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Northern Great Plains Saline Sodic Soil Development, Classification, Remediation, and Management.

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NORTHERN GREAT PLAINS SALINE SODIC SOIL DEVELOPMENT, CLASSIFICATION, REMEDIATION, AND MANAGEMENT.

BY

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DISSERTATION ACCEPTANCE PAGE
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This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This dissertation is dedicated to my children, Just Paul, Chacha, and Little T.
May you always be curious and kind; so far, so good.

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This is the day the Lord has made, let us rejoice and be glad in it (Psalm 118:24).

CONTENTS

ABBREVIATIONS

Abbreviation	Definition (Can add more columns)
Δ	Delta
°C	degrees Celsius
µL	microliter
2:1 clay	layering of Si tetrahedral to Al octahedral to Si tetrahedral clay sheets
cm	centimeter
cmol	centimole
$cmol_c$	centimoles of charge
DI	deionized
dS/m	deciSiemens per meter
EC	electrical conductivity
$EC_{1:1}$	electrical conductivity analyzed on a 1:1 soil-water suspension
EC_e	electrical conductivity analyzed on a saturated paste extraction
ESP	Exchangeable Sodium Percent
FAO	Food and Agriculture Organization of the United Nations
ft	foot
g	gram
ha	hectare
kg	kilogram
km	kilometer
L	liter
lbs	pounds
MAOM	Mineral Associated Organic Matter
mg	milligrams
Mg	megagrams
mL	milliliter
mm	millimeter
mmho/cm	millimhos per centimeter
$mmol_c$	millimoles of charge
mol	mole
N_2O	nitrous oxide
Na:EC	sodium concentration (ppm) to electrical conductivity (dS/m) ratio
NGP	North America Northern Great Plains
OM	organic matter
pXRF	portable x-ray fluorescence
SAR	Sodium Adsorption Ratio

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ABSTRACT

NORTHERN GREAT PLAINS SALINE SODIC SOIL DEVELOPMENT, CLASSIFICATION, REMEDIATION, AND MANAGEMENT.

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Soil salinity and sodicity are issues of growing concern in the United States (U.S.) and globally. Knowledge gaps for glaciated, dryland salt-affected soils exist because much original salinity and sodicity research focused on irrigated systems. Land managers are being asked to produce food, feed, fiber, and fuel for an expanding global population. The number of land managers and crop advisors who are affected by these soils is increasing. Addressing salinity and sodicity knowledge gaps will be critical for their success.

Salinity and sodicity have been impeding crop productivity since the advent of cultivation. Saline and sodic soils form via multiple natural and human-induced pathways. Parent materials that are inherently high in ion (salt) concentrations can, through dissolution of mineral materials, release ions to the soil-water solution. As rainfall patterns in certain regions, namely the North America Northern Great Plains (NGP), trend toward higher seasonal rainfall, water tables rise. Ions are then transported upward with the water table and then to the soil surface via capillary rise. This mechanism of salt accumulation is unique compared to irrigated systems where salts accumulate at the soil surface from applications of irrigation water that has a high electrical conductivity (EC). Fundamental differences between salt-accumulation in non-glaciated, irrigated systems and glaciated, dryland systems insinuate that management

recommendations from irrigation-based systems may not be pertinent or applicable to the NGP. For this reason, there is great need for a comprehensive textbook on salinity and sodicity that encompasses the management challenges faced by land managers and crop advisors in all geographies. Additionally, further research in the NGP is needed to investigate potential salinity and sodicity reclamation strategies that are effective and that can realistically be implemented on working farms.

Throughout this document, Chapter 1 addresses knowledge gaps in more detail. Chapter 2 discusses saline and sodic soil development across multiple geographies, how saline and sodic soils are measured and defined, and the classification system used in the U.S. for these soils. Chapter 3 discusses research findings and the effect of chemical amendments in combination with phytoremediation on soil health in NGP saline-sodic soils. Chapter 4 serves as a summary of the knowledge gaps, of key issues as identified by the research discussed herein, and of areas of future work to address the growing issue of saline and sodic soils.

CHAPTER 1

INTRODUCTION AND KNOWLEDGE GAPS

ABSTRACT

This first chapter highlights the importance, relevance, need, and novelty of the material in Chapter 2 and of the research in Chapter 3. Salinity and sodicity pose serious agronomic, environmental, and socioeconomic risk to communities around the world. Although abundant research has been conducted on the vast topic of soil salinity and sodicity, reliable reclamation and management strategies are still limited in some geographies, namely the North America Northern Great Plains (NGP). Traditionally, adequate drainage, application of chemical amendments, and leaching of salts with high-quality water has been recommended for reclamation of salt-affected soils. Research in the NGP, however, did not find this approach to be successful due to the impracticality of facilitating all three components. Soil degradation from sodium reduces drainage and much of the NGP is under dryland production, which limits the ability to leach salts with adequate quantities of water compared to irrigated systems. The following chapter discusses previous research on traditional reclamation strategies in multiple geographies and in the NGP.

INTRODUCTION AND BACKGROUND

Salinity is the relative amounts of cations and anions, including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), chloride (Cl^{-}), sulfate (SO_4^{2-}), nitrate (NO_3^{-}), and phosphate (PO_4^{3-}), in the soil solution. Saline soils are characterized by the soil electrical conductivity (EC). Salinity causes osmotic imbalances between plants and the soil-water solution that can lead to drought stress. The semi-permeable membrane of plant roots extract water from the soil while screening out salt. As salt concentration increases, plants utilize a majority of overall energy in extracting water such that growth is either stunted or plants will reach the permanent wilting point (Bohn et. al., 1979).

Sodic soils contain a relatively high concentration of Na^+ on soil cation exchange sites (CEC). The percent Na^+ occupying total CEC sites is called the exchangeable sodium percent (ESP). The higher the soil ESP, the greater the Na^+ content in the soil. Similar to salinity, sodicity also leads to restricted plant growth from osmotic stress. Sodic soils additionally exhibit high soil pH levels, which restrict the availability of soil nutrients to plants (Carlson et. al., 2019). Sodium is a weak, monovalent cation with a very large hydration shell resulting in limited flocculation ability (Franzen et. al., 2019). Soils with high Na^+ generally have low aggregate strength and are dispersed (Rengasamy and Walters, 1994). A dispersed soil is highly susceptible to wind and water erosion and will have very low water infiltration (Carlson et. al., 2019, Budak et. al, 2022). For this reason, sodic soils have an added environmental risk. A soil with high EC and high ESP is a saline-sodic soil (Franzen et. al., 2019). Saline-sodic soils can have low plant germination and high erosion risks.

Salinity and sodicity have been a threat to food security for thousands of years. Salinization from salt-laden irrigation water reduced Sumerian harvests in the crux of the Tigris and Euphrates Rivers to one third of original production between 3000 Before the Common Era (B.C.E.). and 1800 B.C.E. (Montgomery, 2007). In more recent times, salt-laden irrigation water has led to salinization in many regions worldwide including Africa, North America, and Asia (Qadir et. al., 2014; Gorji et. al., 2017). In other regions, such as Australia and as South Dakota in the United States (U.S.), natural formation of saline and sodic soils occur due to dissolution of ions from salt-rich parent materials entering the soil-water solution. Ions are then transported upward with the water table and then to the soil surface via capillary rise. Salinization and sodification in these unique ecoregions can be accelerated by human activity when water-efficient, native vegetation is replaced with less efficient annual crops leading to elevated water tables and increased salt accumulation in upper soil horizons from capillary rise (Gorji et. al., 2017; Birru et. al., 2019).

TRADITIONAL RECOMMENDATIONS

Much research on remediation, or reclamation, of salt-affected soils has been conducted in arid or semiarid regions such as California (Reeve et. al., 1955; Qadir et. al., 2014), the Middle East (Qadir et. al, 2014), and Australia (Pannell and Ewing, 2006). Common remediation strategies include drainage improvements, the application of soil amendments, and improved management of irrigation water (Kharel et. al., 2018; Franzen et. al., 2019).

Improved drainage aids the removal of soluble salts via mass flow when adequate surface water is applied through irrigation or rainfall. To improve drainage, some studies recommend the use of deep tillage (Sharma et. al., 1974; Ding et. al., 2021). Some producer-focused print media (i.e., Successful Farming magazine) recommend installation of tile drainage (George, 2015). Extension material from Colorado State

University briefly recommends tile, but the need to soil test for Na^+ concentrations prior to installing tile is not clear (Bauder et. al., 2014). Hopkins et. al. (2012) and Doyle et. al. (2016) recommends that soil sampling should be conducted to assess the risk of clay dispersion following tile drainage installation. Budak et. al. (2022) suggested that clay dispersion risks increase when ammonium acetate extractable Na^+ (mg Na^+ kg^{-1} soil) to $EC_{1:1}$ (dS/m) ratios exceed 600.

Calcium-rich soil amendments are used to remove Na^+ salts from clay exchange sites and have proven to be successful in many areas including Asia and South America (Zhao et. al., 2018; Sundha et. al., 2020; Alcivar et.al., 2018). The most common soil amendment to remove Na^+ salts is calcium sulfate (gypsum, $CaSO_4 \cdot 2H_2O$) (DeSutter and Cihacek, 2009; Zhao et. al., 2018), while calcium chloride ($CaCl_2$) (DeSutter and Cihacek, 2009), calcium carbonate (lime, $CaCO_3$) (Kharel et. al., 2018), and elemental sulfur (S) are also used (Birru et. al., 2019). In soils with a relatively high $EC_{1:1}$, the application of high concentrations of $CaCl_2$ can significantly reduce crop yields (Birru et. al., 2019).

Leaching of cations and anions with low-EC irrigation water or rainfall is the final component of traditional reclamation strategies (Food and Agriculture Organization of the United Nations, 2021). This approach has proven to be an effective and important component of removing cations and anions, including Na^+, from the root zone of salt-affected soils (Reeve et. al., 1955; Bauder et. al., 2014; Zhao et. al., 2018). Although ample bodies of research exist on the above strategies, it is unclear if these methods can be effective in all salt-affected regions such as the NGP.

EFFECTIVENESS OF TRADITIONAL MANAGEMENT STRATEGIES

Drainage

Increasing water drainage via tillage or installing tile drainage has improved the downward movement of cations and anions in many soils (Sharma et. al., 1974; Ding et. al., 2021). However, restoration can take many years. For example, Sharma et. al. (1974) conducted a study on a Huey soil (fine-silty, mixed, superactive, mesic Typic Natraqualf) in south-central Illinois, U.S. from 1964 to 1971. In this study, gypsum was applied at rates of 0, 24, or 62 tons ha^{-1} in 1964 in conjunction with tillage to a depth of 15, 60, or 90 cm. The only treatment that increased corn yields and reduced extractable Na^+ was the application of 62 tons of gypsum ha^{-1} when combined with tillage to a depth of 90 cm. Deep tillage without the application of gypsum led to reduced grain yield and no change in Na^+ level when compared to control treatments (Sharma et. al., 1974). In another study conducted in Egypt, Ding et al. (2021) showed that any form of soil amendment in conjunction with deep tillage had a positive impact on soil chemical and physical properties. They also showed that deep tillage was most beneficial on soil physical properties (i.e. reduced bulk density and increased hydraulic conductivity) and chemical properties (i.e. reduced EC) of all tillage treatments (Ding et. al., 2021). In North Dakota, Doyle et al. (2016) suggested that tile drainage could reduce salinity by removing soluble salts and by lowering the water table. However, if Na^+ content is unknown in both surface and subsurface soils, tile drainage may exacerbate a sodic situation (Hopkins et. al., 2012; Doyle et. al., 2016) or be ineffective (Budak et. al., 2022). Soil testing for soluble cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and $\%Na^+$ is recommended prior to installing tile drainage for management of saline-sodic soils.

Budak et. al. (2022) implemented a study on a toposequence in eastern South Dakota from 2018 to 2020. In this study, the effectiveness of tile drainage on $EC_{1:1}$ and ammonium acetate extractable Na^+ in the shoulder (Great Bend [fine-silty, mixed, superactive, frigid Calcic Hapludoll]-Beotia silt loam [fine, smectitic, frigid, Pachic Argiudoll]), backslope (Beotia [fine, smectitic, frigid, Pachic Argiudoll]), and toeslope (Harmony [fine, smectitic, frigid Pachic Argiudoll] and Aberdeen [fine, smectitic, frigid Glossic Natrudoll]) landscape positions were studied. Deep core samples (112.5 cm) were collected with a Giddings probe and separated into 0-7.5, 50-57.5, 82.5-90, 92.5-100, and 105-112.5 cm depths. Artificial drain tile had been installed in the backslope position in fall of 2017 at a depth of 105 cm with tile lines spaced 12 m apart. In the toeslope position, where $\%Na^+$ exceeded 40% at all depths, the hydraulic conductivity was 0 mm h^{-1} and the drainable porosities were $\leq$0.2 cm^3 water per cm^3 of soil. This study supported findings by He et. al. (2015) that high Na^+ content can reduce drainable porosity and saturated hydraulic conductivity. This research indicates that excess gravimetric water and associated cations and anions contained in the water were not removed by tile drainage. There were improvements in EC and Na^+ concentration from 2018 to 2019 in the backslope and shoulder positions, but not from 2019 to 2020. Weather patterns were very different from 2018 to 2020 and the results of this study suggest that changes in salinity and sodicity may be hinged on climate trends rather than artificial drainage (Budak et. al., 2022).

Gypsum

Gypsum has proven to be a useful soil amendment in numerous studies (Alcívar et. al. 2018; Zhao et. al., 2018; Sundha et. al., 2020). Other studies did not produce positive results at reducing salinity or sodicity through gypsum application (Birru et. al., 2019). Results from Alcívar et. al (2018) in a greenhouse study conducted in Chile showed significant reductions in electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percent (ESP) from an application of 47.7 tons ha^{-1} of gypsum. Specifically, ESP was reduced by 11-fold from gypsum application in this study. Sundha et. al. (2020) conducted a similar simulation study with soils from the Haryana state of India. Results found that applying gypsum at a 50% rate of the gypsum requirement led to significant reductions in EC and soluble salts from the columns.

A field study conducted by Zhao et. al. (2018) measured the effects of flue gas desulfurization gypsum on reclaiming saline and sodic soils in the Songnen Plain of China. The experiment was conducted between 2014 and 2016 on a solonetz soil (FAO classification; presence of a natric horizon in U.S. Soil Taxonomy) under a rice production system. Soil samples to a depth of 20 cm were collected in 2014, 2015, and 2016. The samples collected in 2014 were collected prior to gypsum application and incorporation. Following application of treatments, the plots were flooded, tilled, levelled, drained, allowed to set for two days, flooded, and then rice plants were transplanted to the plots. Soil samples were analyzed for pH, EC, soluble cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+), soluble anions (Cl^-, SO_4^{2-}), exchangeable Na^+, carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-). The sodium absorption ratio (SAR) and exchangeable sodium percent (ESP) were calculated. Initial and post-harvest soil samples and rice tissue were tested for heavy metals. Irrigation water was tested for pH, total dissolved salts, and soluble ion levels. Compared to initial levels, the EC of all reclaimed plots were significantly reduced due to the addition of gypsum. In 2016, EC levels decreased by

38.6% from 2014 levels and by 7.9% from 2015 levels. No notable differences were detected between 2015 and 2016. The concentration of CO_3^{2-} and HCO_3^- were decreased from 87.9% in 2014 to 70.9% in 2016. Soluble anion concentration was also reduced by 90% for Cl^- and by 85.2% for SO_4^{2-} due to improvement in soil structure from addition of Ca^{2+}. Of the total cation concentration, Na^+ accounted for 59.2% in 2014 but the concentration decreased to 34.7% in 2016. From 2014 to 2016, Ca^{2+} levels increased from 17.5% to 25.1%. At the project inception, SAR values ranged from 4.7 to 23.6, but by 2016 they ranged from 0.9 to 2.5 showing large reductions in SAR from the addition of gypsum. Heavy metal concentrations did not increase with the application of gypsum and rice yields increased with the addition of gypsum. The authors conclude that gypsum is a safe and effective reclamation strategy for saline-sodic soils in this region of China.

Although soil amendments have proven to be efficient in greenhouse studies (Alcívar et. al., 2018; Sundtha et. al., 2020) and in regions of the world such as southeastern China (Zhao et. al., 2018), results in the NGP have been less conclusive. A study by Birru et. al. (2019) was conducted to observe the effects of common soil amendments on saline-sodic soil reclamation in eastern South Dakota soils. A randomized complete block experiment was implemented on three different landscape positions: backslope (Harmony soil series [fine, smectitic, frigid Pachic Argiudoll]), footslope (Houdek soil series [fine-loamy, mixed, superactive, mesic Typic Argiustoll]), and toeslope positions (Nahon soil series [Fine, smectitic, frigid Calcic Natrudoll]). Tile drain had been installed in both the backslope and footslope positions, but not in the toeslope position. Four amendment treatments consisting of no-amendment control, calcium chloride, gypsum, and elemental sulfur were applied to each landscape position and incorporated to a 15 cm depth. Soil samples were collected prior to treatment implementation, again in Years 1 and 2 of the study, and again at the termination of the study. Soil samples were analyzed for pH, EC, ammonium acetate extractable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), %Na^{+}, inorganic carbon, gypsum, sulfate, and a subset were sampled for SAR. Results of the subset showed that %Na^{+} is roughly equal to SAR. This is important as measuring %Na^{+} is faster, simpler, and less expensive than running saturated paste extractions to measure SAR. Physical measurements included bulk density and saturated hydraulic conductivity. Plots were sampled for Phospholipid Fatty Acid Analysis (PLFA).

In the backslope position, none of the amendment treatments had a positive effect on yield and the $CaCl_2$ treatment had the lowest yields of all amendments. These results suggest caution should be used if applying soil amendments to non-saline, non-sodic soils without ample soil testing beforehand due to the adverse risk to crop yield. The footslope position also saw reduced yields in the $CaCl_2$ treatment as well as the gypsum treatment in two of the three years with the other year being a crop failure due to excessive water. The toeslope position was highly saturated in both years of the study with crop failure in 2014 and 80% lower than average yields in 2015. The lack of response to gypsum in all three landscape positions was attributed to an abundance of gypsum inherently in the soil. In conclusion, chemical amendments may not reduce salinity or sodicity in eastern South Dakota soils (Birru et. al., 2019).

Leaching

To remove soluble salts from the root zone, leaching with high-quality irrigation water or rainfall is required (Reeve et. al., 1955, Bauder et. al., 2014). Work conducted in Coachella Valley of California evaluated the effectiveness of leaching cations and anions from the soil with water (Reeve et. al., 1955). Flushing consisted of applying a large amount of Colorado River water to plots and allowing surface salts to wash off into waste basins, whereas leaching consisted of slow application of Colorado River Water to a depth of 7.5- to 15 cm allowing for percolation through the profile. Results showed that flushing with 122 cm of water removed 2.32 tons of salt ha^{-1} which only accounted for 1% of the total salts in the soil. Leaching, however, led to significant decreases in EC to a depth of approximately 76 cm (Reeve et. al., 1955). Extension materials from Colorado State University (Bauder et. al., 2014) show that using proper and uniform irrigation water can move salts deeper into the profile and out of the rooting zone. Leaching of soluble salts is important for lowering the salt content of surface soils but may be of temporary or little effect if the water table continues to rise and bring salts back to the surface. This is especially true in regions with salt-laden parent materials such as in the NGP.

Additional management strategies

Many of the papers cited in this review have also studied the effect of organic amendments on salinity and sodicity such as biochar (Alcívar et. al., 2018), compost (Sundha et. al., 2020), and vermicompost (Ding et. al., 2021). All these studies found significant reductions in saline and sodic conditions using organic amendments, which indicates that other solutions to salt-affected soils exist beyond chemical reclamation. These organic amendments also have the potential of being more widely available or cost-effective than gypsum if they can be produced in the region in which they will be used.

In Australia, much of the salinization and sodification of soil is from removal of native vegetation (Pannell and Ewing, 2006; Rengasamy, 2006; Australian Bureau of Statistics, 2013). Similarly, in the NGP, altering the landscape from deep-rooted native prairie plants to less water-efficient annual crops has led to elevated water tables and the transport of soluble salts from marine parent materials closer to the surface (Carlson et. al., 2019; Kharel et. al., 2018; Birru et. al., 2019). Therefore, using salt-tolerant crops such as barely (*Hordeum vulgare* L.), or establishing perennial grasses such as creeping meadow foxtail (*Alopecurus arundinaceus*) in salt-affected soils could be a useful reclamation strategy (Chinnusamy et. al., 2005; Qadir et. al., 2007; Fiedler, D., 2022).

CONCLUSION AND KNOWLEDGE GAPS

Saline, sodic, and saline-sodic soils are highly fragile, require precise management, and could have severe ramifications on food insecurity in the coming decades (Ivushkin et. al., 2019). For these reasons, continued research is needed to address these issues and to find site-specific solutions for the local populations that rely on these soils.

Chapter 2 of this dissertation was written for an upcoming salinity and sodicity textbook designed for land managers, crop advisors, and students. Salinity and sodicity is a heavily researched topic due to the severity and widespread nature of the issue on a global scale. Locating reliable information that encompasses research findings from multiple geographies (i.e. outside the U.S. Salinity Laboratory) is arduous and time-consuming. For this reason, this project was undertaken to improve accessibility of this knowledge. Traditional management strategies for reclamation of saline and sodic soils in the NGP have not reliably provided measurable relief to land managers (Kharel et. al., 2018; Birru et. al., 2019; Fiedler et. al., 2022). The third chapter of this dissertation addresses the need for continued salinity and sodicity reclamation research in the NGP. The final chapter recaps knowledge gaps and the importance of continuing region-specific salinity and sodicity research.

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CHAPTER 2

SALINE-SODIC SOIL DEVELOPMENT, MEASUREMENT, & CLASSIFICATION

INTRODUCTION

This chapter introduces the growing problems associated with salinity and sodicity. Salinity is generally measured by determining total salt concentration via electrical conductivity (EC), whereas sodicity is a measure of the amount of sodium (Na^{+}) contained on the cation exchange sites (CEC). The growing problem of salinity and sodicity is driven by many factors including climate variability and the knowledge gap on how to measure, characterize, and implement reclamation strategies. This chapter also examines the development, measurement, and classification of saline and sodic soils.

THE RELATIONSHIP BETWEEN SOCIETY AND SALT-AFFECTED SOILS

One of the major problems affecting food security is soil salinity and sodicity, which occurs in all climates and can result from natural and/or human-induced causes. Salinity and sodicity are not new and have challenged communities since the cultivation of Mesopotamia in 2400 B.C.E. (Lowdermilk, 1953; Jacobsen and Adams, 1958; Montgomery, 2007). Although found in many climate zones, salinity and sodicity are largely concentrated in arid and semiarid regions where rainfall is not sufficient to meet plant demands or to eluviate salts out of the plant root zone (Wiley, 1953; Buringh, 1979; Armillas, 1961; Tanji, 1990; Shahid et.al., 2018). However, due to rising sea levels, changes in rainfall and temperature patterns, and decreased supplies of quality irrigation water, the extent of saline and sodic soils has grown. Fortunately, as the amount of salt-affected land expands, so does our understanding of these soils. In the North America Northern Great Plains (NGP) soil salinity and sodicity problems result from increasing rainfall, which elevates the risk of capillary movement of Na^+ and other salts from underlying marine sediments to the soil surface. Salt accumulation in these systems can be accelerated by the transition from native, water-efficient plants to agronomic annual crops (Australian Bureau of Statistics, 2013). Similar problems can occur in soils that contain gypsic or petrogypsic soil horizons (Boyadgiev, 1974; Nachtergaele et al., 2009). This situation has placed many otherwise highly productive soils at the tipping point of sustainability. In other regions, salinity and sodicity are the result of management such as use of irrigation water with a high EC. Salts in high concentration at the soil surface can decrease seed germination and limit plant growth, and sodium (Na^+) can lead to soil dispersion and high erosion rates (Figure 2.1).

The world's land surface occupies approximately 149 million sq km (57.5 million sq mi) or about 15 billion ha (37 billion ac) (Weast, 1968). About 50% of the world's land is used for agricultural production (forest, pasture, and crops) with about 1 billion ha affected by salinity and sodicity globally (Fig. 2.2, Table 2.1) (Rengasamy, 2006; FAO and ITPS, 2015; Shahid, et.al., 2018). It has been predicted that human activity will accelerate the spread of salt-affected soils globally (Ivushkin et.al., 2019; Hassani et.al., 2020).

Figure 2.1. Dispersed topsoil (left) and gully formation after a 2.5 cm rain (right) on two saline-sodic soils in eastern South Dakota. When large erosion events such as this occur, sediment, fertilizers, and agrochemicals are transported to streams, rivers, and to the atmosphere. These soils pose significant economic risk to agricultural producers/land managers and significant environmental risk to surrounding ecosystems (Courtesy South Dakota State University).

Human-induced salinity from poor irrigation management impacts approximately 76 million ha (25%) of the 300 million ha of irrigated land worldwide (Oldeman, et. al., 1991; Squires and Glenn, 2011; FAO and ITPS, 2015). In these soils, common concerns are limited amount of available irrigation water, not applying enough irrigation water to meet leaching requirements to wash the ions from the soil, and inadequate drainage from degraded soil structure. Almost half of the irrigation-induced salinity is found in Asia (Pakistan, India, China, Iraq, Afghanistan, Turkey, Syria, Russia, and Kazakstan) (Table 2.1; Figure 2.2). Significant human-induced salinity regions are also found in the United States (U.S.), Mexico, and Egypt. Australia/Oceania has the largest extent of naturally occurring sodic soils while Africa has the largest extent of naturally occurring saline soils (Table 2.1).

IMPACT OF SALT-AFFECTED SOILS ON FOOD SECURITY

Since most of the world's arable land has been cultivated and there is very limited expansion capability, we will need to increase yields on existing cropland to meet expected demands for food, feed, fiber, and fuel. Efforts to prevent production losses and to prevent the depletion of natural resources are going to be paramount to global food security. It is estimated that 15% of the world's arable land has been degraded by erosion, physical and chemical degradation, and by soil salinization (Wild, 2003). Salinity and sodicity are removing 0.3 to 1.5 million ha of land from production per year and yields are reduced on an additional 20 to 46 million hectares of land each year (FAO and ITPS, 2015). Approximately 7% of the Earth's total land area contains salt-affected soils with 23% of the Earth's cultivated land affected (Table 2.1).

Salinity and sodicity are serious concerns that can affect global food security. Many of the problems occur in communities that do not have resources to implement effective restoration practices. For example, farmers in a community observe declining yields and declining available water sources for irrigation. Associated with these decreases are increasing electrical conductivity (EC) in the soil and increasing water demands to produce food for a growing population. In many situations, these farmers do not have the money, resources, or knowledge to manage this problem. The goal of this textbook is to help fill the knowledge gap.

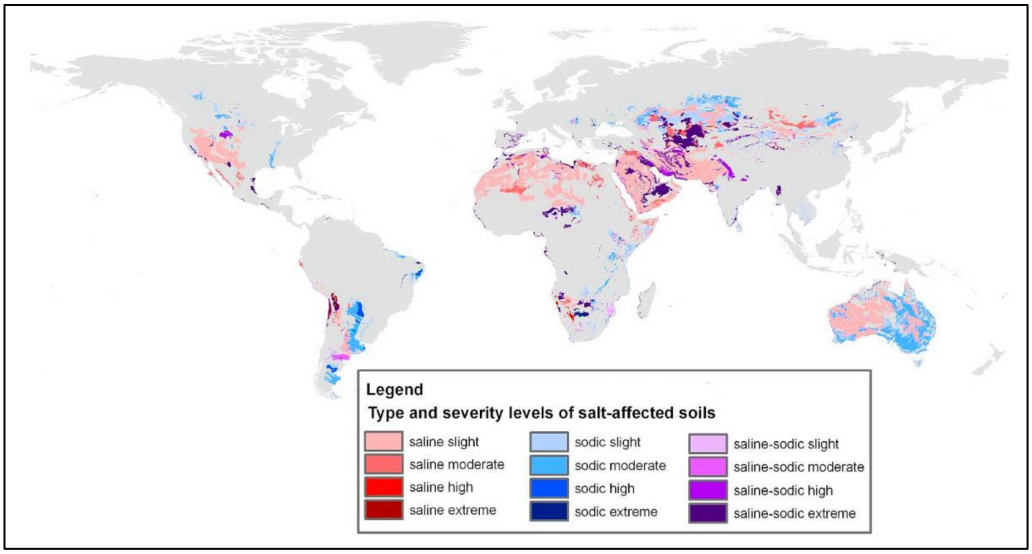

Figure 2.2. Distribution of saline, sodic, and saline-sodic soils throughout the world. (Wicke, et al., 2011).

Table 2.1. Global distribution of salt-affected soils by region (Sources: FAO and ITPS, 2015; Shahid, et.al., 2018, Enchanted Learning, 2021).

Continent/ Region	Saline Soils (m ha)	Sodic Soils (m ha)	Total Salt-affected (m ha)	Total Land Area Continent/ Region (m ha)	% Land Area Salt-affected	% World's Total Saline Soil	% World's Total Sodic Soil
Africa	123	87	210	3007	6.9	29.1	13.6
Antarctica	NA	NA	NA	1321	NA	NA	NA
Australia/ Oceania	18	340	358	769	46.6	4.3	53.2
Europe	9	21	30	994	3.0	2.1	3.2
Mexico/ Central America	2	NA	2	249	0.8	0.5	NA
North America[a]	6	10	16	2041	0.7	1.4	1.5
North, Central, and East Asia	92	120	212	2891	7.3	21.8	18.8
South America	69	60	129	1782	7.2	16.3	9.4
South and West Asia	83	2	84	1112	7.6	19.7	0.3
Southeast Asia	20	NA	20	455	4.4	4.8	NA
World Total	**421**	**639**	**1060**	**14621**	**7.2**	**100**	**100**

[a]Includes Greenland. NA = data not available.

SALINITY AND SODICITY BASICS IN THE SOIL

Saline soils have high concentrations of total ions in the soil solution. Saline soils are primarily composed of sulfates (SO_4^{2-}) and chlorites (Cl^-) of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). These ions slow and prevent seed germination and reduce plant available water. The relative concentration of ions in the soil solution are typically reported as the electrical conductivity (EC). A high EC indicates high concentrations of cations and anions. If a soil contains high Na^+ concentrations, the soil can disperse, which reduces water infiltration and permeability while increasing erosion. The dispersion risks depend on the type of clay and relationship between the Na^+ concentration and EC. Although high ion concentrations lead to saline soils and cause crop injury, the high concentration of positively charged cations will bind negatively charged clay particles together. This is called flocculation. Flocculation creates pore space for air and water exchange in soil. Drainage is not typically a problem in a solely saline soil. However, if the soil is also high in Na^+, there is the very serious risk of soil dispersion as Na^+ has limited flocculating ability and can overwhelm other cations on clay exchange sites.

In many soils, the risk of dispersion increases if the EC were to decrease but the %Na^+ on clay exchange sites remain constant (Figure 2.3). Electrical conductivity values can rapidly decrease when water percolates through soil. This is due to mass flow of ions off clay exchange sites and loss of the cations deeper into the profile as water moves downward. As overall Ca^{2+} concentration decreases with mass flow, dispersion by Na^+ of what had formerly been a flocculated soil may occur. Soils with a high montmorillonite clay to illite clay ratio are at greater risk of Na^+ dispersion (He et al., 2013).

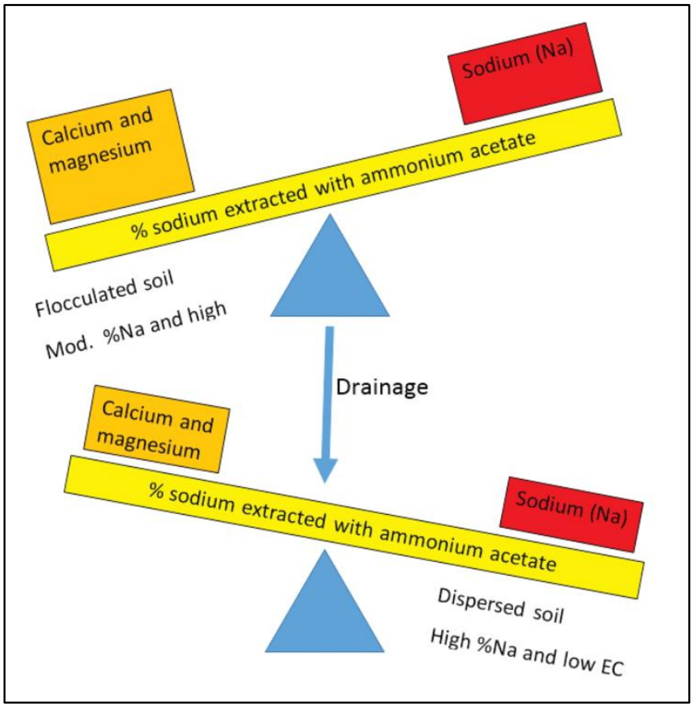

Figure 2.3. The impact of Na^+ and EC on soil dispersion. In flocculated soils, adjacent clay particles are chemically bound together by large cations with a strong valence such as Ca^{2+}. In dispersed soils, clays are no longer chemically bound together but rather are physically separated (courtesy South Dakota State University).

Soils with high concentrations of ions in the soil solution are classified as saline and soils with high concentration of Na^+ in the soil solution are characterized as sodic. However, various laboratories report the EC and amount of Na^+ on clay exchange sites differently. For example, EC can be reported as apparent EC, $EC_{1:1}$, EC_e, $EC_{2:1}$, and $EC_{5:1}$. To further complicate understanding, they often have different values but identical units. The relative amount of sodium in soil can be reported as ppm, $cmol_c$ Na^+ kg^{-1} soil, $\%Na^+$, sodium adsorption ratio (SAR), or exchangeable sodium percent (ESP).

Reliable laboratory methods exist for the identification and quantification of soil salts. However, the method may vary from lab to lab or from analysis method to analysis method. Understanding the laboratory method used is critical for correctly interpreting results and for correctly completing quantification calculations. Laboratory methods to determine the soil EC include saturated paste and soil-water suspension.

Traditionally, saturated paste extractions have been used for measuring soil EC. This extraction technique is often preferred because it does not need to be corrected for soil texture or organic matter content (Whitney, 2011). When completing a saturated paste extraction, the procedure is to mix between 200 and 250 g of air-dry, ground soil with enough distilled or de-ionized (DI) water to create a soil-water solution the consistency of a runny milkshake (Figure 2.4). Enough water has been added once the soil glistens and can run slightly with gravity when the sample is tilted on its side (Whitney, 2011). The amount of water needed varies by soil texture and organic matter content. After allowing the saturated sample to reach equilibrium over a 24-hour period, the soil-water is extracted at -0.3 bar of pressure using a vacuum pump and Büchner funnel apparatus. The solution can then be tested for electrical conductivity (EC), pH, and total dissolved salts (TDS). The Na^+, Ca^{2+},Mg^{2+}, K^+ concentrations are then determined using an appropriate analysis technique. The concentrations of Ca^{2+}, Mg^{2+}, and Na^+ are used to determine the sodium adsorption ratio (SAR). Disadvantages with the saturated paste extractions method are that it is slow, expensive, and requires training to complete correctly. An alternative approach is to prepare a soil-water solution with a predetermined ratio of soil to water such as one part soil to one part water.

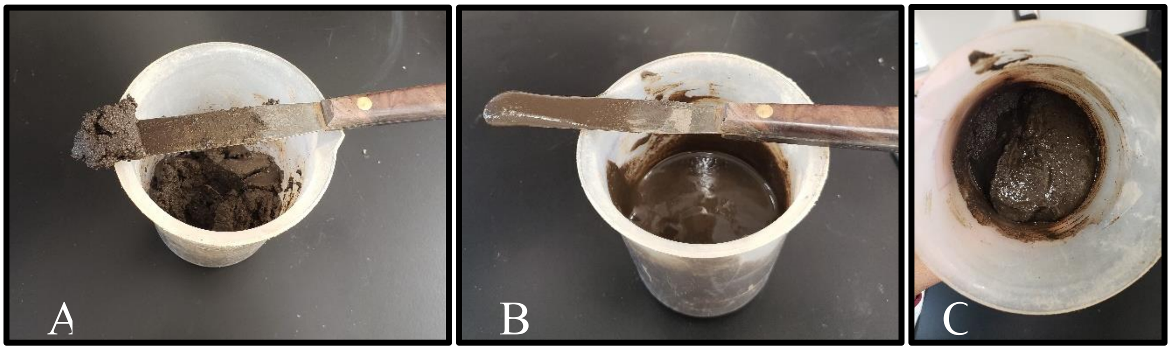

Figure 2.4. A) Undersaturated sample. Does not glisten or flow. B) Oversaturated. Too much water and too runny. C) Overhead view of appropriate saturation for saturated paste. Soil glistens and flows slightly when titled.

Some commercial laboratories will complete saturated paste extractions by request or when certain salinity-based packages are ordered from the lab. However, a soil-water suspension is easier to prepare, can be done quickly, and requires minimal training to complete. Therefore, soil-water suspensions are currently the more common approach to measure EC and pH. For the $EC_{1:1}$ method, 20 g of air-dry, ground soil is mixed with 20 mL of DI water and allowed to equilibrate for 10 to 20 minutes (Whitney, 2011). After reaching equilibrium, readings can be taken for $EC_{1:1}$ and $pH_{1:1}$. Other dilution ratios are also acceptable such as a 1:2 soil to water ratio or a 1:15 soil to water ratio (Corwin and Yemoto, 2017). The soil-water suspension method results in lower EC readings due to increasing the relative amount of water in the sample. As a result, the interpretation of soil test EC results is dependent on the method (Table 2.2).

Electrical conductivity is a measure of how well a solution can carry an electrical current and is directly related to salt content. Higher EC values indicate high salt concentrations in the soil. As noted above, the protocol is to take readings on either a 1:1 soil-water suspension or on a saturated paste extraction (Whitney, 2011). Readings are taken using an electrode submerged into the sample that measures the conductance between the positively and negatively charged electrode. Equivalent units of EC are decisiemens per meter (dS/m), milisiemens per centimeter (mS/cm), or millimhos per centimeter (mmho/cm), and EC can be reported in any of these units (Whitney, 2011). Understanding the laboratory method used is critical for correctly interpreting results.

Table 2.2 shows the difference in EC between a saturated paste and a 1:1 soil-water suspension (Clay et.al., 2012). It is evident that the breaks for a saline soil based on 1:1 soil-water suspension are lower than for saturated paste. Much of the literature available on saline soil reclamation still uses classification boundaries based on saturated paste results (Soil Survey Staff, 2022a). In addition to 1:1 suspensions being more dilute than saturated paste extractions, soil texture must also be considered in the EC results (Table 2.3). Therefore, as a land manager or a crop advisor, you must be able to interpret an analysis, determine which laboratory method was used, and align your recommendations with the appropriate regional guidelines. Electrical conductivity is routinely measured as part of a standard soil test, making it a readily-accessible metric for use by land managers and crop advisors.

Table 2.2. Range in soil salinity by analysis method for silt loam or clay loam soil (Clay et. al., 2012).

Soil Salinity Level	Saturated Paste	1:1 soil-water Suspension
	----------------dS/m----------------	
Non-Saline	0-2	0-1.3
Slightly	2.1-4.0	1.4-2.5
Moderate	4.1-8.0	2.6-5.0
Strongly	8.1-16.0	5.1-10.0
Very	>16.0	>10.0

Table 2.3. Effect of soil texture on EC from 1:1 suspensions compared to saturated paste. Note there is no texture correction for the saturated paste method (Whitney, 2011).

	Degree of Salinity				
Texture	**Non-Saline**	**Slightly Saline**	**Moderately Saline**	**Strongly Saline**	**Very Strongly Saline**
1:1 Method	--------------------------------dS/m--------------------------------				
Coarse - Loamy Sand	0-1.1	1.2-2.4	2.5-4.4	4.5-8.3	9.0+
Loamy Fine Sand - Loam	0-1.2	1.3-2.4	2.5-4.7	4.8-9.4	9.5+
Silt Loam - Clay Loam	0-1.31	1.4-2.5	2.6-5.0	5.1-10.0	10.1+
Silty Clay - Loam - Clay	0-1.4	1.5-2.8	2.9-5.7	5.8-11.4	11.5+
Saturated Paste Method	--------------------------------dS/m--------------------------------				
All Textures	0-2.0	2.1-4.0	4.1-8.0	8.1-16.0	16.1+

When looking at salinity test results, the extraction method used is denoted by a subscript “e” or “1:1”. If a soil test shows EC_e, it is understood that the EC was measured off a saturated paste extraction. If a soil test shows $EC_{1:1}$, then a 1:1 soil-water suspension was used. Results from commercial laboratories that do not specify are most likely completing soil-water suspensions due to time and expense constraints associated with saturated paste extractions. **Before making management recommendations from lab results, verify the method that particular lab used**. The method has a large impact on interpreting results correctly.

Electrical conductivity can also be measured in the field with a variety of instruments including Veris carts and EM-meters. Both sensors measure the ability to conduct an electrical current and the measured values are generally reported as apparent EC (EC_a). The EC_a values are influenced by soil moisture, bulk density, compaction, and the concentration of ions in the soil solution. Apparent EC may or may not be correlated to EC_e values depending on the aforementioned soil properties.

Another measure of soil salts besides EC is to measure total dissolved solids (TDS). Total dissolved solids represents the quantity of solids (i.e. salts, cations, anions, metals, and/or organic matter) present in a saturated paste extract. The procedure to determine TDS is to filter a known volume (mL) of saturated paste extract through a filter membrane three times with nano-pure water and transfer remaining solids to a pre-weighed evaporation dish. Heat the sample at 103°C until all liquid is evaporated. Place evaporation dish into a desiccator until it reaches room temperature and then weigh. The purpose of the desiccator is to prevent the sample from pulling moisture from the air which would impact the weight recorded. Reheat sample at 103°C for one hour, place in desiccator, and reweigh. Repeat the step of reheating, desiccating, and weighing until a constant weight is reported. Calculate the TDS using the equation:

$$TDS\ \left(\frac{mg}{L}\right) = 1000 \times \frac{(Weight\ of\ residue + dish\ (mg)) - (Weight\ of\ dish\ (mg))}{Volume\ of\ saturated\ paste\ extraction\ (mL)} \qquad [1]$$

Results are reported in mg L^{-1} (Corwin and Yemoto, 2017). Although this is the measure of all dissolved solids, not just salts, TDS can provide an estimation of soil salinity compared to non-saline soils. TDS has been estimated by multiplying EC_e by 640. The soil EC has also been used to estimate the dissolved anions or cations in the soil solution. It has been widely reported that $EC_e \times 10$ is equal to the sum of cations (mmol/L). However, this equation may not be appropriate for all soils and climates (Budak et al., 2022).

MEASURING THE RISK OF SOIL DISPERSION

The risk of soil dispersion is determined by measuring the amount of Na^+ on the soil cation exchange (CEC) sites. The Exchangeable Sodium Percent (ESP) is 100 times the amount of Na^+ (cmolc Na^+ kg^{-1}) on the cation exchange sites divided by the CEC. The equation for determining the ESP is,

$$ESP = \frac{\left\{Extractable\ Na^+\left(\frac{cmol_C}{kg\ soil}\right) - \left[\left(WaterSoluble\ Na^+\left(\frac{mmol_C}{L}\right) \times \frac{Water\ Saturation\ Percentage}{1000}\right)\right]\right\}}{Cation\ Exchange\ Capacity\left(\frac{cmol_C}{kg\ soil}\right)} \times 100 \quad [2]$$

The ESP is rarely calculated because it is very expensive and slow to measure both the Na^+ on the exchange sites and the total CEC. An alternative approach that is used by many soil testing laboratories to extract the soluble and exchangeable cations with ammonium acetate. The ammonium acetate extractable Na^+ is then divided by the sum of the cations extracted. The resulting value is $\%Na^+$ and it is determined with the equation,

$$\%Na = \frac{Ammonium\ extractable\ Na^+\left(\frac{cmol_C}{kg\ soil}\right)}{Sum\ of\ Ca^{2+}, Mg^{2+}, K^+, and\ Na^+\left(\frac{cmol_C}{kg\ soil}\right)} \times 100 \quad [3]$$

Sodium adsorption ratio is another traditional measure of sodicity and can only be analyzed from a saturated paste extraction. The SAR value is based on the Na^+, Ca^{2+}, and Mg^{2+} concentrations in the saturated paste extract. It is calculated with the equation,

$$SAR = \frac{\frac{mmol_C of\ Na^+}{L}}{\sqrt{\frac{\left(\frac{mmol_C\ of\ Ca^{2+}}{L} + \frac{mmol_C\ of\ Mg^{2+}}{L}\right)}{2}}} \quad [4]$$

In this equation, the units for Na^+, Ca^{2+}, and Mg^{2+} are mmolc/L of soil extract. Prior research shows that ESP, %Na^+, and SAR are highly correlated (DeSutter et al., 2015). Research conducted in the NGP showed that the %Na^+ is approximately equivalent to the soil SAR up to a SAR value of 20 (DeSutter et.al., 2015).

Based on the soil electrical conductivity or amount of Na^+ on the exchange sites, soils can be characterized as saline, sodic, saline-sodic, or normal. Traditionally, soils are defined as saline at EC_e >4.0 dS/m and as sodic with SAR values >13 or ESP >15 (Table 2.4; Richards, 1969). However, it is important to highlight that yield losses will occur in soils with an EC_e < 4 dS/m and soils will disperse in soils with an SAR value < 13. For example, field corn can experience yield reductions at EC_e values as low as 1.7 dS/m and some horticultural crops, such as strawberries and carrots, are even more sensitive with yield reductions occurring at EC_e of 1 dS/m (Carlson et.al, 2019). Dispersion has been observed in soils with SAR as low as 1 depending on clay mineral composition (He et. al., 2013). Therefore, salinity and sodicity boundaries are region-specific (Table 2.5).

Table 2.4. Saline, sodic, and saline-sodic boundaries as defined by the U.S. Salinity Laboratory (Richards, 1969).

Classification	**EC_e**	**SAR**	**ESP**	**pH**
	-----dS/m-----		-----%-----	
Normal	< 4	< 13	< 15	6 - 8
Saline	> 4	< 13	< 15	< 8.5
Sodic	< 4	> 13	> 15	8.5 - 10
Saline-Sodic	> 4	> 13	> 15	≤ 8.5

Table 2.5. Saline, sodic, and saline-sodic boundaries as identified in the NGP. (DeSutter et. al., 2015; Kharel et. al., 2018; Carlson et. al., 2019)

Classification	**EC_e**	**$EC_{1:1}$**	**SAR**	**ESP**	**pH**
	----------dS/m----------			-----%-----	
Normal	< 4	< 2	< 5	< 4	6 - 8
Saline	> 4	> 2	< 5	< 4	< 8.5
Sodic	< 4	< 2	> 5	> 4	8.5 - 10
Saline-Sodic	> 4	> 2	> 5	> 4	≤ 8.5

In conclusion, there are many laboratory measures of soil salinity and sodicity. Not all measurements have direct or easy to interpret application to land managers who are attempting to reduce the impact of salinity and sodicity on their operations.

Most commonly, electrical conductivity is the method used to determine presence of a salinity issue. The major consideration when interpreting EC is the laboratory method used. If a saturated paste extraction was used, there would be no need for a texture correction. However, if a 1:1 soil-water suspension was used, the influence of soil texture would need to be addressed before management decisions are made. Additionally, the method used will determine the boundaries used for a saline soil. If saturated paste was used, then the number of concern is 4 dS/m. If the more dilute 1:1 soil-water method was used, the number of concern decreases to 2 dS/m.

Traditionally, ESP or SAR are used to determine presence of a sodicity issue. Original research completed at the U.S. Salinity Laboratory observed SAR values exceeding 13 as the point where soil function was reduced due to sodium content (Richards, 1969). In the NGP, soil dispersion and reduced infiltration are observed at SAR values of 5 or greater. Understanding the variation in the effect of sodicity by region is important when assisting land managers on best management practices for their specific location. Although SAR has been used in the past, a less expensive and more easily obtained value for sodicity is the %Na^+. This number is approximately equal to SAR up to a value of 20% Na^+ and is routinely reported on standard soil tests (DeSutter et. al. 2015).

Depending on the land manager and the specific situation, one or more measurements for salinity and sodicity may be the most sensible to use. Understanding how salinity and sodicity numbers were derived in the lab, and how different methods influence results, is imperative to being an effective crop advisor or land manager.

TAXONOMIC CLASSIFICATION OF SALT-AFFECTED SOILS

During soil genesis weathering products accumulate in arid and semiarid climate zones because of mineral and rock decomposition. Mineral and rock decomposition results in the release of chlorides (Cl^-), carbonates (CO_3^{2-}), and sulfates (SO_4^{2-}) of Ca^{2+}, Mg^{2+}, Na^+, and K^+ ions into the soil solution. These ions can accumulate in upper soil horizons due to a lack of rainfall to flush them deeper into the profile. High concentrations of ions in the soil solution can affect land use. For U.S. soils, the source and location of these salts are considered by Soil Taxonomy for the characterization of salt-affected soils.

The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) conducted modern soil surveys across much of the U.S. starting in the 1960's. From these surveys, soils have been grouped, described, and classified according to the U.S. Soil Taxonomy System. Surveys were completed through physical description of soils (by hand and on foot) and encompass the majority of U.S.

soils. Soil surveys have been digitized into user-friendly formats such as Web Soil Survey (Soil Survey Staff, 2022b) and Soil Web (California Soil Resource Lab, 2022) utilizing the Soil Survey Geographic Database (abbreviated as SSURGO) (Soil Survey Staff, 2022c). These soil surveys are accompanied by laboratory analysis to confirm what is approximately measured in the field by skilled soil scientists. Total salts (EC) and sometimes SAR are included in the laboratory data, but the analyses vary from survey to survey. Taxonomic classifications are made based on results of the aforementioned soil surveys.

Soil Taxonomy is a system of soil classification used to organize soil characteristics into groups and categories as a means of communicating soil properties effectively and efficiently (Soil Survey Staff, 1999). A taxonomic name will convey information about the soil order, moisture regime, diagnostic subsurface horizons, temperature regime, clay mineralogy, particle size distribution, and potentially more. This information is organized right to left from the soil order, the broadest piece of information, to the suborder, great group, subgroup, and finally the family which is the most specific component of a taxonomic name (Figure 2.5). Currently, there are 12 soil orders, 69 suborders, 320 great groups, 3,000 subgroups, and 8,000 families defined within the U.S. Soil Taxonomy system (Osterloh, 2022).

The Houdek soil series is the state soil of South Dakota. The taxonomic name for the Houdek series is “Fine-loamy, mixed, superactive, mesic Typic Argiustoll.” While a bit of a mouthful, the taxonomic name conveys important information about the Houdek soil series. This soil is a Mollisol (prairie-derived), formed in an environment with a ustic moisture regime (crop will experience moisture stress later in the growing season) and mesic temperature regime (mean annual soil temperature ranges from 8 - 15 °C), has a significant increase in clay or the presence of clay films resulting in an argillic horizon, likely has a high CEC (superactive) from a mixture of 2:1 clays such as smectite and vermiculite, and has a clayey (fine) to loamy soil texture (Soil Survey Staff, 1999). How to dissect this taxonomic name is provided in Figure 2.5 and an example of a salt-affected soil series taxonomic name is in Figure 2.7.

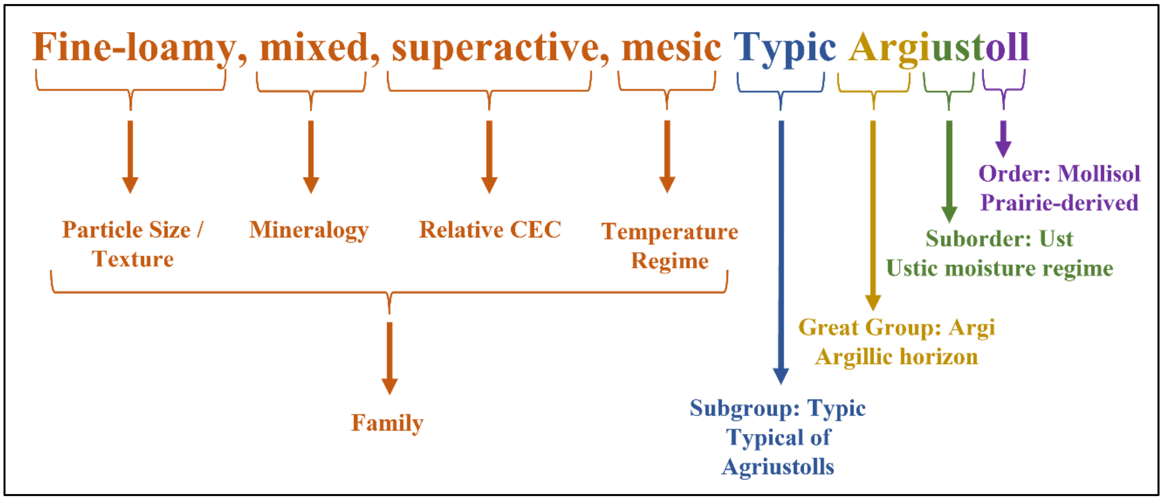

Figure 2.5. Dissection of the taxonomic name of the Houdek soil series.

Soil series can be separated into soil horizons (Fig. 2.6). Soil horizons have specific meanings that are useful for understanding individual soils. In soil horizon names, master soil horizons with subhorizon symbols k (calcium carbonate accumulation), km (calcium carbonate cemented), kk (engulfment of soil materials by calcium carbonate), n (sodium accumulation), y (gypsum accumulation), ym (gypsum cemented), yy (engulfment of soil materials by gypsum), and z (soluble salts accumulation other than calcium carbonate and gypsum) reflect the accumulation of salts due to soil genesis (e.g., Az, Bk, Bym, Byy., etc.).

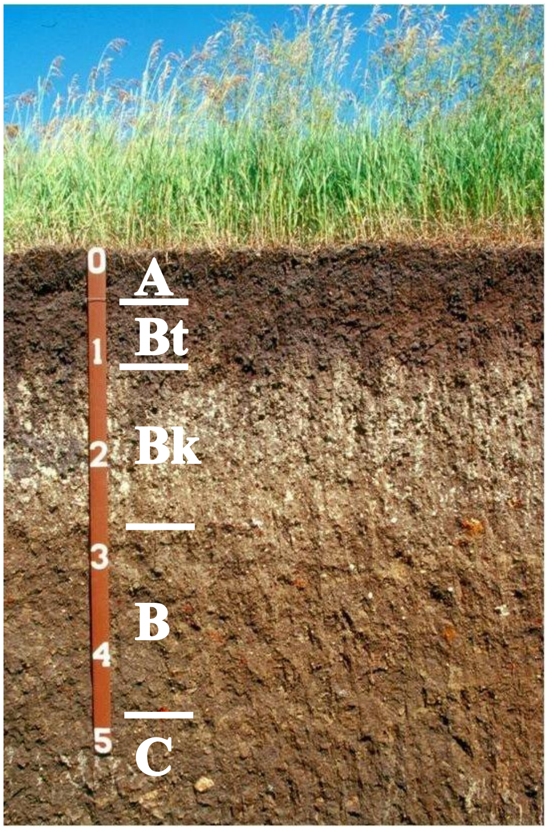

Figure 2.6. Houdek soil series and horizonation; scale is in feet. The soil profile is separated into 5 horizons, A, Bt, Bk, BC, and C. Each designation has a specific meaning. Bt means that the layer is enriched in clay, whereas the Bk means that calcium carbonate has accumulated in this layer (Courtesy of D. Malo).

WHY DOES CLASSIFICATION MATTER FOR

SALINITY AND SODICITY MANAGEMENT?

Soil Taxonomy is the classical method used in the U.S. for grouping soils with specific properties, such as salinity and sodicity. In this system, the requirements for a salic, or saline, horizon include that the EC_e must be greater than 30 dS/m (Soil Survey Staff, 1999). This value is much higher than where crop injury will be observed (Table 2.4). Therefore, many potentially saline soils may not be identified by Soil Taxonomy. This can lead to confusion when soils are mapped based off taxonomic descriptions and can lead to a gross underestimation of the issue within a region. For example, Figure 2.7 shows the taxonomic name for the Cresbard soil series. The presence of a sodic horizon is evident by the “natr” great group. This formative element stands for “natric” which is defined as a horizon having a significant clay increase and an ESP ≥15 (or SAR ≥ 13). The Cresbard is common near Clark, SD and is a soil known to have salinity issues ($EC_{1:1}$ of > 6.0 dS/m). However, the presence of salinity is not identified in the taxonomic name. Differences between Table 2.4 and the information readily available to land managers and crop advisors in Web Soil Survey means that salinity risks will be underestimated using taxonomy alone.

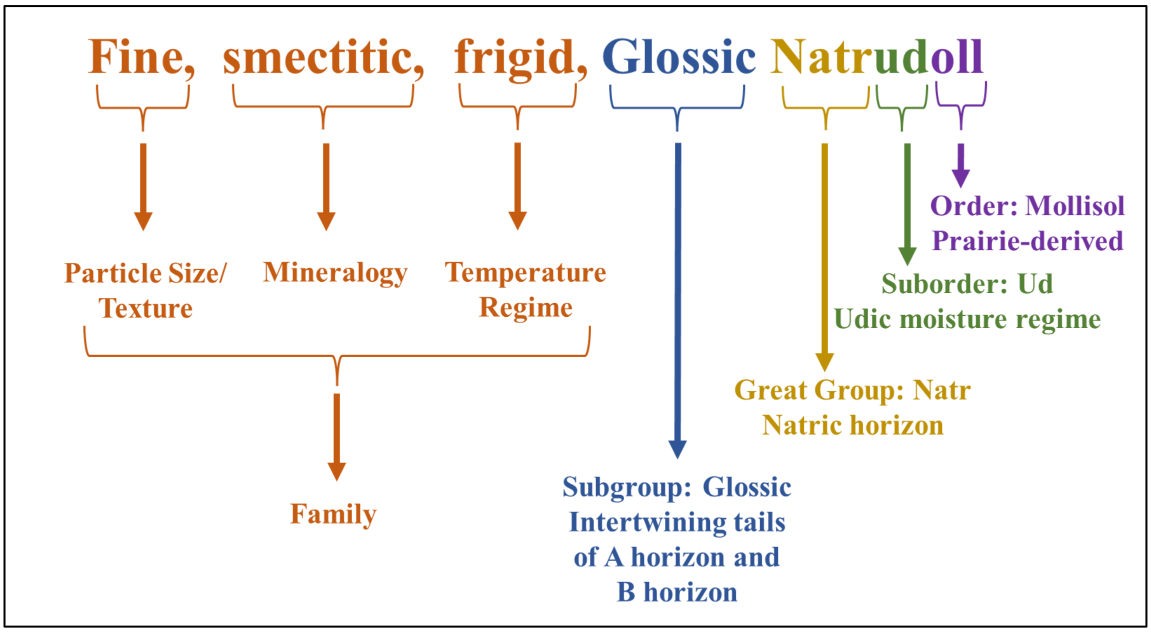

Figure 2.7. Dissection of the taxonomic name of the Cresbard soil series

As discussed in the previous section, in the NGP soils can undergo sodium-induced dispersion at SAR values as low as 5. Given that the official classification boundary for a natric horizon is an SAR ≥ 13, many soils in the NGP may experience dispersion due to elevated Na^+ concentration that are not captured in the taxonomic classification. Additionally, manmade changes to the ecosystem can accelerate salinization and sodification of soil. Human-induced acceleration of salinization and sodification is not accurately reflected in taxonomic designations.

Soil Taxonomy is abundantly useful for relaying summarized soils information in an effective and efficient format. However, it does have important limitations that must be considered when mapping the extent of salinity and sodicity, and when developing management strategies.

FORMATION PROCESSES

Artesian water: Salty artesian water (water under pressure) moves up through parent materials due to hydraulic pressure (Figure 2.8). As the water moves it carries with it ions that were released during mineral dissolution. The source area for artesian water can be local or from great distances away (e.g., the Rocky Mountains are the source for artesian water in the NGP). Evaporation and transpiration losses of water also help to draw water upward. As water evaporates, the salts are left behind at the soil surface. With time, salts accumulate and cause the formation of a saline or sodic soil (whether or not a soil will become saline or sodic will depend on the specific salts dissolved in the artesian water). The soils immediately above the source of the salty artesian water (the permeable sandstone layer) generally are bare or have very sparse vegetation. As one moves away from the area immediately above the artesian source area, the vegetation increases in height and production. With time, the salt-affected soil area tends to increase in size unless some method of intercepting the salty artesian water is found. Possibilities for interception include tile drain and ditches to prevent the water table from approaching the soil surface or planting annual or perennial plants that lower the water table.

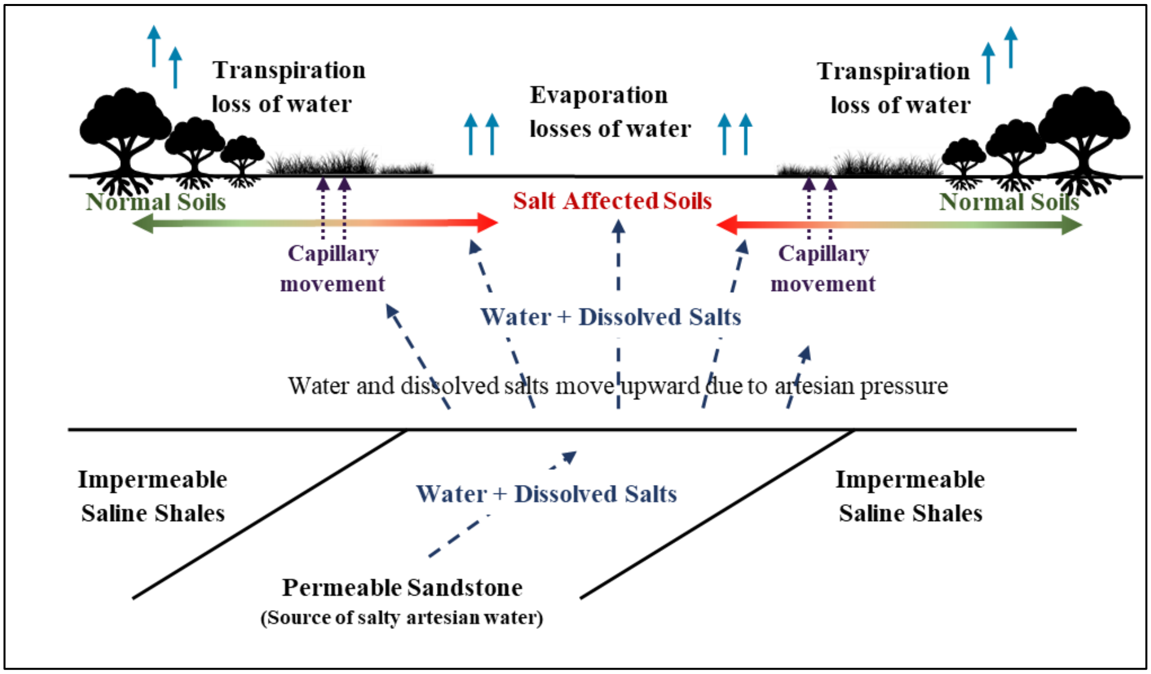

Figure 2.8. Salty artesian water and salt-affected soil formation. Salt concentration is very high above the source of artesian water and the ability for the soil to support higher plants is limited (Courtesy of D. Malo).

The Wick Effect: In many landscapes, the rims around closed depressions have elevated concentrations of ions. This is especially true in the recently glaciated areas of the NGP (Worcester et. al., 1975). In closed depressions, water accumulates in a pond at the base of the depression (Figure 2.9). The water in the pond often contains large amounts of dissolved salts from dissolution of ions present in parent materials. As water moves upward via capillary action from the pond to the shoreline or rim area around the pond, ions are transported and deposited in the rim. As the water evaporates from the rim areas the salts are left behind. Generally, soils in the middle of these seasonally flooded potholes are slightly to moderately acid while the rim soils' solum is very saline and may contain limestone and gypsum minerals. With increasing salt content, plant growth decreases and the affinity for water increases, tending to draw more water more rapidly from the pond. Plant growth decreases as the soil becomes more salt-affected. This process is often called "The Wick Effect" in that the soil behaves like a wick.

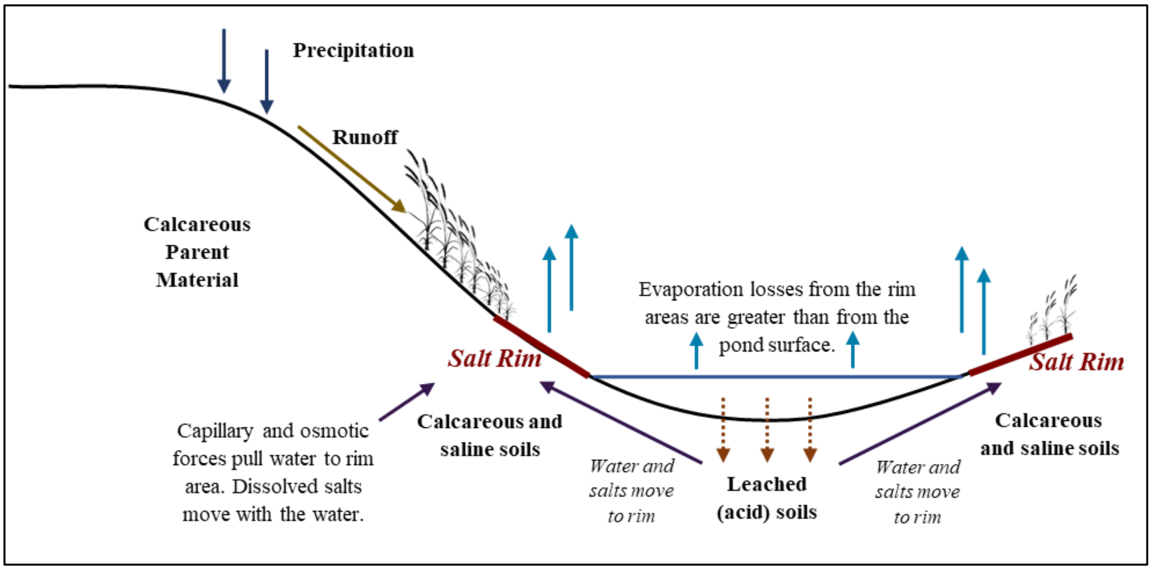

Figure 2.9. Salt rim areas surrounding prairie potholes (closed depressions) in glaciated areas. (Courtesy of D. Malo)

<u>High Water Table in low, flat areas containing salt bearing parent materials</u>: Much of the NGP was covered by a shallow inland sea during the Cretaceous Period and therefore has marine shale parent material (Darton, 1909). In South Dakota, for example, the marine formation is known as the Pierre Shale (Darton, 1909). Glaciers later scoured regions of the NGP and left deposits of glacial parent materials overtop the marine sediments (Flint, 1955). Depending on location, the glacial parent materials may be thick or thin. The marine parent material is very high in inherent Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, SO_4^{2-}, and Cl^{-} ions, and provides a deep reservoir of salt in these ecosystems. Water tables in these environments are often sitting in salt-laden parent materials and have many dissolved salts. If water inputs to a system are greater than what can drain out of the solum, water tables will rise. Under these conditions, capillary flow will carry water and soluble salts to the soil surface. The type of salt-affected soil depends on the composition of the water transported through the soil. The critical depth for capillary rise depends on the texture of the soil material, ranging from 20 cm in sand to >100 cm in clay (Keeling and Roach, 2004).

<u>Saline Seeps:</u> Summer fallow has been used for weed control and to store water from one season to another. If more water is stored than is transpired or evaporated, downward percolation occurs (Figure 2.10). As the water moves through the permeable soil profile and the underlying parent materials, the water dissolves mineral salts present in parent materials which release ions into the soil solution. Eventually, due to the topography of the system and of water hitting a layer of impermeable parent material deeper in the profile, water will flow horizontally to seep out of the soil and/or a spring will be formed. Depending on the ion composition of the water, the soils can be characterized as saline and/or sodic.

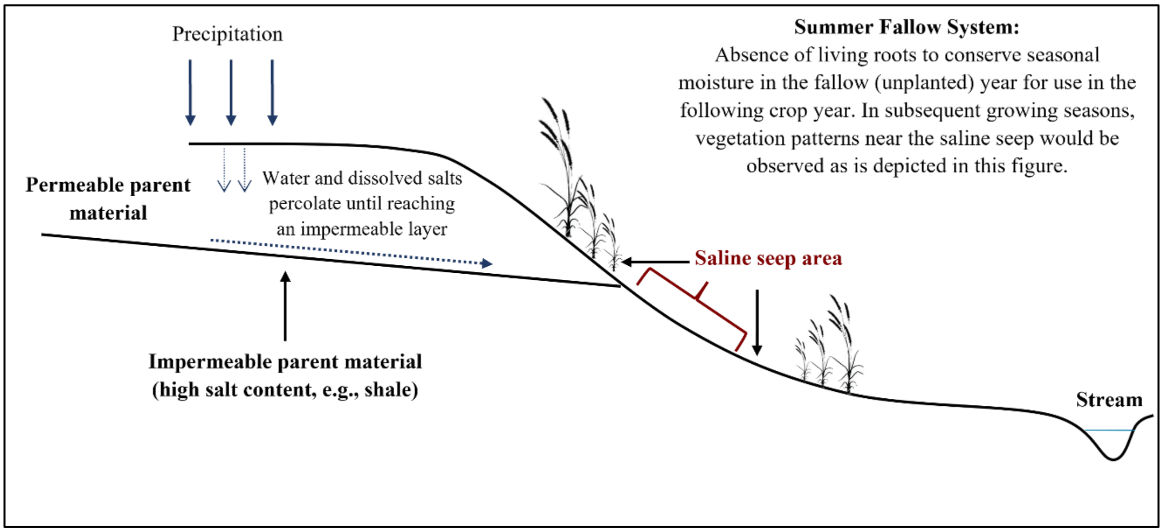

Figure 2.10. Saline and sodic soil formation by saline seep in the NGP. (Courtesy of D. Malo)

Aerosol Spray from Oceans and Large Saline Lakes: Near ocean coasts and large saline lake shorelines (20 to 100 km) aerosol spray can be a significant source of salts that result in saline or sodic soils over a period of time. For example, Na^+ additions through wet ion deposition can range from 2 to 32 kg/(ha×yr) (Figure 2.11).

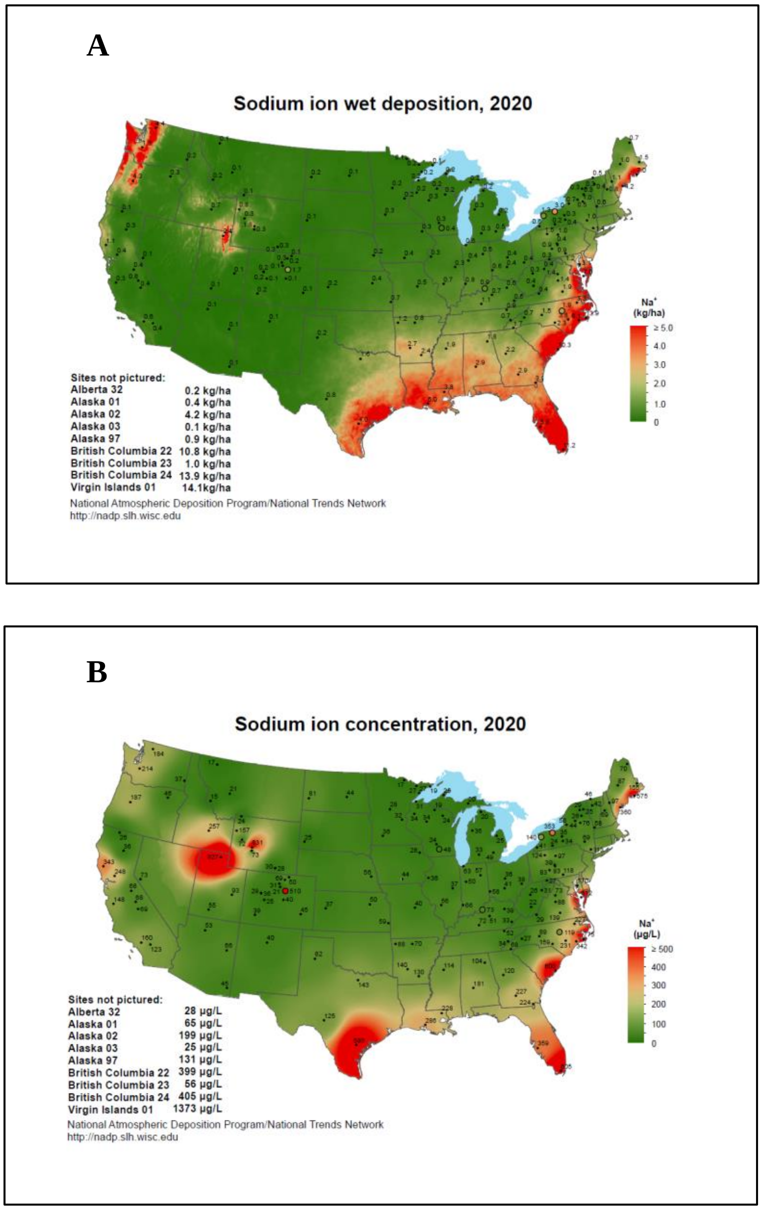

Figure 2.11. A) 2020 Sodium Ion Deposition and B) 2020 Sodium Ion Concentration in the US. Note the concentration along the coastlines and the levels of Na^+ ion additions. Source – National Atmospheric Deposition Program. 2022. https://nadp.slh.wisc.edu/maps-data/ntn-gradient-maps/ .

<u>Tides and Rising Sea Levels:</u> Another important area of salt-affected soils are the soils impacted by tides and rising sea levels. As sea levels rise, the impact of saline sea water on surrounding ecosystems has increased. More saline water is reaching inland (tidal inundation) and causing saline soil conditions due to capillary rise and salt additions from sea water inundation. Sea levels rise due to water from melting ice sheets and glaciers, and by the expansion of seawater as it warms. Note the increasing rate of sea level change since 1900 (Figure 2.12). The current rate of change is 3.4 mm increase per year (NASA, 2022).

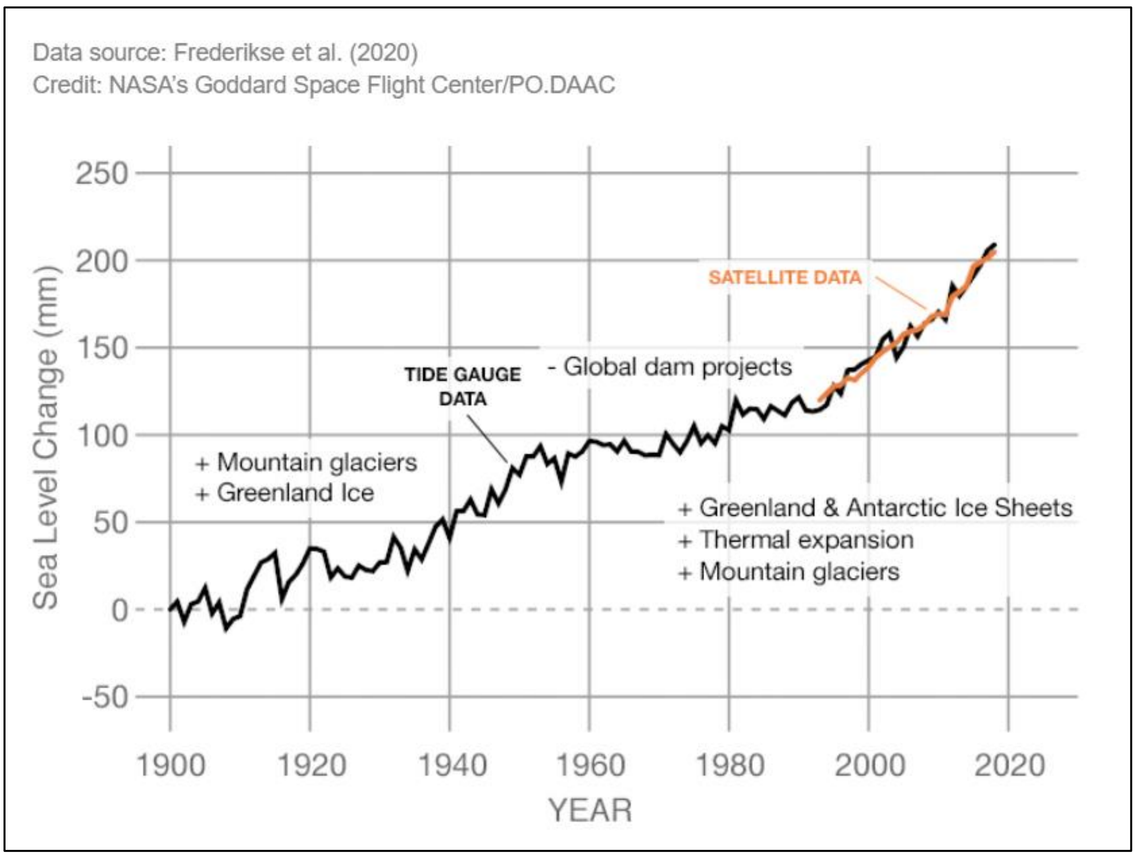

Figure 2.12. Sea Level changes from 1900 to 2020 using coastal tide gauges from 1900 to 1993 and satellite data from 1993 to present. Source – NASA, 2022. Available at https://climate.nasa.gov/vital-signs/sea-level/.

Use of Poor-Quality Irrigation Water and Poor Irrigation Management:

Irrigating crops with water that has a high concentration of sodium bicarbonate ($NaHCO_3$) can cause soil dispersion, increase the soil pH, reduce soil permeability thus restricting air and water movement, and can reduce water and nutrient availability. These reactions occur because $NaHCO_3$ reacts with hydrogen (H^+) to form carbonic acid (H_2CO_3) which forms carbon dioxide (CO_2) and water. At the completion of the reaction, the H^+ concentration decreases, Na^+ remains in the soil solution, and CO_2 is emitted to the atmosphere. All irrigation water contains dissolved cations and anions. If the irrigation practices do not account for these ions, they can increase to the point of reducing yields. If poor irrigation management (e.g., lack of good internal drainage, not adding enough high-quality water to leach salts out of the root zone, and not checking water compatibility with soil conditions) is followed, the concentration of cations and anions in the soil solution can increase and lead to saline or sodic soil conditions. When evapotranspiration happens, pure water is lost, and the salts dissolved in the water are left behind. In arid and semiarid regions, the groundwater aquifers used for irrigation are often high in salts having flowed through parent materials that are naturally high in weatherable minerals that release salt to the water. Many tons of salt can be added to a soil each year by irrigation.

When the water table in irrigated soils is close to the soil surface, capillary rise can transport ions from the water table to the rootzone. Failure to consider irrigation water salinity can reduce short- and long-term soil productivity.

Landuse Management Decisions: Changes in landuse from perennial, native, deep-rooted plants to annual, shallow-rooted crops result in reduced seasonal water usage. This change in land management can accelerate the elevating, or rising, of water tables. Depending on parent material, these water tables may be filled with dissolved ions. Elevated water tables bring salts closer to the soil surface and allow capillary rise to transport salts into the root zone creating physical and chemical soil problems.

Salt Used on Roads in Temperate Climates: Deicing materials used on winter roads over long periods of time can cause severe salt problems in roadside soils (Figure 2.13) and salt-spray damage to vegetation. As deicing materials are washed from roads, saline and sodic soil conditions develop in areas where precipitation is not sufficient to leach the salts out of the soil profile, resulting in tree and plant damage. These salts can also displace soil nutrients and reduce water absorption.

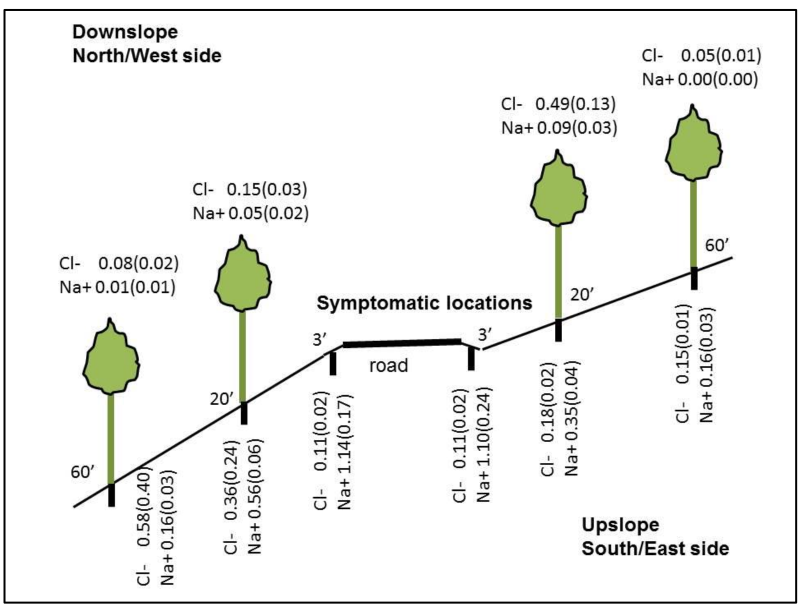

Figure 2.13. Mean (SE) foliage concentration and soil amounts (6–12 inch depth) for locations with ponderosa pines (*Pinus ponderosa*) expressing symptoms of deicing salt injury in the Black Hills of SD (Ball et al., 2017).

SUMMARY

Salinity and sodicity are global issues of historical and present concern. Although not a new agronomic/socioeconomic problem, salinity and sodicity pose a very real and very current threat to global food security. An estimated 1.5 million hectares are removed from crop production annually as a result of salinity (FAO and ITPS, 2015). With 7% of the Earth's landmass affected by salinity and sodicity, this issue is of paramount importance.

Land management has a large impact on the rate at which these soils spread. Saline and sodic soils form via multiple pathways. In the NGP, salinity and sodicity continue to expand as water tables rise, perennial systems are converted to less water-efficient annual crops, and marine parent materials provide an ample reservoir of soluble salts. In regions like California with high-value horticultural crops, brackish and salty irrigation water are contributing to salinization of productive land.

Measurement of saline and sodic soils is rooted in analyses completed on a saturated paste extraction. However, this method of extraction is time consuming and not commonplace on standard soil tests. Therefore, the 1:1 soil-water suspension for EC is more common as is ammonium acetate extraction for cations to calculate $\%Na^+$. Electrical conductivity is how total salts in the soil are measured. Most literature will cite presence of a saline soil at an EC_e of 4 dS/m. On a 1:1 soil-water suspension, a saline soil is identified at 2 dS/m or greater (Table 2.5). Understanding the relationship between EC_e and $EC_{1:1}$ is critical for land managers and crop advisors to make accurate management decisions and recommendations. Although SAR and ESP are the traditional measures of sodicity, it is not an easy value to obtain. Percent sodium, however, is commonly included in a standard soil test. Percent sodium is approximately equal to SAR up to a value of 20% Na^+ (DeSutter et.al., 2015). For soils in the NGP, an SAR of 5 or an ESP of 4% indicates high risk of clay dispersion by Na^+ (Kharel et. al., 2018; Carlson et. al., 2019).

Soil Taxonomy is a detailed classification system for relaying soil science information in a concise and repeatable manner. Although it is a living system and Soil Taxonomy is regularly receiving new edits and additions to the taxonomic hierarchy, real-time changes in soil properties are not reflected in taxonomic descriptions. It has been discussed in many parts of this chapter the serious effect human activity can have on these soils. In the U.S., many soils were surveyed and described in the 1960's, but changes in salinity and sodicity have been observed since then. Therefore, Soil Taxonomy, while helpful in grouping and categorizing soils by their key genetic and formative principles, may not be the most reliable approach to identifying and mapping saline and sodic soils.

EXAMPLE PROBLEM

- A soil has a %Na^+ of 20 and a sum of ammonium acetate extractable cations of 30 cmolc/kg soil. The land manager wants to reduce the %Na^+ to 5. How much gypsum ($CaSO_4{\cdot}2H_2O^-$) should be applied to the top 15 cm of soil? Complete this problem with the following assumptions: a) the gypsum is 100% effective and b) there are 2,000,000 kg ha^{-1} of soil in the top 15cm of the profile.

Solution:

a. Determine how many $cmol_c$ Na^+ per kg soil present when soil has 20% Na^+

$$\%Na = \frac{Na^+\left(\frac{cmol_c}{kg\ soil}\right)}{30\ \frac{cmol_c}{kg\ soil}} \times 100 = 20,\ Na^+_{Initial} = \frac{6\ cmol_c}{kg\ soil}$$

b. Determine how many $cmol_c$ Na^+ per kg soil present when soil has 5% Na^+

$$\%Na = \frac{Na^+\left(\frac{cmol_c}{kg\ soil}\right)}{30\ \frac{cmol_c}{kg\ soil}} \times 100 = 5,\quad Na^+_{Final} = \frac{1.5\ cmol_c}{kg\ soil}$$

c. Determine how much Na^+ needs to be replaced

$$6 - 1.5 = \frac{4.5\ cmol_c}{kg\ soil}$$

d. Gypsum has a molecular weight of 136 g/mol. Convert g/mol to kg/$cmol_c$.

$$\frac{kg\ of\ gypsum}{cmol_c} = \frac{136\ g}{mol} \times \frac{1\ mol}{100\ cmol} \times \frac{1\ cmol}{2\ cmol_c} \times \frac{1\ kg}{1000\ g}$$

$$= \frac{0.00068\ kg\ gypsum}{cmol_c}$$

e. How much gypsum in kg/ha would be needed to replace 4.5 $cmol_c$ of Na^+ per kg soil?

$$\frac{kg\ of\ gypsum}{ha} = \frac{4.5\ cmol_c\ Na^+}{kg\ soil} \times \frac{0.00068\ kg\ gypsum}{cmol_c} \times \frac{2{,}000{,}000\ kg\ soil}{ha}$$

$$= \frac{6{,}120\ kg\ gypsum}{ha}$$

f. Convert to tons/acre. (1 ha = 2.471 acres; 1 kg = 2.205 pounds; 1 ton = 2000 lbs)

$$\frac{Tons\ of\ gypsum}{Acre} = \frac{6{,}120\ kg\ gypsum}{ha} \times \frac{1\ ha}{2.471\ A} \times \frac{2.205\ lbs}{kg} \times \frac{1\ Ton}{2{,}000\ lbs}$$

$$= \frac{2.73\ Tons}{A}$$

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CHAPTER 3

CHEMICAL AMENDMENTS IN COMBINATION WITH PHYTOREMEDIATION CAN IMPROVE SOIL HEALTH IN NORTH AMERICA NOTHERN GREAT PLAINS SALT-AFFECTED SOILS

ABSTRACT

Saline-sodic soils impact millions of hectares in the North America Northern Great Plains (NGP). High salt concentrations reduce crop yields, increase erosion, and increase nitrous oxide emissions. Classically, chemical amendments such as gypsum ($CaSO_4 \cdot 2H_2O$) or elemental sulfur (S) are used for reclamation. Previous research indicates that reclamation is a multilayer process that involves reducing the risk of dispersion, reducing capillary movement of salts to the soil surface, and maintaining water infiltration. Remediation may not be successful if any of the layers are missing. The hypothesis of this paper was that remediation can be accelerated by combining chemical amendments alongside phytoremediation. The objective of this study was to measure the impact of landscape position and chemical amendments in conjunction with phytoremediation, on changes in the soil electrical conductivity ($EC_{1:1}$), sodium concentration (mg Na^+ kg^{-1} soil or ppm Na^+), %Na^+, the Na:EC ratio, and aggregate stability from 2020 to 2022. In May of 2018, 8.30 Mg ha^{-1} (3.7 tons $acre^{-1}$) of gypsum and 1.57 Mg ha^{-1} (0.7 tons $acre^{-1}$) of elemental S were applied to an upland soil and to a lowland soil across four phytoremediation treatments in a split-plot design. Soil samples to a depth of 15 cm were analyzed for $EC_{1:1}$ and Na^+ concentration in 2018, 2019, 2020, and 2022. Aggregate stability was measured in 2020 and 2022. In the upland soil from 2020 to 2022, phytoremediation + gypsum reduced $EC_{1:1}$ and did not influence Na^+.

Different results were observed in the lowland soil where phytoremediation + gypsum reduced $EC_{1:1}$ by 1.71 ± 1.43 dS/m, Na^+ by 1445 ± 578 ppm Na^+, and the Na:EC ratio by 117 ± 51. Sulfur and the no-amendment control had mixed impacts on the measured properties. Therefore, these findings suggest that the use of gypsum + phytoremediation is a successful management strategy for reducing salinity and sodicity in the NGP.

INTRODUCTION

Annually, soil salinity and sodicity reduce crop potential on 46 million hectares of arable land and remove up to 1.5 million hectares of arable land from production entirely (FAO and ITPS, 2015). Crop yields are severely reduced and metric tons of soil erode annually due to salinity and sodicity (Carlson et. al., 2019). The source of salts varies by region. In irrigated systems, such as California, United States (U.S.), the source of many dissolved cations and anions is salt-contaminated irrigation water, whereas in dryland South Dakota, North Dakota, and other regions of the North America Northern Great Plains (NGP) the source of salt is buried marine sediments that were deposited during the Cretaceous and Paleogene periods (Darton, 1909). Saline-sodic soils are highly susceptible to wind and water erosion due to weakened soil aggregation and increased dispersion of soil clays (Franzen et. al., 2019). Understanding the relationship among the salt source, soil characteristics, clay type, climatic conditions, and remediation strategies is needed for reclaiming and safeguarding these fragile soils.

In the NGP, salt-laden shale parent materials can be exposed on the soil surface or be deeply buried in the subsoil by overlying glacial till (Darton, 1909). Across the NGP region, the closer the marine sediments are to the soil surface, the greater the salinity and sodicity risk. Within a landscape the greatest problems are observed in low elevation areas and closed drainage systems where water tables are elevated (Franzen, 2003; Malo et. al., 1974). The relative location of marine sediments, the replacement of native mixed prairie vegetation to annual row crops, and an overall regional trend of increased annual rainfall has the potential to lead to a rising water table. As water tables rise, the capillary movement of subsurface salts to the soil surface increases. Unless a high rainfall event occurs in the presence of adequate drainage to allow for water infiltration, excess cations and anions remain in the surface soil after the water evaporates. The extent of this problem appears be increasing and is expected to increase 50% by 2050 (Butcher et al., 2016; He et al., 2018). The failure to address these concerns will threaten global food security.

Previous research indicates that reclamation is a multilayer process that involves reducing the risk of dispersion, reducing capillary movement of salts to the soil surface, and maintaining water infiltration. Remediation may not be successful if any of the layers are missing. Soil dispersion risks can be evaluated by considering the Na^+ (mg Na^+ kg^{-1} soil) to EC (dS/m) ratio (Kharel et al., 2018, Budak et al., 2022). Soil EC and Na^+ have opposite impacts on soil dispersion with EC shrinking the clay diffuse double layer (flocculating soil) and Na^+ expanding the double layer (dispersing soil) (Essington, 2000). Expansion of the clay diffuse double layer will eventually result in soil dispersion. He et al. (2013) reported that dispersion occurs at different Na^+ concentrations depending on clay mineralogy. For instance, montmorillonite clays can disperse at SAR values as low as 1. Dispersed soils can adversely affect soil, water, and air quality from intense erosion events (Figure 3.1).

Water movement through soil and the removal of excess gravimetric water is often improved by installing tile drainage. However, for tile drainage to be effective, gravimetric water must be able to percolate through the soil layer. Budak et al. (2022) reported that water transport through a soil layer may slow when the Na:EC ratio exceeds 600 due to Na^+ dispersion of clays and reducing pore space. In these soils, the movement of Na^+ from the soil surface to the subsurface can increase the Na:EC ratio and eventually result in drainage failure. This ratio suggests that it may be possible to preserve water movement by maintaining or increasing the EC while reducing the Na^+ concentration. This is often accomplished by applying gypsum ($CaSO_4 \cdot 2H_2O$) to the soil (Kharel et. al., 2018; Franzen et. al., 2019; Prapagar et.al., 2012). Gypsum provides a source of Ca^{2+}, which is used to replace Na^+ on negatively charged clay exchange sites (Zhao et. al., 2018; Alcivar et.al., 2018; Sundha et. al., 2020). The Na^+ is then removed from the root zone with percolating rain or irrigation water via mass flow.

The need to maintain a relatively high EC value must be balanced with the effect of EC on plant growth. Crop yields and high EC are negatively correlated to each other, and depending on the crop species, yield losses can occur at EC_e values as low as 1 dS/m (Carlson et al., 2019). Prior studies have highlighted the serious risk of crop failure if the balance between soil and plant health is not appropriately established (Birru et al., 2019). Findings from these studies show that reclamation of sodic and saline-sodic soils is a balancing act between elevating EC to a level that prevents dispersion, but not so high as to adversely impact crop production.

This is the fourth 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 N_2O emissions 268%. The second paper assessed the impact of phytoremediation on soil and plant health (Fiedler et. al., 2022). The third paper reported on the amount of biomass produced in the phytoremediation treatments (Clay et. al., 2022). This is the fourth paper, and it reports on the combined impact of phytoremediation and chemical amendments on $EC_{1:1}$, Na^+ (mg Na^+ kg^{-1} soil), $\%Na^+$, and aggregate stability. A related paper conducted at a separate study site assessed the effectiveness of tile drainage as a potential solution for managing salinity and sodicity (Budak et al., 2022).

Phytoremediation has had some restoration success in the NGP (Birru et al., 2019; Budak et al., 2022; Fiedler et. al., 2022). However, what these studies failed to consider was the effect of using multiple reclamation treatments in tandem on saline-sodic soil restoration. Therefore, to fill the missing knowledge gap, the hypothesis of this paper was that remediation can be accelerated by combining chemical amendments with phytoremediation. The objective of this study was to measure the impact of landscape position and chemical amendments, in conjunction with phytoremediation, on changes in the soil electrical conductivity ($EC_{1:1}$), sodium concentration (mg Na^+ kg^{-1} soil), $\%Na^+$, the Na:EC ratio, and aggregate stability from 2020 to 2022. Corn yield and phytoremediation biomass were also monitored as a component of this research.

MATERIALS AND METHODS

Site Description

This four-year study took place near Carpenter, SD (44.70323°, -97.8784°) beginning in fall of 2017 in a conventionally-managed corn (*Zea mays*)- soybean (*Glycine max* (L.)) rotation (Figure 3.1). Baseline composite soil samples were taken in

2018 and initial soil properties are reported in Table 3.1. Fiedler et al. (2021) provided information on the soil microbial community structure and water infiltration.

The experiment was conducted on a non-saline upland soil and on a saline-sodic lowland soil. The upland soil was a Forman-Cresbard loam with 3 to 6 percent slopes (Fine-loamy, mixed, superactive, frigid Calcic Argiudoll; Fine, smectitic, frigid Glossic Natrudoll) and the lowland soil was a Cresbard-Cavour loam with 0 to 3 percent slopes (Fine, smectitic, frigid Glossic Natrudoll; Fine, smectitic, frigid Calcic Natrudoll) (Soil Survey Staff, 2018). The upland and lowland 0-15 cm soils had $EC_{1:1}$ values of 0.5 and 6.7 dS/m, respectively, and SAR values of 1.79 and 22, respectively (Fiedler et al., 2022). Based on the EC and SAR values, the upland soil was classified as non-saline and non-sodic, whereas the lowland soil was characterized as saline-sodic. The organic matter content was determined using the loss on ignition technique (Combs and Nathan, 2011) and was 2.37 and 2.16 mg kg^{-1} in the upland and lowland soils, respectively. The bulk densities were 1.16 and 1.37 g $cm^{3\ -1}$ in the upland and lowland soils, respectively. Sum of cations was the sum of the Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} extracted with 1 M ammonium acetate. The $\%Na^{+}$ value was determined with the equation, $100 \times \frac{Na_{cmol\ charge}}{\sum cations_{cmol\ charge}}$, where the cations were Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}.

Figure 3.1. Photo of field edge highlighting high erosion potential, gully formation, and soil loss from field (Soil series: Cresbard-Cavour loam). Photo taken by Dr. Cheryl Reese May 15, 2018.

Table 3.1. Baseline 2018 soil chemical and physical characteristics for the study site

Soil	$EC_{1:1}$	$pH_{1:1}$	Ca^{2+}	Na^{+}	$\%Na^{+}$	SAR	Sum of cations	SO_4^{2-}	Cl^{-}	SOM	Bd
	dS/m	-	mg/kg	mg/kg	%	-	$cmol_c/kg$	mg/kg	mg/kg	mg/kg	g/cm^3
Upland	0.5	6.9	2376	160	1.9	1.79	18.3	132†	13†	2.37	1.16
Lowland	6.7	7.7	3214	3021	30.1	22	43.2	2807†	187†	2.16	1.37

† - Sulfate and chloride data from samples collected in 2021 (Clay et. al., 2022)
SOM- Soil Organic Matter; Bd- Bulk Density; Upland Soil Series: Forman-Cresbard loam, 3-6% slope; Lowland Soil Series: Cresbard-Cavour loam, 0-3% slope

Experimental treatments

In 2018, four phytoremediation treatments were established on the two landscape positions in a randomized complete block design (RCBD). The four vegetation treatments were 1) no-vegetation control (nothing was planted), 2) corn seeded at a rate of 79,000 seeds per hectare, 3) perennial grass Mixture 1 (Certified First Strike slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Shinners], and Shoshone beardless wildrye [*Leymus triticoides* (Buckley) Pilg.]), and 4) perennial grass Mixture 2 (Certified First Strike slender wheatgrass, Garrison creeping meadow foxtail (*Alopecurus arundinaceus*) western wheatgrass (*Agropyron smithii* Rydb) and AC Saltlander green wheatgrass (*Elymus Hoffmannii*)). The perennial grass mixtures were dormant seeded at a 6 mm depth using a FLEX-II drill (Traux Company, Inc., New Hope, MN) into 13 m strips on 15th December 2017 and overseeded with the same mixture on 24th October 2018 due to limited establishment in 2017. Seeding rates are reported in Fiedler (2020). Corn was not seeded in either the upland or lowland soil in 2021 or 2022. From 2019 onward, perennial plants were allowed to establish in the no-vegetation control and corn plots (Clay et al., 2022). Because phytoremediation treatment differences in biomass production were not detected in 2020 and 2021 (Clay et. al., 2022), soil chemical and physical treatment differences were attributed to the combined impact of phytoremediation + chemical amendments.

In May of 2018, the phytoremediation treatments were divided into a split-plot design with three amendment treatments (gypsum, elemental sulfur, and no-amendment control) that were randomly established as RCBD in each phytoremediation treatment (Freund et. al., 2010). Gypsum was applied at a rate of 8.30 Mg ha^{-1} (3.7 tons per acre), and elemental sulfur was applied at a rate of 1.57 Mg ha^{-1} (0.7 tons per acre) to the appropriate plots. Gypsum and elemental sulfur rates were calculated using exchangeable sodium percent and cation exchange capacity based on methods for sodium replacement outlined in Clay et. al. (2012). Amendments were lightly raked into the top 15 cm of soil.

Soil Sample Collection

Ten, 0-15 cm soil cores were collected from each amendment plot using a 2 cm diameter probe. These cores were composited into one sample per plot (n_{upland} = 48, $n_{lowland}$ =48). Sampling was completed on 29 June 2018, 13 June 2019, 15 June 2020, and 6 June 2022. Samples were analyzed for $EC_{1:1}$ and ammonium acetate extractable Na^{+} as reported in Fiedler (2020). Soil $EC_{1:1}$ was determined from a 1:1 soil-water suspension. Aggregate samples collected on 23 June 2020 were separated into the 0-5 cm and 5-15 cm depths. Aggregate stability samples collected 6 June 2022 were taken from the 0-15 cm depth to correspond to the composite samples. Aggregates between 1-2 mm were analyzed for stability via wet sieving (Yoder, 1936).

Statistical analysis

The statistical analysis was conducted in R Studio (R Core Team, 2021) using analysis of variance (ANOVA) for split plot design from the library agricolae. Landscape positions were reported separately by ANOVA. Chemical amendments impact on soil chemical and physical properties were aggregated over phytoremediation due to no phytoremediation × amendment interaction. Yield from the phytoremediation treatments were reported in Clay et al. (2022). Fisher's Least Significant Difference (LSD) at the 0.05 level was used to determine differences between means.

RESULTS AND DISCUSSION

Climatic conditions

The mean annual precipitation for this site is 43-61cm and the mean annual air temperature is 2.8-7.8°C with 120-150 frost-free days (Soil Survey Staff, 2018). Annual precipitation (mm) and temperature (°C) totals for the duration of the study are reported in Table 3.2. South Dakota experienced an abnormally wet, cool year in 2019. In 2019, rainfall was approximately 30% higher and temperatures were 1.4°C cooler than the 30-year average. High rainfall in 2019 provided an opportunity for excess water to percolate through the soil in areas where adequate drainage was feasible. However, Fiedler et. al. (2021) reported severely reduced water infiltration in the lowland soils at this site. Limited infiltration would not allow for percolation of salts out of the root zone in the lowland soils, although the abnormally high rainfall would still contribute to rising water tables from infiltration at non-saline, non-sodic upper landscape positions (Fiedler et. al., 2021). Environmental conditions in 2018 and 2020 were overall warmer and drier than the 30-year average, while 2021 was similar to the 30-year average.

Table 3.2. Average annual (Jan-Dec) precipitation (mm) and air temperature (°C), for 2018-2022, and the 30-year average (1981-2010). Data retrieved from the National Oceanic and Atmospheric Association NOWData portal using data from Clark, SD weather station ID CLARK NUMBER 2, SD US (44° 52' 54.84" N, -97° 44' 3.12" W).

	Precipitation					
Month	2018	2019	2020	2021	2022	30 Year Average
			----------mm----------			
January	0	25	18	14	8	13
February	14	31	9	9	12	14
March	7	58	16	37	9	31
April	37	78	34	63	68	50
May	51	197	53	57	155	75
June	54	75	101	42	39	100
July	81	171	99	89	118	89
August	83	139	36	73	45	72
September	58	133	28	75	10	71
October	59	65	21	139	10	52
November	79	19	10	16	48	23
December	14	38	20	11	-	14
Total	537	1029	445	625	464	604

	Average Air Temperature					
Month	2018	2019	2020	2021	2022	30 Year Average
			----------°C----------			
January	-11	-12	-10	-4	-12	-11
February	-14	-17	-8	-13	-11	-8
March	-2	-5	1	3	-1	-2
April	0	6	5	6	3	6
May	11	11	12	13	13	13
June	22	20	22	23	20	19
July	22	22	23	23	22	22
August	21	20	22	22	21	21
September	17	17	15	18	18	15
October	6	4	4	12	9	8
November	-4	-2	3	2	-2	-1
December	-4	-6.5	-4	-5	-	-9

Treatment impacts on $EC_{1:1}$ and yields in 2018 and 2019

In the upland soil, the application of gypsum increased the $EC_{1:1}$ in 2019 (Table 3.3). This increase was expected and was attributed to the solubilization of gypsum into Ca^{2+} and SO_4^{2-}. These results are consistent with the goal of maintaining the $EC_{1:1}$ above a critical soil dispersion value (He et. al., 2013). In some soils, increasing the $EC_{1:1}$ can have detrimental impacts on crop yields (Carlson et al., 2019). However, in this upland soil, the $EC_{1:1}$ values would not be expected to reduce corn yields as they are less than 2.0 dS/m (Carlson et. al., 2019). In the upland soil, corn yields in 2018 and 2019 were 6881 and 2002 kg ha^{-1}, respectively (Clay et al., 2022). Low yields in 2019 were attributed to high rainfall and cool conditions (Table 3.2). The perennial grass yields in Mix 1 increased from 1705 kg ha^{-1} in 2018 to 9038 kg ha^{-1} in 2019. This increase was attributed to plant establishment that occurred in 2018. Mix 2 had similar yield increases.

In the lowland soil, the application of gypsum or elemental S did not influence $EC_{1:1}$ in 2019. However, due to the $EC_{1:1}$ values exceeding 2 dS/m in the lowland soils, yields were expected to be lower than in the upland soil. Corn yields in 2018 and 2019 were 1302 and 1448 kg grain ha^{-1}, respectively (Clay et al., 2022). These yields were much lower than the county average and they were attributed to many factors including salt concentration, flooding, late planting, and cool conditions. Perennial cool season grasses show greater potential for increased biomass potential than conventional corn production in these heavily saline-sodic soils. In this soil, biomass yields for Mix 1 increased from 246 kg ha^{-1} in 2018 to 6400 kg ha^{-1} in 2019 (Clay et al., 2022). Perennial cool season biomass yields in 2018 were lower than corn yields because this was the year of establishment, whereas yields in 2019 were higher than the corn yields.

Treatment impacts on $EC_{1:1}$ and yields in 2020 and 2022

In the upland soil in 2020, $EC_{1:1}$ increased from 0.26 in the no-amendment control to 0.42 and 0.39 dS/m in the gypsum and sulfur treatments, respectively ($p = 0.038$). Neither gypsum or sulfur reduced ammonium acetate extractable Na^+. Reductions in $EC_{1:1}$ and the lack of impact on ammonium acetate extractable Na^+ resulted in gypsum and sulfur reducing the upland Na:EC ratio from 351 in the no-amendment control to 153 and 166, respectively ($p < 0.001$). In 2022, chemical amendments did not have an effect on upland $EC_{1:1}$ or Na^+, but sulfur did reduce the Na:EC ratio from 244 in the no-amendment control to 139 ($p = 0.01$) (Table 3.3). In the upland position, corn yield and perennial plant seed germination would not be expected to be reduced by $EC_{1:1}$ in either 2020 or 2022. In 2020, the upland corn yield was 10684 kg ha^{-1}. Corn was not seeded in 2021 or 2022. For Mix 1, yields were 3985 kg ha^{-1} in 2020 and 2123 kg ha^{-1} in 2021. Mix 2 had similar yields. Biomass yields in the non-planted control plots were 4043 kg ha^{-1} in 2020 and 2002 kg ha^{-1} in 2021. These yields were similar to the yields of Mix 1 and 2 indicating widespread colonization of bare soil by phytoremediation treatments across the study site.

In the lowland soil in 2020, the chemical treatments did not influence $EC_{1:1}$, ammonium acetate Na^+, or the Na:EC ratio (Table 3.3). However different results were observed in 2022 when gypsum lowered the $EC_{1:1}$ from 6.49 to 4.54 dS/m and elemental sulfur increased $EC_{1:1}$ from 6.49 to 7.53 dS/m ($p = 0.005$) (Table 3.3). Because the decrease in $EC_{1:1}$ was unexpected it is likely that multiple mechanisms, such as climate differences and drainage facilitation by phytoremediation, contributed to this change.

In 2021 and 2022 corn was not planted in the lowland site. Mix 1 biomass yields were 3962 kg ha^{-1} in 2020 and 1785 kg ha^{-1} in 2021. Yields in Mix 2 were 4922 kg ha^{-1} in 2020 and 1801 kg ha^{-1} in 2021. In the no-vegetation control sites, biomass yields were 3476 kg ha^{-1} in 2020 and 1851 kg ha^{-1} in 2021. These results show that by 2021, biomass yields in the no-vegetation control plots and perennial grass treatments were similar.

Table 3.3. Electrical conductivity ($EC_{1:1}$), Na^+ concentration, and Na:EC ratio in surface soil (0-15 cm) collected from upland and lowland landscape positions in 2018 (baseline), 2019, 2020, and in 2022 as affected by chemical amendments. The 95% confidence intervals for $\Delta_{2020\text{-}2022}$ are reported in the final column. A positive Δ value indicates that the value decreased from 2020 to 2022.

Landscape position	Treatment	Year				
		2018	2019	2020	2022	$\Delta_{2020\text{-}2022}$
$EC_{1:1}$				dS/m		
	None	0.5	0.38a	0.26a	0.23	0.03 ± 0.10
Upland	Sulfur		0.59b	0.39b	0.25	0.14 ±0.46
	Gypsum		0.89c	0.42b	0.20	0.22 ±0.11
	p-value		<0.001	0.038	ns	
Lowland	None	6.7	8.42	6.70	6.49b	0.21 ± 2.01
	Sulfur		9.04	7.12	7.53b	-0.41 ± 2.53
	Gypsum		7.80	6.25	4.54a	1.71 ± 1.43
	p-value		ns	ns	<0.005	
Na				mg /kg		
Upland	None	160	92.8	92.8	50.5	42.3 ± 34.1
	Sulfur		97.8	66.3	37.4	28.9 ± 52.2
	Gypsum		99.9	80.2	39.4	40.8 ± 42.4
	p-value		ns	ns	ns	
Lowland	None	3021	3487	3456	2466ab	990 ± 775
	Sulfur		3533	3826	2867b	959 ± 1034
	Gypsum		3175	3186	1741a	1445 ± 578
	p-value		ns	ns	0.03	
Na/EC				ppm Na/$EC_{1:1}$		
Upland	None	320	259b	351b	244b	107 ± 71.7
	Sulfur		165a	153a	139a	14 ± 48.5
	Gypsum		149a	166a	203b	-37 ± 73.4
	p-value		0.01	<0.001	0.01	
Lowland	None	451	416	497	352	145 ± 65.2
	Sulfur		392	527	347	180 ± 48.6
	Gypsum		413	495	378	117 ± 51.1
	p-value		ns	ns	ns	

Lower case letters indicate significant differences within columns $\alpha = 0.05$. (ns = not significant). (Upland Soil Series: Forman-Cresbard loam, 3-6% slope; Lowland Soil Series: Cresbard-Cavour loam, 0-3% slope).

Temporal changes in $EC_{1:1}$ and ammonium acetate extractable Na^+

From 2020 to 2022, $EC_{1:1}$ decreased in the upland gypsum treatment. In the upland no-amendment control the decrease in $EC_{1:1}$ was 0.03 ± 0.10 dS/m and was 0.14 ± 0.46 dS/m in the elemental sulfur treatment. In the gypsum treatment, the decrease was 0.22 ± 0.11 dS/m. Differences between the treatments suggest that high rainfall in 2019, alongside a combination of time and phytoremediation, numerically reduced $EC_{1:1}$ in the no-amendment control and in the elemental S treatment, but significantly reduced $EC_{1:1}$ in the gypsum treatment. In the lowland soil, mixed results were observed. The changes in $EC_{1:1}$ from 2020 to 2022 were 0.21 ± 2.01, -0.41 ± 2.53, and 1.71 ± 1.43 dS/m in the no-amendment control, sulfur, and gypsum treatments, respectively. A negative value suggests that $EC_{1:1}$ numerically increased in the sulfur treatment although it was not significant based on the 95% confidence interval. Gypsum + phytoremediation had the greatest effect in reducing $EC_{1:1}$ from 2020 to 2022 in both the lowland and upland soil.

From 2020 to 2022 in the upland soil, Na^+ decreased from 42.3 ± 34.1, 28.9 ± 52.2, and 40.8 ± 42.4 mg Na^+ kg^{-1} in the untreated, elemental S, and gypsum treatments, respectively. In the lowland soil the decrease was 990 ± 775, 959 ± 1034, and 1445 ± 578 mg Na^+ kg^{-1} soil in the untreated, elemental S, and gypsum treatment, respectively, from 2020 to 2022. These results show that, while all treatments saw numeric reductions in Na^+ in both the lowland and upland soils, only gypsum and the no-amendment control had significant changes from 2020 to 2022.

The theory behind applying elemental sulfur is that microbial populations in the soil will oxidize S to sulfuric acid ($H2SO_4^{2-}$) and release hydrogen ions (H^+) (Zhao et. al., 2022). As H^+ cations are released to the soil-water, the pH will decrease, facilitating the solubilization of soil salts and exchange off clay exchange sites, which allows for the downward movement of exchanged salts out of the root zone with rainwater. Fiedler et. al. (2021) determined through phospholipid fatty acid analysis that microbial biomass is greatly reduced in saline-sodic soils compared to normal soils. Lower microbial populations could be one explanation for why elemental sulfur was less effective in reducing $EC_{1:1}$ or Na^+ in the lowland soil.

Reductions in both $EC_{1:1}$ and Na^+ were observed in the lowland gypsum treatment from 2020 to 2022. Gypsum reduces sodicity by replacing Na^+ on clay exchange sites with Ca^{2+} thus allowing Na^+ to leach through the soil via mass flow with rainwater. However, in highly degraded and dispersed sodic soils, the ability for Ca^{2+} to replace Na^+ and to flocculate soil clays to the degree of producing channels for water movement is limited. Given that the no-amendment control also saw significant reductions in Na^+, it is feasible that phytoremediation influenced the efficacy of gypsum by creating root channels for mass flow of cations. For example, in 2018 biomass yields were less than 558 kg ha^{-1} in all treatments, whereas in 2020 biomass yields in no-vegetation control and planted plots were >3400 kg ha^{-1} (Clay et. al., 2022). Biomass was so great in non-planted plots due to colonization by weed species such as foxtail barley (*Hordeum jubatum*) and kochia (*Bassia scoparia*), and by encroachment of the planted perennial grass mixes. For this reason, separating phytoremediation effects from amendment effects is difficult.

The importance of plants in the restoration of saline-sodic soils was previously reported by Halvorson (1984) in a study conducted in Montana. In this semiarid to arid region, fallow was historically used to conserve water. This study investigated if the use of fallow contributed to a growing salinity problem in lower landscape positions. In 1979, the EC_e in the surface soil at two saline seeps were measured. In the saline seep area, the treatments were soil ridging, straw mulch, application of gypsum, fallow, and no-treatment. Of these three treatments, straw mulch was the most effective at preventing EC_e increases. At one of the sites, when alfalfa growing in the water recharge area was replaced with fallow, soil EC_e in the saline seep appeared to be returning to its original value. Halvorson (1984) attributed this increase to a reduction in evapotranspiration, which resulted in a decrease in depth to the water table and increased capillary movement water and associated cations and anions to the soil surface. Halvorson (1984) findings support our hypothesis that, in complex landscapes, phytoremediation interacts with physical and chemical amendments to affect soil health.

Soil aggregate stability

A metric that provides an index of soil strength and aggregate stability is the Na^+ to $EC_{1:1}$ ratio (Table 3.3). This ratio can be used to assess water movement and the clay dispersion risk as Na^+ and $EC_{1:1}$ counterbalance each other with Na^+ expanding the clay diffuse double layer (dispersion) and $EC_{1:1}$ shrinking the diffuse double layer (flocculation) (Essington, 2000). However, because different clays disperse at different Na:EC ratios, guidelines are site-specific (He et al., 2013). Budak et al. (2022) showed that in Great Bend (fine loamy, mixed, super active, Typic Argiustoll), Beotia (fine, smectitic, frigid, Pachic Argiudoll), Harmony and Aberdeen (fine silty, smectitic frigid Calcic Natrudoll) soils, the risk of dispersion (when hydraulic conductivity decreases to 0 mm/hr) occurs at a Na:EC ratio of approximately 600.

In this study, associated with changes in $EC_{1:1}$ and Na^+ concentrations from 2020 to 2022, were decreases in the Na:EC ratio. In the upland soil from 2020 to 2022, the Na:EC ratio decreased in the no-amendment control by 107 ± 71.7 and numerically by 14 ± 48.5 in the sulfur treatment. The Na:EC ratio numerically increased by -37 ± 73.4 in the gypsum treatment. In the lowland soil from 2020 to 2022, the ratio decreased 145 ± 62.2, 180 ± 48.6, and 117 ± 51.1 in the no-amendment control, sulfur, and gypsum treatments respectively. These findings support our hypothesis that in the lowland soil, growing plants produced root channels, which allowed for oxygen exchange and the movement of water and dissolved anions and cations from 2020 to 2022 (Table 3.3).

Soil aggregate stability was determined on selected soils in 2020 and on all treatments in 2022. In 2020, the percent stable aggregates were lower in the 0-5 cm than the 5-15 cm depth in both the upland and lowland positions (Fig. 3.2). In addition, soils from the lowland position were less stable than in the upland. There were many differences between the upland and lowland soil chemical characteristics. Lowland soil had higher Na^+, $\%Na^+$, and SO_4^{2-} concentrations than upland soils. The relatively low sulfate concentrations in the upland soils may have resulted from downward movement of SO_4^{2-} with percolating water.

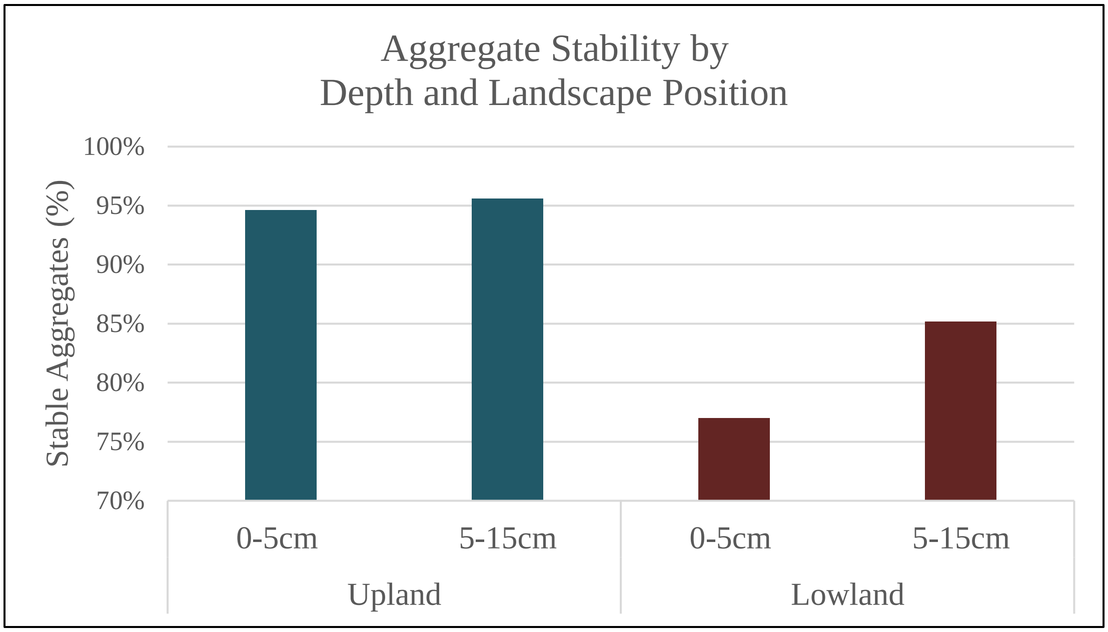

Figure 3.2. The average aggregate stability in the upland position was 94.61% (n = 48) and 95.61% (n = 48) in the 0-5 cm and 5-15 cm depths respectively. The average aggregate stability in the lowland position was 77.02% (n = 14) and 85.20% (n = 19) in the 0-5 cm and the 5-15 cm depth respectively. (Upland Soil Series: Forman-Cresbard loam, 3-6% slope; Lowland Soil Series: Cresbard-Cavour loam, 0-3% slope).

Understanding the difference in stability by depth is critical for management decisions as surface soil is at greater risk of erosion soil at the 5-15 cm depth. Saline-sodic soils often occur in lowland areas and can be irregular in size and scope (He et al., 2018). Their spatially-dependent nature and varying degree of severity make management of these acres difficult or very time- and resource-intensive. However, when saline-sodic acres are not removed from production, or when management practices are not altered, expensive synthetic fertilizers and agrochemicals are prone to deposition or loss to the surrounding ecosystem.

In 2022, aggregate stability was higher and %Na^+ lower in the upland than in the lowland soils (Table 3.4). However, neither value confirmed that the chemical amendments improved aggregate stability or reduced the risk of dispersion in either soil.

The lack of differences in the upland soils were unexpected because elemental S had the lowest Na:EC ratio in 2022. In the lowland soils, the lack of aggregate stability differences due to chemical amendments were expected because the Na:EC ratio and the $\%Na^+$ were similar between treatments (Tables 3.3 and 3.4). Results reported in Table 3.4 for the lowland soil are similar to those reported by Casas et. al. (2020) for a saline-sodic soil.

Table 3.4. The aggregate stability and $\%Na^+$ in the upland and lowland landscape positions in surface soil (0 to 15 cm) as impacted by the chemical amendments at the 95% confidence interval.

Landscape Position	Soil Amendment	Aggregate Stability (% Stable)	Sodium (%)
Upland	None	94.40 ± 1.10	1.57 ± 0.51
	Sulfur	91.71 ± 2.09	1.00 ± 0.88
	Gypsum	94.02 ± 1.49	1.25 ± 0.52
Lowland	None	70.02 ± 10.30	23.80 ± 7.10
	Sulfur	68.75 ± 9.81	28.00 ± 7.27
	Gypsum	78.07 ± 6.32	21.51 ± 6.33

(Upland Soil Series: Forman-Cresbard loam, 3-6% slope; Lowland Soil Series: Cresbard-Cavour loam, 0-3% slope).

Research conducted by Casas et. al. (2020) introduced deep-rooted panicum (*Panicum coloratum*) into a saline-sodic soil and determined the effect of the perennial grass on soil EC, pH, biological properties, and aggregate stability. The study took place in the Flooding Pampa of Argentina on a Typic Natraqualf in a cattle-grazing management system. Panicum was established over a seven-year period and soils were assessed for pH, EC, SAR, microarthropod populations, aggregate stability, and mineral associated organic matter (MAOM) amongst other metrics. Although the panicum treatment led to a 37% reduction in EC, there was a reduction in aggregate stability.

Authors attribute this to higher soil biology populations and greater MAOM turnover than in the saline-sodic soil. Findings from this paper indicate that, while improvements in chemical measures of salinity and sodicity may improve with remediation, aggregate stability is not guaranteed to increase at the same timescale as salinity-sodicity decreases.

Correlation between elemental concentrations and aggregate stability

Many of the soil properties where highly correlated to each other (Figure 3.3). Soil aggregate stability (stable percent) were negatively correlated to SO_4^{2-}, Na^+, $EC_{1:1}$, $\%Na^+$, pH, Ca^{2+}, and Na:EC while being positively correlated to K^+ concentration and organic matter (OM). Many of the negative correlations to aggregate stability were the result of positive correlations between the soil chemical properties. For example, Na^+ and SO_4^{2-} had a correlation coefficient of 0.97. The strong correlation makes it difficult to assess the single factor responsible for the results, and it suggests that the factors responsible for high Na^+ concentrations also contributed to SO_4^{2-} concentration. In this landscape, Na^+ and SO_4^{2-} are present in the water table from weathering of parent materials and were likely transported to the soil surface with capillary water.

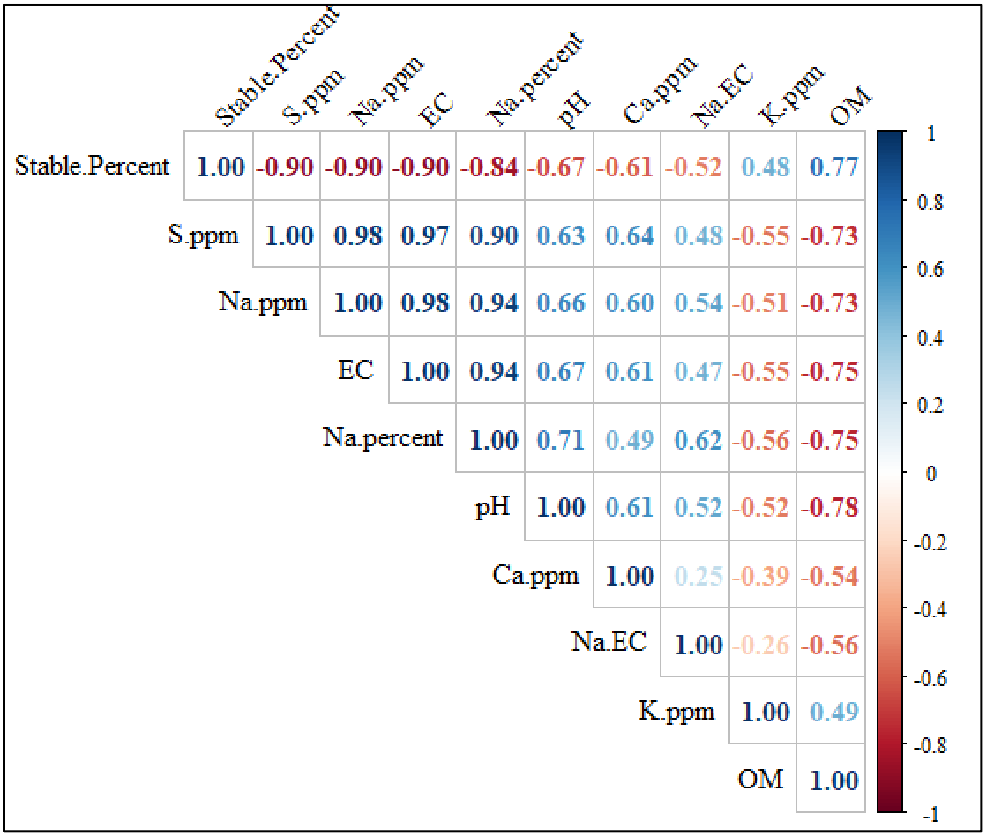

Figure 3.3. Correlation matrix displaying r values of measured variables. The data used in this analysis was from soil samples collected from the 0-15 cm depth in 2022. Aggregate stability – Stable.Percent. S.ppm – sulfate concentration, Na.ppm – sodium concentration, EC – $EC_{1:1}$, Ca.ppm – calcium concentration, Na.EC – Na:EC ratio, K. ppm – potassium concentration, OM – organic matter. All correlations in this table are significant at $p < 0.001$. (Upland: Forman-Cresbard loam, 3-6% slope; Cresbard-Cavour loam, 0-3% slope).

There was no apparent interaction between chemical amendment and phytoremediation treatment. This lack of statistical difference was attributed to plant colonization of the study area that resulted in the no-vegetation control areas having biomass yields that were similar to the planted areas. Inspection of the site suggests that plants must impact soil health (Figure 3.4). In this image, the white areas had evidence of very high salt concentrations. Areas with perennial grasses did not have these white precipitates. Perennial plants have multiple impacts on soil salinity and sodicity via many mechanisms including that they reduce the sodium concentration by utilizing Na^+ in the soil and they produce expansive root systems that not only bind the soil together but also produce channels for water flow through the soil profile.

Figure 3.4. Perennial vegetation establishing up to study edge. Producer tilled the field adjacent to the study site and salt accumulation can be observed along the length of the drainage way/low elevation portion of the field. Image taken by Mr. Dwarika Bhattarai April 22, 2021. (Upland Soil Series: Forman-Cresbard loam, 3-6% slope; Lowland Soil Series: Cresbard-Cavour loam, 0-3% slope).

A study conducted in a similar geography of the NGP focused on the application of solely chemical amendments to reduce salinity and sodicity. Birru et. al. (2019) conducted a randomized complete block experiment on three different landscape positions: backslope (Harmony soil series [fine, smectitic, frigid Pachic Argiudoll]), footslope (Houdek soil series [fine-loamy, mixed, superactive, mesic Typic Argiustoll]), and toeslope positions (Nahon soil series [Fine, smectitic, frigid Calcic Natrudoll]). Four amendment treatments consisting of no-amendment control, calcium chloride ($CaCl_2$), gypsum, and elemental sulfur were applied to each landscape position and incorporated to a 15 cm depth. Soil samples were analyzed for pH, EC, ammonium acetate extractable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), %Na^+, inorganic carbon, gypsum, sulfate, and a subset were sampled for sodium adsorption ratio (SAR). In the backslope position, none of the amendment treatments had a positive effect on yield and the $CaCl_2$ treatment had the lowest yield of all treatments. The footslope position also had lower yields in the $CaCl_2$ treatment. In the model toeslope position, a crop failure occurred in 2014 and the yield was 80% lower than the county average yields in 2015. These results were attributed to high rainfall and poor drainage. The lack of chemical amendment response in the toeslope position was attributed to marginal corn establishment to facilitate adequate drainage of gravimetric water. Results from this study suggest that different findings may have occurred if corn had been replaced with perennial grasses. Other research has also determined soil amendments to be an important component to managing this problem in the NGP (Franzen et. al., 2019; DeSutter and Cihacek, 2009). However, this present study highlights the importance of combining chemical amendments with the establishment of perennial phytoremediation on reducing salinity and sodicity in this geography. Similar results were observed in Montana (Halvorson, 1984), where multiple treatments were used to manage a saline-sodic soil seep but perennial alfalfa production maintained soil health whereas the fallow system did not.

This present study suggests that gypsum + phytoremediation reduces $EC_{1:1}$, Na^+ concentration, and the Na:EC ratio. The lowland soil is highly saline-sodic with 2018 baseline $EC_{1:1}$ of 6.7 dS/m, Na^+ of 3021 mg Na kg^{-1} soil, and Na:EC ratio of 451. By the termination of the experiment in 2022, $EC_{1:1}$ in the gypsum treatment was 4.54 dS/m, Na^+ was 1741 mg Na kg^{-1} soil, and the Na:EC ratio was 378 in the lowland soil. Changes in these values suggest the gypsum + phytoremediation can reduce salinity and sodicity in this geography.

SUMMARY AND CONCLUSION

Increases in $EC_{1:1}$ and Na^+ in 2019 are attributed to excessive rainfall (Table 3.2) reducing the depth to the salt-laden water table and allowing for capillary rise to bring dissolved salts to the soil surface. Rainfall was either less than or was aligned with the 30-year average for this site from 2020 to 2022. This climatic change, alongside establishment of the deep-rooted perennial phytoremediation treatments, increased the depth to the water table and allowed for ion movement out of the root zone along root channels. Fiedler et. al., (2021) reported severely reduced water infiltration at this site due to Na^+ dispersion of clay aggregates. Sodium was replaced by Ca^{2+} on clay exchange sites from the application of gypsum. Without the added effect of drainage facilitated by phytoremediation, ion movement out of the root zone would not have been possible. This work also showed that restoration takes time and is a slow process as significant differences in $EC_{1:1}$ and Na^+ were not observed until 2022. These findings are consistent with Sharma et al (1974), who reported that remediation may take 13 to 15 years.

Based the results of this study, producers could implement the use of gypsum alongside the establishment of salt-tolerant perennials to reduce soil $EC_{1:1}$ and Na^+ concentrations. The efficacy of this approach is dependent on weather conditions and requires ample time to facilitate the necessary chemical reactions and plant establishment. Although salinity and sodicity were reduced at this study site, final $EC_{1:1}$ and Na^+

concentrations were still too high to support annual crops. This is an important consideration for producers as they map out long-term management plans for these acres. Future research should include additional applications of soil amendments, additional sampling, and potentially working with new plant species for phytoremediation. Salinity and sodicity consume more and more arable acres every year in South Dakota and in other regions of the NGP. These degraded and fragile soils pose serious financial risk for producers and serious environmental risk for surrounding ecosystems. Working toward a large-scale solution to reclaim, or at the very least stall the expansion of, these acres will be critical for the fate of food security in South Dakota and beyond.

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CHAPTER 4

SUMMARY

In summary, salinity and sodicity are two issues threatening global food security. Nearly a quarter of Earth's cultivated land is salt-affected (FAO and ITPS, 2015). Although both problems have been present since the beginning of agriculture (Lowdermilk, 1953; Jacobsen and Adams, 1958; Montgomery, 2007), the continued advancement of saline and sodic acres onto productive land should be of utmost concern to land managers, crop advisors, and society as a whole. The body of research on saline and sodic acres is vast, however, it is also region-specific, and one resource may contradict another. There is need for a consolidated and concise resource for use by land managers and crop advisors as they navigate managing and caring for salt-affected soils.

Saline and sodic soils form via both natural and human-induced pathways. In regions such as the California in the United States (U.S.) and as the Middle East, salinization and sodification of soils has been caused by the use of poor-quality irrigation water (Qadir et. al., 2014; Gorji et. al., 2017). In arid regions, such as South Africa, saline and sodic soils are present due to insufficient rainfall to eluviate salts from the soil (de Villiers et. al., 2003). In the North America Northern Great Plains (NGP), saline and sodic soils form by saline seeps (Worcester et. al., 1975) and from rising water tables transporting dissolved salts from marine parent material closer to the soil surface (Darton, 1909). It is reasonable to believe that a management regime in one of these geographies would not be effective for all salt-affected soils due to large differences in climate, rainfall, and formation of saline and sodic soils.

This is evident from previous research in which traditional management recommendations were followed but did not lead to reductions in salinity or sodicity (Birru et. al., 2019; Budak et. al., 2022). Additionally, the classification of salt-affected soils will vary by geography. The U.S. Salinity Laboratory considers a soil sodic if the SAR value is greater or equal to 13 (Richards, 1969). This is the value most commonly reported in the literature for sodic soils. In the NGP, however, clay dispersion has been observed at SAR values of 5 (Carlson et. al., 2019) and others have observed clay dispersion at SAR values as low as 1 depending on clay mineralogy (He et. al., 2013). Another source of confusion for land managers or crop advisors may be that much of the published literature reports the boundary for a saline soil as an electrical conductivity (EC) greater or equal to 4 dS/m (Whitney, 2011). Electrical conductivity was historically conducted on a saturated paste extraction, whereas in current times it is much more common for commercial testing laboratories to complete EC measurements on 1:1 soil-water suspensions. When interpreting results from a 1:1 soil-water suspension, the values will be more dilute, and a saline soil would actually be observed at 2 dS/m. Sensitive crops could experience salt damage at $EC_{1:1}$ values less than 2 dS/m (Carlson et. al., 2019). These are major deviations from what is commonly found in the published literature and have substantial ramifications when making management recommendations.

The research reported in Chapter 3 highlights how following the traditional management guideline of applying gypsum to a saline-sodic soil may not be independently effective. Gypsum + phytoremediation reduced $EC_{1:1}$, Na^+ concentration, and the Na:EC ratio in a saline-sodic NGP soil. The lowland soil was highly saline-sodic with 2018 baseline $EC_{1:1}$ of 6.7 dS/m, Na^+ of 3021 mg Na^+ kg^{-1} soil, and Na:EC ratio of 451. By the termination of the experiment in 2022, $EC_{1:1}$ in the gypsum treatment was 4.54 dS/m, Na^+ was 1741 mg Na^+ kg^{-1} soil, and the Na:EC ratio was 378 in the lowland soil. Changes in these values suggest the gypsum + phytoremediation will reduce salinity and sodicity in this geography. Much of the changes in salinity and sodicity at this site were attributed to changes in water table dynamics. Increases in $EC_{1:1}$ and Na^+ in 2019 are attributed to excessive rainfall reducing the depth to the salt-laden water table and allowing for capillary rise to bring dissolved salts to the soil surface. Rainfall was either less than or was aligned with the 30-year average for this site from 2020 to 2022. This climatic change, alongside establishment of the deep-rooted perennial phytoremediation treatments, increased the depth to the water table and allowed for ion movement out of the root zone along root channels. Fiedler et. al. (2021) reported severely reduced water infiltration at this site due to sodium dispersion of clay aggregates. Sodium was replaced by Ca^{2+} on clay exchange sites from the application of gypsum. Without the added effect of drainage facilitated by phytoremediation, ion movement out of the root zone would not have been possible. This work also showed that restoration takes time and is a slow process as significant differences in $EC_{1:1}$ and Na^+ were not observed until 2022. These findings are consistent with Sharma et al (1974), who reported that remediation may take 13 to 15 years.

RECOMMENDATIONS AND FUTURE WORK

Regional differences in the source, cause, classification boundaries, and in the efficacy of traditional management recommendations for saline and sodic soils are evidence enough for the need to consolidate the vast information available on salt-affected soils into a concise and easy-to-use resource for land managers and crop advisors. Compiling expertise from resources around the world and throughout academia will result in reliable information from repeatable studies on salinity and sodicity. A textbook on this subject is of utmost importance as salinity and sodicity continue to spread.

As noted in Chapter 2, there are considerable limitations to the way salt-affected soils are classified within U.S. Soil Taxonomy. Soils in the NGP are deemed “saline” at EC_e values of 4 dS/m, however, soils are not classified as having a salic horizon until EC_e values are 30 dS/m or greater. Similarly, soils in the NGP are deemed “sodic” when SAR values exceed 5 but are not classified as having a natric horizon until SAR values are 13 or greater. These differences between Soil Taxonomy and what is happening in real-time at the field-level need to be improved for Soil Taxonomy to maintain relevancy and utility for properly managing soils. Therefore, a working group of subject matter experts from around the U.S. should be assembled to address these shortcomings of Soil Taxonomy and to fill in the gaps as identified by this work. Updates to Soil Taxonomy, such as adding suborders for parent material to identify the source of salinity/sodicity or adding EC or Na^+ information to the taxonomic family, is cumbersome. Cumbersome but not impossible, and this work is necessary for the successful identification, quantification, and management, of these salt-affected soils.

Future research should encompass an expansion of the interaction between phytoremediation and soil amendments on the reduction of soil EC and Na^+ concentration. A factorial experiment designed to monitor the change in EC and Na^+

from soil amendments alone, phytoremediation alone, and soil amendments + phytoremediation would be an excellent way to verify the results of the study reported in Chapter 3. This would need to be a long-term experiment as perennial grasses take time to establish, and this experiment would also require a high level of management to keep control plots devoid of vegetation. However, gaining more insight into the specific mechanisms of phytoremediation that facilitated the efficacy of gypsum could potentially lead to new remediation strategies. Finding feasible, as well as, time- and cost-effective remediation strategies for land managers is critical as the amount of arable land in the world is decreasing.

Additional research should be completed in the NGP to determine the relationship between clay mineralogy and the Na:EC ratio to generate models for soil dispersion. Understanding the point where soils will disperse is critical for land managers who may be encroaching on the tipping point of saline-sodic to solely sodic soils. Budak et. al. (2022) determined that soils will reach saturated hydraulic conductivities of 0 cm h^{-1} (disperse) when the Na:EC ratio reaches 600. However, the study in Chapter 3 reports Na:EC ratios lower than 600 but the soils were dispersed, and the aggregate stability was weaker, in the lowland position than in the upland position. Dispersion can be observed at an SAR of 5 in many NGP soils (Carlson et. al., 2019), but depending on clay composition, dispersion can be observed at SAR values as low as 1 (He et. al., 2013). These studies all highlight the complexity of salt-affected soils, as well as the need for additional, repeated studies across the NGP region to fine-tune recommendations.

Overall, much work has been done in the area of salinity and sodicity research. Many remediation strategies have been suggested around the world for the management of these soils. However, it has also been found that not all remediation methods will be effective in each geography. Based the results of this study, producers in the NGP could implement the use of gypsum alongside the establishment of salt-tolerant perennials to reduce soil $EC_{1:1}$ and Na^+ concentrations. The efficacy of this approach is dependent on weather conditions and requires ample time to facilitate the necessary chemical reactions and plant establishment. Although salinity and sodicity were reduced at this study site, final $EC_{1:1}$ and Na^+ concentrations were still too high to support annual crops. This is an important consideration for producers as they map out long-term management plans for these acres.

The research within this document highlights the lack of a “silver bullet” or rapid remediation option for successfully managing and caring for these fragile soils. Additional research is needed on region-specific remediation strategies to create the most efficient path forward for those who are responsible for the productivity and sustainability of saline, sodic, and saline-sodic soils. Thank you for your attention and interest in this topic.

CONTACT INFORMATION

The dataset used in Chapter 3 of this dissertation is available upon request. Please contact me (Shaina.Westhoff@sdstate.edu), Dr. David Clay (David.Clay@sdstate.edu), or the Agronomy, Horticulture, and Plant Science Department at South Dakota State University (605-688-4600) for a copy. Thank you.

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