vegetation or postharvest residue. The experiment was conducted in three soil zones (productive, transition, and saline/sodic). Each soil zone had four phytoremediation treatments: bare soil (control), corn, perennial grass mixture 1, or perennial grass mixture 2 (described below). Within a soil zone, the experiment was replicated in four blocks. In the control treatment, nothing was planted and it was used as nonvegetation control plot. In this treatment, plants were prevented from growing in 2018 using combination of mowing and herbicide treatments throughout the growing season.

In the corn treatments, DeKalb DKC45-65RIB (Monsanto Co., St. Louis, Missouri), a 95-day Smartstax corn hybrid, was seeded on May 17, 2018, and DKC40-77RIB (Monsanto Co., St. Louis, Missouri), a 90-day Smartstax hybrid, was planted on May 31, 2019. In 2020, DeKalb DKC43-75RIB (Bayer Co., St. Louis, Missouri), a 93-day corn, was seeded on June 2, 2020. In all years, corn was seeded at the rate of 79,000 seeds ha^{-1} at a row spacing of 76 cm.

Perennial grass mixture 1 contained Certified First Strike slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinners) and Shoshone beardless wildrye (*Leymus triticoides* [Buckley] Pilg.). These two cultivars were seeded at a rate of 3.9 kg pure live seed (PLS) ha^{-1}. Perennial grass mixture 2 consisted of Certified First Strike slender wheatgrass planted at 2.2 kg PLS ha^{-1}, Garrison creeping meadow foxtail (*Alopecurus arundinaceus*) planted at a rate of 2.2 kg PLS ha^{-1}, western wheatgrass (*Agropyron smithii* Rydb) planted at a rate of 6.7 kg PLS ha^{-1}, and AC Saltlander green wheatgrass (*Elymus Hoffmannii*) planted at a rate of 3.6 kg PLS ha^{-1}. The perennial grass mixtures were dormant seeded at a 6 mm depth using a FLEX-II drill (Traux Company, Inc., New Hope, Minnesota) into 13 m strips on December 15, 2017, and overseeded with the same mixture on October 24, 2018. Additional information on these grasses is available in Tilley et al. (2004, 2011), Ogle et al. (2009), Steppuhn et al. (2006), Young-Mathews and Winslow (2010), and Hybner et al. (2014).

To control weeds, appropriate herbicides (including dicamba, bromoxynil, and mesotrione) were applied to all vegetative treatments, with glyphosate added to the nonplanted control plots on June 6, 2018, and June 27, 2018 (Fiedler 2020). In addition, the perennial grasses and nonplanted control plots were mowed to a 15 cm height using a lift rotary mower on June 21 and September 12, 2018. In 2019, the same herbicides were applied to the plots on June 6 and July 26. In 2020, no herbicides were applied. Weedy areas in all plots were mowed August 15, 2020. Fertilizers were not applied to any of the treatments during this study.

Plant Yields. In the 2018 corn plots, grain and stover yields were measured when corn reached physiological maturity from two 5.3 m of row on September 11, 2018. In 2019, high spring rainfall and cool conditions contributed to delayed planting and a failure to reach physiological maturity. Therefore, corn plant biomass was measured at R5 growth stage from two 2.7 m of row on August 29, 2019. In 2020, corn grain and stover was harvested on September 28, 2020. Biomass and grain samples were dried at 60°C in a forced air drier.

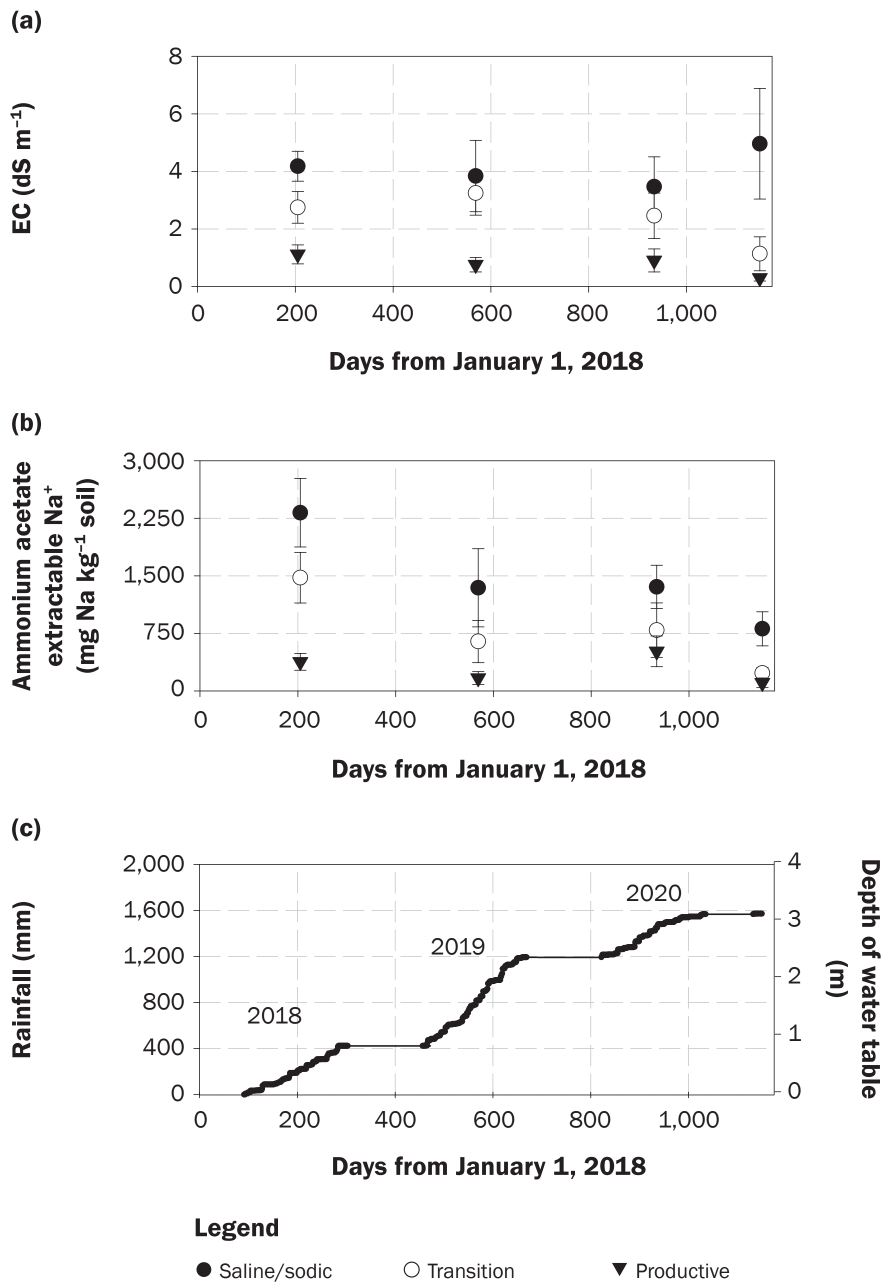
In the none and perennial grass treatments, biomass was measured in two 1 m^2 areas (due to sparse growth) on September 10, 2018, and from two 0.1 m^2 on July 11, 2019, and July 28, 2020. Biomass samples were dried at 60°C in a forced air drier.

Soil Measurements. Soil samples from all plots were collected from 0 to 15 cm on July 24, 2018 (VT corn growth stage), July 23, 2019, and April of 2021. Additional soil samples were collected from the 0 to 15 cm soil depth from the two perennial grass treatments in July of 2020. All soil samples were dried at 37.8°C, ground, sieved to <2 mm, and $EC_{1:1}$ and pH determined using soil to solution ratio of 1:1 (Grafton 2015; Dose et al. 2017). Sodium was extracted (1 M ammonium acetate) and quantified following Grafton (2015). The Na^+ dispersion risk was estimated based on the ratio between Na^+ and $EC_{1:1}$ (Kharel et al. 2018; He et al. 2013).

Soil organic matter was determined by loss on ignition. Ammonium-N (NH_4^+) and nitrate-N (NO_3^--N) were extracted using 1.0 *M* potassium chloride (KCl) and quantified using an Astoria Nutrient Analyzer (Astoria-Pacific, Inc. Clackamas, Oregon) following Maynard and Karla (1993). The NH_4^+ and NO_3^- concentrations are reported in Fiedler et al. (2021). Soil samples collected in 2018 and 2019 from the 0 to 15 cm soil depth following Veum et al. (2019) were analyzed to determine the phospholipid fatty acid analysis (PLFA) microbial community structure using methods discussed in Buyer and Sasser (2012) and Thies et al. (2020). In this analysis, 19:0 phosphatidylcholine was used as the internal standard, and a check sample was used to confirm final values. Hydraulic conductivity was measured in August of 2020 from the productive and saline/sodic zones using the single ring infiltrometer method.

Laboratory Experiment. The purpose of the laboratory experiment was to determine if plant induced increases in CO_2 emissions or exudates would lower the soil pH, thereby increasing $CaCO_3$ solubility. For this experiment, a salt tolerant plant, barley (*Hordeum vulgare*), was selected, because preliminary testing showed that it was well for this experiment. Five hundred grams of air-dried soil having an $EC_{1:1}$ of 6.29 dS m^{-1}, pH of 6.49, Na^+ concentration of 2,190 mg kg^{-1}, and NO_3^- concentration of 519 mg kg^{-1}, was placed into each of eight 1 L jars.

Figure 2
The (a) soil electrical conductivity ($EC_{1:1}$) and 95% confidence interval, (b) ammonium acetate extractable sodium (Na^+) and 95% confidence interval, and (c) accumulative rainfall from 2018 to 2021 in the perennial grass treatments and depth of the groundwater at the groundwater monitoring site. The soil zones were productive, transition, and saline/sodic soil.



Water, with an EC < 0.01 dS m^{-1}, was added to increase the gravimetric soil moisture to 0.3 g g^{-1}. Twelve barley seeds were planted into four jars and allowed to grow for seven weeks, whereas the other four jars had no plants. After seven weeks, barley biomass over the rim of the jars was removed and GHG (CO_2-C, N_2O-N, and methane [CH_4-C]) emissions were measured for four days with a LI-COR 8100A (LI-COR, Lincoln, Nebraska) system, which was connected to a Picarro G2508 cavity ringdown spectrometer that was used to determine CO_2-C, N_2O-N, and CH_4-C concentrations (Picarro Inc., Santa Clara, California). The LI-COR system was configured according to the flask sampler protocol.

In this experiment, the chambers were sealed with a lid that had inlet and outlet airports for air circulation. For each chamber, the concentration of CO_2-C, N_2O-N, and CH_4-C were measured every hour following Fiedler et al. (2021). Every 24 hours, flasks were weighed and water added to maintain gravimetric soil moisture between 0.30 and 0.35 g water (g soil)$^{-1}$. At the end of the experiment, tissue samples were collected, dried at 60°C for 72 hours, ground, digested, and analyzed for Na^+ using flame photometry.

Statistical Analysis. The field experimental design was a split block randomized block design. The split was the three soil zones where the four phytoremediation treatments were applied as strips across the three soil zones (figure 1). Within a soil zone, the experiment contained four blocks. Each plot had the dimensions of 3 by 13 m. An analysis of variance (ANOVA) was conducted with R version 1.1.383 (de Mendiburu 2021; R Core Team 2017). Because interactions between soil zone and phytoremediation treatment were not detected, only the main effects are reported. Data were analyzed using correlation and linear regression analyses using appropriate packages in R (ver. 1.1.383). To test the hypothesis that plants and rainfall contributed to lower EC and Na^+ concentrations, a one-sided *t*-test was used.

The laboratory study contained two treatments, with and without barley. The experimental design was random and treatment differences were determined using a *t*-test.

Results and Discussion

Field Environmental Conditions. The total annual precipitation (April 1 to October 30) in 2018, 2019, and 2020 was 421, 770, and 373 mm, respectively, whereas the 30-year (1981 to 2010) average precipitation was 499 mm (figure 2). The seasonal total precipitation amounts mirrored the growing season (May through September) precipitation rates, which were 2.11, 4.05, and 1.99 mm d^{-1} in 2018, 2019, and 2020, respectively. Differences in precipitation influenced the depths to the water table, which were 3.63, 1.76, 1.11, and 2.66 m on June 13, 2018, June 18, 2019, June 2, 2020, and June 22, 2021, respectively. Air temperatures were warmer in 2018 and 2020 than 2019, and growing degree days (base 10°C and maximum 26°C) from April to October were 872 in 2018, 773 in 2019, and 884 in 2020.

Across the three seasons, there was a linkage among rainfall amounts, groundwater depth, biomass production, and the soil $EC_{1:1}$ and Na^+ concentrations. During the high rainfall year (2019), the water table depth and the $EC_{1:1}$ and Na^+ concentration decreased in all zones (figure 2). However, when rainfall decreased in 2020 through 2021, soil zone treatment differences became apparent.

Grass and Corn Biomass Produced. In 2018, the most biomass was produced in the productive zone and the least in the saline/sodic zone (table 2). Across the soil zones, corn had the greatest yield compared to either of the grass mix treatments since the perennial grasses were slow to establish and had minimal growth during the first year. Different results were observed in 2019 where cool and wet conditions and late planting suppressed corn growth. However, these conditions were more favorable for the perennial grasses with both grass mixes yielding slightly more than the 2018 corn yield. In 2020, all treatments produced similar amounts of biomass.

Table 2

The total amount of biomass produced in the three productivity zones and seeding mixes. For corn in 2019, no grain was produced due to late planting and wet soils throughout the season.

Soil zone	Biomass (kg ha^{-1}) 2018	2019	2020
Productive	3,450a	7,870a	7,530a
Transition	2,180ab	7,440a	7,410a
Saline/sodic	690b	4,500b	5,490b
p-value	<0.001	<0.001	0.01
None	0	4,370b	6,340
Mix 1	920b	9,320a	6,970
Mix 2	1,520b	8,810a	7,780
Corn	5,990a	3,900b	6,150
p-value	<0.001	<0.001	0.37

Soil Measurements. In all years, $EC_{1:1}$ and Na^+ were higher in the saline sodic zone than the transition or productivity zones (table 3). In 2018, $EC_{1:1}$ ranged from 1.16 dS m^{-1} in the productive zone to 5.24 dS m^{-1} in the saline sodic zone, whereas Na^+ ranged from 312 mg kg^{-1} in the productive zone to 2,484 mg kg^{-1} in the saline sodic zone. Slightly different results were observed for the Na^+ to $EC_{1:1}$ ratio, where the $Na^+/EC_{1:1}$ ratio was similar in the saline/sodic and transition zones in 2018.

In 2018 and 2019, total microbial biomass was higher in the productive zone than the saline/sodic soil (Fiedler et al. 2021), and in all soils, fungal biomass was very low, suggesting very low concentrations of fungal hypha and glomalin-related proteins. The lack of fungi when combined with a high Na^+ to $EC_{1:1}$ ratio indicated that these soils are fragile with a high risk of soil dispersion (Fiedler et al. 2021). The risk of soil dispersion was assessed by dividing the Na^+ concentration by $EC_{1:1}$. The use of this ratio was based on He et al. (2013) and Kharel et al. (2018). He et al. (2013) reported that for illite, decreasing the solution EC from 2 to 1 dS m^{-1} for a soil with Na^+ adsorption ratio (SAR) value of 24 increased the percentage of dispersed clays from near 0% to about 25%. For illite, the SAR to EC ratio was 24. For montmorillonite, in a solution with a SAR value of 24, dispersion increased from near 0% to over 50% by decreasing the solution EC from 5 to 4 dS m^{-1}. For montmorillonite, the SAR to EC ratio was 5.3. Both minerals are common in the central United States and are 2:1 layer silicates (Vilde 2001). However, montmorillonite is an expanding clay mineral and illite is a nonexpanding clay mineral. These SAR to EC ratio values suggest that the dispersion risk varies with mineral type, and that montmorillonite disperses at a lower Na^+ concentration than illite. Understanding clay dispersion risks are important because, as water percolates through the surface soil, decreases in the soil $EC_{1:1}$ can result in an expansion of the diffuse double layer and ultimately dispersion. Under these conditions, erosional soil losses can be very high.

In the saline/sodic zone from 2018 to 2019, $EC_{1:1}$ (–1.39 ± 1.333 dS m^{-1}), Na^+ (–1,155 ± 422 mg Na kg^{-1}), and the Na^+ to $EC_{1:1}$ ratios (–150 ± 49.6) all decreased (table 4). These decreases were attributed to soluble salts moving through the soil with the percolating water. However, from 2019 to 2021, $EC_{1:1}$ increased (1.61 ± 1.51, $p = 0.1$) and the Na^+ to $EC_{1:1}$ ratio (–150 ± 96.3) decreased. The increase in $EC_{1:1}$ was attributed to capillary movement of water and salts from the water table to the soil surface. The decrease in the Na^+ to $EC_{1:1}$ ratio suggests that the dispersion risk was reduced, while the increase in the EC indicates that seed germination would have been decreased.

In the productive zone from 2018 to 2019, $EC_{1:1}$ (–0.37 ± 0.32 dS m^{-1}), Na^+ (–175 ± 94 mg Na^+ kg^{-1}), and the Na^+ to $EC_{1:1}$ ratio (–89.1 ± 56) ratio decreased. However, from 2019 to 2021, $EC_{1:1}$ (–0.37 ± 0.26 dS m^{-1}) and Na^+ (–34.9 ± 34.0 mg Na^+ kg^{-1}) concentrations decreased, whereas the Na^+ to $EC_{1:1}$ ratio increased (89.1 ± 79). The increase in the Na^+ to $EC_{1:1}$ suggests that despite the decrease in Na^+ and $EC_{1:1}$, the aggregate dispersion risk increased.

Plant Effects on Electrical Conductivity and Sodium Concentration. From 2018 to 2019, the Na^+ concentrations decreased in the four phytoremediation treatments. However, the loss of Na^+ relative to the $EC_{1:1}$ was greater (–183 ± 57 mg Na^+ [dS m^{-1}]) in the corn and perennial grass treatments than the no-plant control treatment (–73 ± 62 mg Na^+ [dS m^{-1}]). These results indicate that the plants contributed a relative decrease in the exchangeable Na^+ concentration, which reduced the risk of soil dispersion. The effects of the plants on Na^+ concentrations could be attributed to plant uptake, enhanced water flow, or some other unknown factors. It was not attributed to the release of Ca^{+2} resulting from a plant-induced increase in $CaCO_3$ solubility (see laboratory study below). Others have reported that some plants take up significant amounts of Na^+ (Everitt et al. 1982; Bosnic et al. 2018; Geilfus et al. 2018). Plants also influence water cycling within the soil profile. For example, Reicks et al. (2021) showed that water loss was 0.0283 ± 0.0013 cm^3 (cm^3 × d)$^{-1}$ in soil with a cover crop and 0.01 ± 0.0013 cm^3 (cm^3 × d)$^{-1}$ in a fallow soil not containing a cover crop. Increased water loss through transpiration may reduce the transport of water and associated salt to the soil surface through capillary movement.

Laboratory Study. The laboratory study was conducted to further investigate the effects of plants as a phytoremediation tool. In this experiment, two components were investigated. The first was nutrient uptake and the second was plant induced decreases in soil pH leading to Na loss (table 5). In this experi-

Table 3

Soil electrical conductivity ($EC_{1:1}$), sodium (Na^+), $Na^+/EC_{1:1}$ ratio, change in $EC_{1:1}$ and Na^+ from 2018 to 2020, in the three soil zones, and four vegetation treatments. Mix 1 contained beardless wildrye and slender wheatgrass and mix 2 contained slender wheatgrass, creeping meadow foxtail, western wheatgrass, and AC Saltlander green wheatgrass. Treatments with different letters differ at $p < 0.05$.

	2018			2019			2021		
Soil zones	$EC_{1:1}$ (dS m^{-1})	Na^+ (mg kg^{-1})	$Na^+/EC_{1:1}$ (mg kg^{-1})/(dS m^{-1})	$EC_{1:1}$ (dS m^{-1})	Na^+ (mg kg^{-1})	$Na^+/EC_{1:1}$ (mg kg^{-1})/(dS m^{-1})	$EC_{1:1}$ (dS m^{-1})	Na^+ (mg kg^{-1})	$Na^+/EC_{1:1}$ (mg kg^{-1})/(dS m^{-1})
Productive	1.16c	312c	278b	0.76c	136c	189c	0.4a	101a	278ab
Transition	2.96b	1,428b	490a	2.25b	667b	261b	0.895b	220a	351a
Saline/sodic	5.24a	2,484a	480a	3.94a	1,329a	330a	5.5b	789b	182b
p-value	<0.001	<0.001	0.0007	<0.001	<0.001	<0.001	<0.001	<0.001	0.04
Treatment									
None	4.84a	1,963a	341b	3.5a	1,162a	267	2.49	380	324
Mix 1	2.63b	1,291bc	502a	2.09bc	601bc	256	1.86	374	269
Mix 2	2.74b	1,494ab	496a	2.47ab	839ab	305	2.41	393	316
Corn	2.40b	883c	326b	1.23c	241c	213	2.11	331	182
p-value	0.03	0.09	0.04	0.02	0.03	0.12	0.35	0.79	0.37

ment, barley reduced NO_3 and $EC_{1:1}$ values and increased CO_2-C and N_2O-N emissions for the four days after clipping the plants. Because the closed jar system prevented the downward movement of water out of the soil, decreases in soil $EC_{1:1}$ was attributed to soil nutrient uptake and N_2O emissions. Even though barley did not reduce the bulk Na^+ content of the soil, the harvested plants contained 5% Na^+, which must have been obtained from the soil. Shelef et al. (2012) had similar results and reported that *Brassia indica* (an annual broadleaf halophyte) reduced the Na^+ concentration 20% to 60% in the effluent from a constructed wetland. Even though barley increased CO_2 emissions by 344%, the soil pH did not decrease and may have increased (p = 0.07). These findings do not support the hypothesis that plant induced decreases in the soil pH result in increased solubility of $CaCO_3$ and the loss of Na. However, it does support the hypothesis that nutrient uptake can contribute to decreases in Na^+ and soil $EC_{1:1}$. These findings were attributed to several factors including (1) that the Forman-Cresbard mapping unit has a relatively high CEC, (2) that denitrification consumes H^+, and (3) that these soils had very high N_2O-N emission rates (Fiedler et al. 2021).

The scope and magnitude of salinity and sodicity is increasing globally due to climate change. In the NGP, increased spring rainfall, when combined with rising water tables over marine sediments, has resulted in poorly drained saline/sodic soils that are supersaturated with gypsum. Salt-affected soils are concentrated, at first in the lowest lying areas of a field, which may over time progress upslope (Birru et al. 2019). Annual crop yields in affected soils can be low, whereas the GHG emissions from these soils can be very high (Fiedler et al. 2021).

In salt affected soils, sparse vegetation, and destabilized surface soils, slow water infiltration rates can result in high erosion and N_2O-N emissions (Fiedler et al. 2021). Even in a dry year, these areas do not dry out and soil stability is so poor that ruts from typical production equipment (tractors, sprayers, and combines) can be 20 or more centimeters deep. This study investigated the effects of phytoremediation and natural rainfall on soil and plant health. During the study, contrasting climate events occurred; in 2018 to 2019 precipitation was nearly double the 10-year average, whereas from fall of 2019 to spring of 2021, rainfall was about or a little lower than average. During the high rainfall period, depth to the water table decreased, phytoremediation lowered the $Na^+/EC_{1:1}$ ratio, and $EC_{1:1}$ and Na^+ concentrations decreased in all treatments. The reductions in $EC_{1:1}$ and Na^+ were attributed plant uptake and nutrient transport with percolating water.

During the reduced rainfall period from 2019 to 2021, the depth to water table increased, the risk of soil dispersion increased in the productive zone, and soil $EC_{1:1}$ increased in the saline/sodic zone. In the saline/sodic zone, these results were attributed to low plant growth and limited transpiration, which was not sufficient to impede the movement of salts from the groundwater to the soil surface. However, in the productive zone plant, growth was more robust, which when combined with increased transpiration, may have slowed the capillary movement of salts from the water table to the soil surface. These findings suggest that during the reduced rainfall period there was an upward transport of water and associated salts in the saline/sodic zone and a downward movement of salts in the more productive zone.

A laboratory study did not support the hypothesis that the plant root release of exudates, H^+, or CO_2 increased $CaCO_3$ solubility. Even though we did not a observe a plant-induced pH decrease, analysis showed that plants reduced the risk of dispersion. These results were attributed to several factors including that denitrification can increase soil pH and that the growing plants altered nutrient and water cycling. Our research did not investigate the effects of plants on water flow in these zones. However, other studies have reported that plants change water cycling by increasing transpiration and water infiltration (Carvalho et al. 2019).

Summary and Conclusions

High rainfall and phytoremediation contributed to soil health improvements in the three zones in this east central South Dakota field. Our findings also suggest that in the poorly drained saline/sodic zone, at least two possibilities exist over the long term. The first was that if the water table is close to the soil surface, then rainfall-induced decreases in $EC_{1:1}$ may be short lived. Evidence supporting this is the increase in $EC_{1:1}$ from 2019 to 2021. The second was that, because plants establishment into the saline/sodic zone was slow, the capillary movement of water and salts from the water table to the soil surface had not yet

Table 4
The impact of soil zone and vegetation treatment change in the electrical conductivity ($EC_{1:1}$), sodium (Na^+), and the $Na^+/EC_{1:1}$ ratio between 2019 and 2018 and between 2021 and 2019. A negative value indicated a decrease in $EC_{1:1}$, Na^+, or $Na^+/EC_{1:1}$ ratio. In the none-treatment from 2019 onward significant amounts of biomass were produced.

	$EC_{1:1}$ (dS m^{-1})		Na^+ (mg kg^{-1})		$Na+/EC_{1:1}$ (mg kg^{-1})/(dS m^{-1})	
Soil zones	**2019 to 2018**	**2021 to 2019**	**2019 to 2018**	**2021 to 2019**	**2019 to 2018**	**2021 to 2019**
Productive	−0.39	−0.37b	−175.5	−34.9a	−89.1	88.7a
Transition	−0.71	−1.36a	−761	−447ab	−227.9	88.6a
Saline/sodic	−1.38	1.61b	−1,155	−540b	−150ab	−147b
p-value	0.12	<0.001		0.01	0.05	0.001
Treatment						
None	−1.34	−1.0	−800.5	−782c	−73.8	57.0
Mix 1	−0.54	−0.23	−690.7	−227ab	−247	13.7
Mix 2	−0.27	−0.06	−655.3	−446bc	−191	11.5
Corn	−1.16	0.87	−641.4	92.3a	−113	−28.8
p-value	0.7	0.29	ns	0.03	0.12	0.85

Table 5
Barley impact on average nitrous oxide (N_2O-N) and carbon dioxide (CO_2-C) emissions from the saline/sodic soil during the four-day incubation. Soil electrical conductivity (EC), pH, sodium (Na^+), and nitrates (NO_3-N) in the soil following the four-day incubation.

	Average emission		Soil value after incubation			
Treatment	**N_2O-N (ug N_2O-N kg^{-1})**	**CO_2-C (ug CO_2-C kg^{-1})**	**$EC_{1:1}$ (dS m^{-1})**	**$pH_{1:1}$**	**Na^+ (mg kg^{-1})**	**NO_3-N (mg kg^{-1})**
Barley	1.16	709	5.92	6.6	2,028	428
No-plant	0.36	206	6.3	6.49	2,086	509
p-value	<0.001	<0.001	0.041	0.07	0.151	<0.001

been disconnected. If this hypothesis is correct, then disturbing this soil and preventing the plants from producing a protective soil cover will slow restoration.

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