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Revegetating Salt-Impacted Soils in The Northern Great Plains

Abigail P. Blanchard
South Dakota State University

REVEGETATING SALT-IMPACTED SOILS IN THE NORTHERN GREAT PLAINS

BY

ABIGAIL P. BLANCHARD

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THESIS ACCEPTANCE PAGE

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis 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.

Lora Perkins
Advisor Date

Michele R. Dudash
Department Head Date

Nicole Lounsbery, PhD
Director, Graduate School Date

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ABSTRACT

REVEGETATING SALT-IMPACTED SOILS IN THE NORTHERN GREAT PLAINS

ABIGAIL P. BLANCHARD

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In the northern Great Plains (NGP), an estimated 10.6 million hectares of land are affected by naturally occurring salt-impacted soil. Naturally occurring salt impaction results when rainfall causes salts in parent material to move upward through the soil profile and remain in the root zone causing osmotic and ionic stress, negatively affecting seed imbibition, germination, and plant growth. Common methods to remediate salt-impacted soils were developed in the irrigated soils of the Southwestern U.S., are ineffective in the non-irrigated soils of the NGP, and can exacerbate the problem. Therefore, new methods to remediate salt-impacted soil in the NGP are needed. In this study, two objectives were assessed: 1) identification of native species that exhibit salt tolerance during imbibition and germination, and 2) evaluation of the performance of native species used to revegetate a salt-impacted site. To address objective 1, the response of 16 native plant species to seed treatment (mechanical scarification) and four soil solutions (deionized water, and soil solutions with high, medium, and low salt concentrations) was evaluated. The effects of soil solution and seed treatment were species-specific for imbibition and germination, and eight species (*Asclepias speciosa*, *Desmodium canadense*, *Elymus canadensis*, *E. trachycaulus*, *Gaillardia aristata*, *Helianthus maximiliani*, *Pascopyrum smithii*, and *Sporobolus airoides*) exhibited salt tolerance. To address objective 2, eight species (identified in objective 1) were planted in a salt-impacted field and survival and performance were evaluated. Survival and performance results indicated that most species tolerated the medium and low salt concentrations, except *S. airoides*, which increased survival in high salt conditions. Results of our study provide native plant species recommendations for revegetating salt-impacted soil in the NGP.

CHAPTER 1: INTRODUCTION

Salt-impacted soil is found worldwide, primarily in arid and semi-arid landscapes where evapotranspiration is greater than precipitation for most of the year (Jurinak 1990). Worldwide, approximately 900 million hectares (ha) of land are salt-impacted, which is 6% of land area or 20% of cultivated land (Flowers 2004). An estimated 0.3 to 1.5 million ha of agricultural land may be lost worldwide annually as salt impaction increases resulting in a 20 to 46 million ha reduction in yield potential (FAO and ITPS 2015). The northern Great Plains (NGP) contains an estimated 10.6 million ha, with approximately 3.4 million ha in South Dakota (Seelig 2000; Millar 2003; Hopkins et al. 2012; Carlson et al. 2013; Soil Survey Staff). From 2008 to 2012, over 500,000 ha, or approximately 13% of South Dakota's cropped land showed a 1 dS/m electrical conductivity (EC) increase (Kharel 2016).

Salt impaction causes severe economic impacts worldwide. Annually, land degradation from salt impaction results in a loss of $441 per ha as of 2013, which is up from $264 per ha in 1990 due to lower yields (Qadir et al. 2014; UNU-INWEH 2014). This loss per ha equates to a projected worldwide annual loss of $27.3 billion (Qadir et al. 2014). In South Dakota counties Beadle, Brown, and Spink, 113,000 ha of salt impaction resulted in an estimated $26.2 million per year economic loss (NRCS 2012). Further, the cost of remediation generally increases as the degree of salinity increases (Murtaza 2013).

Salt-impacted Soil: Cause and Classification

Salt-impacted soils occur by anthropogenic or natural means. Anthropogenic activities that contribute to salt impaction include the application of fertilizers and other soil amendments (Rengasamy 2010), irrigation with saline water (Maas and Grattan 1999), application of roadway deicers (Dudley et al. 2014), and oil and gas production, where saltwater is unearthed during drilling (Merrill et al. 1990). Naturally occurring salt-impacted soils result when salts are deposited into the soil through wind or rain, seawater intrusion, or parent material (Maas and Grattan 1999), and can fluctuate due to season and rainfall (Rengasamy 2002). In the NGP, marine sediments in parent material have high salt concentrations and vary in depth from <1 m to >100 m. Salts are transported upward through the soil profile by capillary action as the water table rises (Rhoades and Halverson 1976; Seelig 2000; Carlson et al. 2016) due to increased precipitation and temperature (Lobell et al. 2010). After evaporation, salts remain near the soil surface affecting seed imbibition, germination, and plant growth.

Salt-impacted soils are categorized into three classes: saline, saline-sodic, or sodic, and are based on two measurements: sodium adsorption ratio (SAR) and electrical conductivity (EC). Saline soil has high amounts of salts (such as chlorides and sulfates of sodium, calcium, magnesium, and potassium), sodic soil has high amounts of exchangeable sodium ions, and saline-sodic soil has high amounts of salts and exchangeable sodium ions (Rhoades and Halverson 1976). SAR measures sodicity by comparing the amount of sodium relative to the amount of calcium and magnesium. EC measures salinity by determining the absence or presence of salts in the soil. Saline and saline-sodic soil have EC values greater than 4 dS/m whereas sodic soils have EC values less than 4 dS/m. Saline soils have SAR values less than 13 whereas sodic and saline-sodic have larger SAR values (Brady and Weil 2000). However, these SAR values are used in many parts of the world except in the NGP where percent sodium (%Na), or relative sodium content, is typically used and the relationship between SAR and %Na has been determined as SAR = 1.04 x %Na - 0.35 (DeSutter et al. 2015). %Na values of 4 are considered the threshold of sustainability in the NGP for crop production (Carlson et al. 2016).

Impacts on Seeds and Plants

Salts affect seeds or plants in two ways: osmotic stress and ionic stress (Ryan et al. 1975). Osmotic stress reduces the osmotic potential of the soil water, which is the amount of available water in the soil that seeds or plants can uptake. In salt-impacted soils, salts lower the osmotic potential and restrict water uptake by seeds and plants (Nishida et al. 2009). Imbibition, or water uptake, begins the germination process (Bewley and Black 1994). In salt-impacted soils, the lower osmotic potential makes it difficult for seeds to imbibe sufficient water to begin germination. Low osmotic potential can affect plants as well and results in plants having reduced water uptake and decreased root and leaf growth (Munns and Tester 2008). Ionic stress is the accumulation of a high concentration of salts that can result in salt toxicity and occurs after water uptake is reduced, usually with long-term effects (Munns and Tester 2008). Ionic stress can result in lower germination (Qadir et al. 2003; Greenberg et al. 2008). Plants begin to accumulate salt within their leaves, leading to reduced growth and possible plant death (Munns and Tester 2008).

Excess salt decreases rangeland forage production and agricultural crop yield (Choukar-Allah 1996) and increases habitat loss for native flora and fauna on non-agricultural land (McFarland et al. 1987; Auchmoody and Walters 1988). Plants experience reduced growth, nutrient imbalance, and poor soil structure in salt-impacted soil. Due to reduced plant growth, salt-impacted soils have low soil organic matter. Dispersion and erosion caused by salt impaction also contribute to lower soil organic matter, which leads to reduced soil organic carbon (Hubble et al. 1983). Dispersion also affects water movement and results in reduced water infiltration, which makes salt leaching and water retention/drainage difficult. Further, salt-impacted soil affects soil microbial activity. The effects of osmotic stress and ionic stress cause a nutrient imbalance, which affects microbial growth and enzyme synthesis (Batra and Manna 1997). Salt-impacted soil has little to no fungi present which creates a microbiome distinct from non-impacted soil (Jakubowski 2021). Salt-impacted soil has disrupted soil structure and poor aggregation due to the dispersive properties of sodium ions (Bronick and Lal 2005). Soil structure is an important part of ecosystem function by affecting soil processes, nutrient cycling, productivity (Bronick and Lal 2005), root growth (Lal 1991), and water uptake (Rampazzo et al. 1998, Pardo et al. 2000).

Plant Salt Tolerance Mechanisms

At some point of increasing salt concentration, all plants will be negatively impacted and extirpated from a site. However, species-specific mechanisms allow some plants to have greater tolerance to increasing salt concentrations. Physiological mechanisms for salt tolerance include osmotic stress tolerance, sodium exclusion, and tissue tolerance (Munns and Tester 2008). Some plants respond less severely and can achieve greater leaf growth, root growth, and photosynthesis capacity due to osmotic stress tolerance. Some plant species have roots that stop salts from being absorbed. This ensures that salts do not accumulate in plant tissue and cause negative impacts (Munns and Tester 2008). Plant species with roots unable to stop the absorption of salts can respond by storing them in older leaves. Unlike plants that use the exclusion mechanism, plants that store sodium ions and salts have delayed effects of salt toxicity (Munns and Tester 2008).

Plants can be classified by their response to salt as halophytes, salt-tolerant non-halophytes, and salt-sensitive non-halophytes (Barrett-Lennard 2002). Halophytes are highly tolerant of salt-impacted soils and exhibit increased growth at low salt concentrations using three salt tolerance mechanisms: salt-excluding, salt-evading, and salt-enduring (Waisel 1972). Salt-excluding halophytes secrete salts from their roots before salts accumulate and salt toxicity begins. Salt-evading halophytes neither absorb nor transport salts to their leaves, which lowers the risk of salt toxicity. Salt-enduring halophytes fully tolerate salt accumulation in their cells (Waisel 1972). Salt-tolerant non-halophytes maintain growth in low salt concentrations whereas salt-sensitive non-halophytes decrease growth at low salt concentrations. The physiology of salt-tolerant non-halophytes allows them to be somewhat tolerant in salt-impacted soil, with moderately restricted water uptake and salt toxicity. Salt-sensitive non-halophytes lack mechanisms for salt tolerance, with severely restricted water uptake and salt toxicity (Barrett-Lennard 2002).

Although plants have adapted several growth responses and physiological mechanisms for salt tolerance, seeds have also developed mechanisms for tolerating adverse environmental conditions, including salt impaction. Seed dormancy is a mechanism that allows seeds to prevent germination until environmental conditions improve which increases the probability of survival and reduces possible recruitment failure (Venable 2007; Childs et al. 2010). The five classes of seed dormancy include physiological, morphological, morphophysiological, physical, and physical and physiological or combinational (Table 1). Differences among classes are due to differences in the type of internal and external stimuli necessary for imbibition and germination, such as chemical, thermal, or mechanical scarification (Baskin and Baskin 2004). Mechanical scarification may promote imbibition and germination in three classes of seed dormancy: physiological, physical, and combinational. Physiological dormancy is characterized by a water-permeable seed coat and seed embryos with low growth potential, which restricts radicle emergence. Scarification can enhance imbibition and germination by breaking the seed coat and allowing physiologically dormant seeds to germinate. Physical dormancy is characterized by water-impermeable seed coats and mechanical scarification may benefit imbibition and germination by breaking the water-impermeable seed coat. Seeds with combinational dormancy have characteristics of physiological and physical dormancy and therefore require both types of dormancy to be broken before imbibition and germination. Scarification may benefit the imbibition and germination of seeds with combinational dormancy by breaking through the water-impermeable seed coat and removing the surrounding embryo structure (Baskin and Baskin 2014). For our imbibition and germination experiments, mechanical scarification was chosen as the method of breaking dormancy. By using mechanical scarification to break physiological, physical, and combinational dormancy, seeds in salt-impacted areas may imbibe and germinate easier.

Common Restoration Methods

Common methods of treating salt-impacted soil include tile drainage, soil amendments, and salt leaching with low salt-concentrated water. Tile drainage is a common strategy to improve soil drainage. By removing excess groundwater, dissolved salts in the groundwater are also leached from the soil. Soil amendments, including the application of calcium sources such as gypsum and lime, help improve soil structure. Since sodium acts as a dispersive agent, the application of a calcium source replaces the sodium and restores the soil structure. The application of low salt-concentrated water helps leach salt from the soil, similar to tile drainage (Seelig 2000; Carlson et al. 2013). However, these strategies were developed in the arid, irrigated regions of the Southwestern U.S. and are ineffective in the semi-arid, non-irrigated regions, such as the NGP, due to differences in soil properties, gypsum concentration, and soil drainage (Birru et al. 2019) and using these methods to remediate salt-impacted soil may even worsen the degree of salt impaction. Because of high bulk densities and low drainable porosities, tile drainage in the NGP is ineffective for many salt-impacted soils. Most soils in the NGP already have high concentrations of gypsum so additional application may not be effective. In addition to low drainable porosities, salt-impacted soils of the NGP typically occur in areas of low elevation without natural water drainage (Birru et al. 2019). Therefore, new methods of remediation, including revegetation, are being researched.

Autogenic recovery can be initiated by revegetation that increases soil structure and improves water movement. Plants produce soil organic matter that can benefit soil structure and water movement by increasing plant residue and aggregation. Plant roots increase aggregation by enmeshing soil particles and releasing compounds that help aggregate soil particles (Bronick and Lal 2005). Plant roots also create macropores, which improve gas exchange and water movement by creating alternate wetting and drying cycles. Once new plants establish and old roots decay, more macropores form and new plants use the pores for root growth (Elkins et al. 1977). The ability of plants to initiate autogenic recovery suggests revegetation can be an effective method of remediating salt-impacted soils.

Using native plants for revegetation further benefits the remediation of salt-impacted soil in the NGP. Native plants provide numerous ecosystem services including water regulation, carbon sequestration, wildlife habitat and forage, and pollinator forage (Oldfield et al. 2019). The NGP is an endangered ecosystem (Samson et al. 2004); therefore, remediating salt-impacted soil using native plants is crucial because it has the opportunity to remediate the landscape and reintroduce ecosystem services to these degraded areas.

Research Overview

The purpose of this study was to identify native plants suitable for the revegetation of salt-impacted soil. Our first objective was to identify which native plant species exhibit salt tolerance during imbibition and germination with and without mechanical scarification. Imbibition and germination experiments were conducted and differences in species response to seed treatment and soil solution were analyzed. We hypothesized that mechanical scarification would increase imbibition and germination by breaking the seed coat and ending seed dormancy, allowing seeds in salt-impacted areas to imbibe or germinate easier.

Our second objective was to use the eight species that demonstrated salt tolerance during imbibition and germination and determine which species are better suited for revegetation. Plants were grown in a greenhouse and planted into salt-impacted soil. Survival and several transplant performance variables were measured to analyze the differences in species response to salt impaction.

Table 1. Classes of seed dormancy with the type of dormancy, cause of dormancy, and conditions necessary to break dormancy (Baskin and Baskin 2014).

Classes of Seed Dormancy			
	Type of Dormancy	Cause of Dormancy	Dormancy Break
Physiological	Internal	Physiological Inhibiting Mechanism (PIM)	Scarification, Warm/Cold Stratification
Morphological	Internal	Underdeveloped Seed Embryo	Conditions for Embryo Growth/Germination
Morphophysiological	Internal	PIM + Underdeveloped Seed Embryo	Warm/Cold Stratification
Physical	External	Water-Impermeable Seed Coat	Scarification
Combinational	Internal + External	PIM + Water-Impermeable Seed Coat	Scarification, Warm/Cold Stratification

CHAPTER 2: EFFECTS OF SALT IMPACTION ON IMBIBITION AND GERMINATION OF NATIVE SEEDS

Abstract

In the northern Great Plains (NGP), salt-impacted soil occurs naturally as salts in marine sediments move upward as the water table rises. To remediate salt-impacted soils using native plants, identification of suitable native species is important. Our objective was to identify native plant species that could tolerate salt impaction during imbibition and germination and if mechanical scarification was beneficial. Therefore, our study evaluated the imbibition and germination of sixteen plant species to high, medium, and low salt concentrations with and without mechanical scarification. Seeds were left intact or mechanically scarified and soil solutions were derived from field-collected soil. Two seed treatments (control and scarified) and four soil solutions (deionized water, and high, medium, and low salt concentrations) were used for imbibition and germination experiments. Results indicated that the effects of seed treatment and soil solution were species-specific for imbibition and germination; however, eight species showed promise as suitable species for the revegetation of salt-impacted soil. Additionally, results indicated that mechanical scarification was beneficial for imbibition and germination in salt-impacted conditions. Seven of the eight species experienced moderate salt tolerance during imbibition and germination, similar to salt-tolerant non-halophytes whereas *S. airoides* exhibited halophytic salt tolerance during imbibition and germination. Overall, we recommend these species as suitable candidates for the revegetation of salt-impacted soil in the NGP and suggest further experimentation with these species in field studies.

We also recommend mechanical scarification as a beneficial practice of breaking seed dormancy for imbibition and germination in salt-impacted areas.

Introduction

Salt-impacted soil is found worldwide, with approximately 900 million hectares affected globally (Flowers 2004). Almost 11 million hectares of salt-impacted soil occur within the northern Great Plains (NGP) region of North America, with over 3 million hectares in the state of South Dakota alone (Seelig 2000; Millar 2003; Hopkins et al. 2012; Carlson et al. 2013; Soil Survey Staff). Salt impaction occurs primarily in arid and semi-arid landscapes where evapotranspiration rates exceed precipitation for most of the year (Jurinak 1990) and affects all soil types (Rengasamy 2006). In the NGP, salt-impacted soil is a naturally occurring phenomenon. Salt from marine sediments moves upward through the soil profile as the water table rises and remains in the root zone after evaporation (Rhoades and Halverson 1976; Seelig 2000; Carlson et al. 2016). Although salts are natural components of soil and are essential micronutrients, elevated salt concentrations lead to salt impaction.

Salt-impacted soil can decrease seed imbibition and germination by restricting water uptake and causing salt toxicity (Ryan et al. 1975). Before seedling growth, seeds first undergo imbibition and germination. Imbibition, or water uptake, initiates germination. Germination continues until radical emergence, which signifies the end of germination and the beginning of seedling growth (Bewley and Black 1994). In salt-impacted soil, water uptake is restricted due to changes in osmotic potential and a lower amount of available water (Ryan et al. 1975). The osmotic stress caused by restricted water uptake can affect seed development, specifically by limiting necessary hormonal and enzymatic processes (Thiam et al. 2013; Yacoubi et al. 2013). Salt toxicity increases the amount of sodium and chloride ions within seeds, which can also alter seed development (Gupta and Huang 2014; Maathius et al. 2014); however, the magnitude of the effects depends on the number of ions absorbed (Sharma 1973). As a result, seeds struggle to successfully imbibe and germinate (Qadir et al. 2003; Greenberg et al. 2008).

Seeds possess mechanisms to improve their survival in adverse environmental conditions, including salt-impacted soil. Seed dormancy is one such mechanism that allows seeds to prevent germination until conditions are optimal, increasing the likelihood of survival and reducing possible recruitment failure (Venable 2007; Childs et al. 2010). Five classes of seed dormancy occur: physiological, morphological, morphophysiological, physical, and physical and physiological (combinational), with each class differing in the type of internal and external stimuli necessary for imbibition and subsequent germination (Baskin and Baskin 2004). Mechanical scarification may promote imbibition and germination in three classes of seed dormancy, including physiological, physical, and combinational.

Physiological dormancy is characterized by water-permeable seed coats and embryos with low growth potential, making the seed coat restrictive for radicle emergence (Baskin and Baskin 2004). Scarification may increase the imbibition and germination of seeds with physiological dormancy by removing the seed coat and allowing the once restricted embryo to fully imbibe and germinate. Seeds with physical dormancy have a water-impermeable seed coat (Baskin and Baskin 2004) and scarification may increase imbibition and germination of seeds with physical dormancy by breaking through the water-impermeable palisade layer of cells. Finally, combinationally dormant seeds have water-impermeable coats and dormant seed embryos, characteristics of both physical and physiological (Baskin and Baskin 2004).

Scarification may increase the imbibition and germination of seeds with combinational dormancy by breaking through the water-impermeable seed coat and removing the surrounding embryo structure (Baskin and Baskin 2014). By breaking seed dormancy through scarification, seed in salt-impacted areas may imbibe and germinate easier.

Plants can be classified by their growth responses to salt impaction as halophytes, salt-tolerant non-halophytes, and salt-sensitive non-halophytes (Barrett-Lennard 2002). Halophytes are plants that are highly salt tolerant and capable of increasing growth as salt impaction increases. Salt-tolerant non-halophytes are plants that are moderately salt tolerant, with maintained growth in low salt concentrations and decreased growth in high salt concentrations. Salt-sensitive non-halophytes have poor salt tolerance. Their growth decreases in even the lowest salt concentrations (Barrett-Lennard 2002).

To remediate salt-impacted soils in the NGP using native plants, the identification of halophytes and salt-tolerant non-halophytes is crucial. In this study, we evaluate the response of sixteen plant species to high, medium, and low salt concentrations. Our objective was to identify which native plant species can tolerate salinity during imbibition and germination with and without mechanical scarification. We hypothesized that mechanical scarification would increase imbibition and germination by breaking seed dormancy and allowing seeds to imbibe and germinate easier in salt-impacted conditions.

Methods

This research occurred in the Rangeland Plant Ecology Lab at South Dakota State University in the fall of 2019. Imbibition and germination experiments were conducted using two seed treatments (control and scarified seed) and four soil solutions (deionized water [control], and soil solutions derived from soils that had high, medium, and low salt concentrations.

Study Species and Seed Source

Sixteen plant species including 7 native grasses, 8 native forbs, and one non-native forb were chosen for this study. Species were chosen via expert opinion, literature review, fact sheets (USDA NRCS 2007), and a Northern Great Plains Herbaria search. Keywords ‘salt’ and ‘saline’ were included in the search in the Northern Great Plains Herbaria Network (Great Plains Herbaria 2021). Fifteen species with these keywords in the description of their collection location that were native to South Dakota (USDA, NRCS) were identified. Native grass species included perennials *Distichlis spicata* (Inland saltgrass), *Elymus canadensis* (Canada wildrye), *Elymus trachycaulus* (Slender wheatgrass), *Panicum virgatum* (Switchgrass), *Pascopyrum smithii* (Western wheatgrass), *Spartina pectinata* (Prairie cordgrass), and *Sporobolus airoides* (Alkali sacaton; Poaceae). Native forb species included *Asclepias speciosa* (Showy milkweed), *Asclepias syriaca* (Common milkweed; Asclepiadaceae), *Desmodium canadense* (Showy ticktrefoil; Fabaceae), *Gaillardia aristata* (Blanketflower), *Helianthus maximiliani* (Maximilian sunflower), *Solidago missouriensis* (Missouri goldenrod; Asteraceae), *Sphaeralcea coccinea* (Scarlet globemallow; Malvaceae), and *Symphyotrichum ericoides* (White heath aster; Asteraceae). Non-native forb species *Trifolium fragiferum* (Strawberry clover; Fabaceae) was also included. All forbs are perennial except *S. coccinea*, which is both biennial and perennial. Seed for all species was purchased and seed viability was not tested (Table 1).

Seed Treatments

Two seed treatments were used for imbibition and germination experiments: control (no scarification) and mechanical scarification. We mechanically scarified seeds using a Forsberg Seed Cleaning Machine (Fred Forsberg & Sons, Inc., Thief River Falls, MN). Six hundred grit sandpaper (3M) lined the scarifier drum. The sandpaper was removed between each species treatment to clean the sandpaper and remove any seeds or debris. Seeds were treated at 10-second intervals until scratching or seed cracking was visible under a dissecting microscope. Due to a prolonged winding down period, the scarifier was run for 4 seconds with 6 seconds left for winding down, for a total of 10-second intervals. Scarification times varied from 10-270 seconds depending on the species (Table 1).

Soil Solutions

Soil solutions from field-collected soil were used for imbibition and germination experiments. The soil was collected (0-15 cm depth) from three landscape positions in Clark County, South Dakota. Soil samples were sent to Ward Laboratories, Inc. (Kearney, NE) for analysis. Based on paste EC (electrical conductivity) values and SAR (sodium absorption ratio), soils were classified as high (EC = 19.9 dS/m, SAR = 19.3), medium (EC = 10.1 dS/m, SAR = 12.2), low (EC = 4.3 dS/m, SAR = 0.9) salt concentrations. To make the soil solutions, a 1:1 slurry (g to ml) by weight was made using field-collected soil and deionized water. The slurry was mixed to remove any aggregates and left to sit overnight. The mixture was strained through a 230-mesh sieve to separate the soil from the soil solution. This process was repeated for all three salt concentrations. Deionized water served as the fourth soil solution (control). EC values, from high salt to low salt concentrations, were 14.2, 7.9, and 3.2 dS/m whereas SAR values were 15.8, 10.3, and 0.7.

Imbibition

Imbibition experiments consisted of 640 seeds per species [10 seeds * 8 replications * 4 soil solutions (high, medium, low, and control) * 2 seed treatments (scarified and control)], except *A. ericoides*, *S. missouriensis*, and *S. airoides*, which used 100, 80, and 70 seeds per replication respectively. Seed weights for these species were sufficiently smaller than the other species, leading to more seeds needed per replication. Total imbibition experiments n = 1,024 [16 species * 8 replications * 4 soil solutions * 2 seed treatments]. Seeds were counted and weighed before imbibition. Seeds were immersed in 5 ml of the appropriate soil solution for 24 hours. After 24 hours of immersion, excess soil solution was vacuumed off (Rocker 300 Vacuum, Rocker Scientific Company, New Taipei City 244, Taiwan), and to ensure all excess soil solution was removed, seeds were also blotted dry. Seeds were weighed again to determine their weight after imbibition. Imbibition was calculated using the following equation:

$$\text{Imbibition} = (w_a - w_b)/(w_b)$$

where w_a is weight (g) after imbibition and w_b is weight (g) before imbibition

Germination

Germination experiments consisted of 1,600 seeds per species [25 seeds * 8 replications * 4 soil solutions (high, medium, low, and control) * 2 seed treatments (scarified and control)] with total germination experiments n = 1,024 [16 species * 8 replications * 4 soil solutions * 2 seed treatments]. Twenty-five seeds per species per replicate were placed on moistened germination paper (Regular Weight Seed Germination Paper, Anchor Paper Company, St. Paul, Minnesota) and enclosed in labeled plastic bags (L.D. Poly Seal-Top Bags 2 mil 6 in. x 9 in., Elkay Plastics Company, Chicago, Illinois). The germination paper was moistened with one of the four soil solutions. Seeds were placed in a growth chamber at a 15 ℃ nighttime/ 24 ℃ daytime temperature regime, with 12 hours of nighttime and 12 hours of daytime. Germination was checked every 3 days for radicle emergence and bags were randomized when placed back in the growth chamber to ensure similar irradiance and temperature. Germination papers were moistened as needed, with their appropriate soil solution, to ensure adequate moisture. After 48 days, all germination experiments had concluded. Germination had concluded for most species after 30 days, which was the initial length of time chosen for the germination experiments. However, species *D. spicata* and *S. coccinea* were slow to germinate and given more time. Three germination indices were used for analysis: total germination, mean germination time, and mean germination rate. Total germination (TG) is the percentage of seeds that germinate (0 ≤ TG ≥ 100; %). Mean germination time (MGT) is the mean number of days seeds take to germinate (0 ≤ MGT ≥ k; time) and mean germination rate (MGR) is the reciprocal of mean germination time (0 ≤ MGR ≥ 1; time^{-1}). Total germination, mean germination time, and mean germination rate was calculated by the following formula using R package GerminaR (Lozano-Isla et al. 2019):

$$\text{Total Germination} = \left(\frac{\sum_{i=1}^{k} n_1}{N}\right) x\ 100$$

$$\text{Mean Germination Time} = \frac{\sum_{i=1}^{k} n_i t_i}{\sum_{i=1}^{k} n_i}$$

$$\text{Mean Germination Rate} = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} n_i t_i}$$

where n_i is the number of seeds germinated on the i^{th} day, t_i is the number of days between the beginning of the experiment to the i^{th} observation, N is the total number of seeds per replicate, and k is the last day of the experiment.

Statistical Analysis

Statistical analyses were conducted using ANOVA, with imbibition and germination as response variables, and species, seed treatment, and soil solution as explanatory variables. Species *D. spicata* and *S. coccinea* were excluded from the germination analysis due to low germination. *D. spicata* had 16 seeds germinate and *S. coccinea* had 134, which corresponds to 1% and 8% total germination respectively. Initial analysis indicated that species was significant for imbibition ($F = 132.09$, $df = 15$, $p < 0.001$), total germination ($F = 310.08$, $df = 13$, $p < 0.001$), mean germination time ($F = 48.54$, $df = 13$, $p < 0.001$), and mean germination rate ($F = 43.97$, $df = 13$, $p < 0.001$); therefore, subsequent analysis was conducted separately for each species. Seed treatment was not significant for mean germination time ($F = 0.35$, $df = 1$, $p = 0.554$); therefore, analysis for mean germination time included soil solution as the explanatory variables for each species. Interaction effects included seed treatment x soil solution. The imbibition data and germination data did not meet the assumptions of normality or equal variance and were transformed. However, neither response variable could be transformed to meet the assumptions of normality, therefore, least-square means were used to estimate population marginal means. The post-hoc test, Student's t-test, was performed to determine differences in explanatory variable effects. RStudio (RStudio Team 2020) and JMP (JMP Pro, Version 14, SAS Institute Inc., Cary, NC) software were used for statistical analysis.

Results

Imbibition

Three species (*A. speciosa*, *D. canadense*, and *G. aristata*) had a significant response ($p < 0.05$) to seed treatment only, with increased imbibition for scarified seed (Table 2, Figure 1). Two species (*E. canadensis and S. ericoides*) had a significant response to soil solution but not seed treatment nor the interaction (Table 2, Figure 2). For *E. canadensis*, imbibition was similar among soil solutions except in the deionized water and high salt soil solution, and for *S. ericoides*, imbibition was significantly higher in the deionized water and medium and low salt soil solutions compared to imbibition in the high salt soil solution. Seed treatment and soil solution but not the interaction had a significant effect on two species: *D. spicata* and *T. fragiferum* (Table 2, Figures 1 and 2). Both species had higher imbibition with scarified seed and similar imbibition in the deionized water and medium salt soil solution. Imbibition (g) for *P. smithii* ($\mu = 0.416$, $SD = 0.072$) had no significant response to seed treatment, soil solution, or their interaction (Table 1). The remaining eight species had a significant response to the interaction, with similar imbibition in the high, medium, and low salt soil solutions compared to deionized water (Table 2, Figure 3).

Germination

Total germination (%) for *A. speciosa* ($\mu = 87.56$, SD = 7.65), *E. trachycaulus* ($\mu = 82.19$, SD = 10.46), and *H. maximiliani* ($\mu = 37.00$, SD = 10.61) had no significant response ($p < 0.05$) to seed treatment, soil solution, or their interaction (Table 3). One species, *D. canadense*, had a significant response to seed treatment only, with higher germination for scarified seed (Table 3, Figure 4). Two species (*G. aristata* and *P. virgatum*) had a significant response to seed treatment and soil solution only (Table 3, Figure 4 and 5), and germination was higher for scarified seed for both species. The remaining eight species had a significant response to the interaction (Table 3, Figure 6). Species response was variable, but four species (*E. canadensis*, *P. smithii*, *S. airoides*, and *T. fragiferum*) had high germination (> 60%). All species except *D. canadense* had a significant response to soil solution for mean germination time (Table 4). Several species (*A. speciosa*, *E. trachycaulus*, *G. aristata*, *H. maximiliani*, and *S. airoides)* had the lowest mean number of days until germination among soil solutions (< 6 days). All species had a significant response to the interaction for mean germination rate (Table 5, Figure 7) and *S. airoides* had high mean germination rates.

Discussion

Our results suggest that *A. speciosa*, *D. canadense*, *E. canadensis*, *E. trachycaulus*, *G. aristata*, *H. maximiliani*, *P. smithii*, and *S. airoides*, are species that can imbibe and germinate in salt-impacted soil solutions and may be candidates for the restoration of salt-impacted soils in the NGP. Each species exhibited varying degrees of salt tolerance that could be used to restore salt-impacted areas. *A. speciosa* provides pollinator forage and habitat, *D. canadense* and *H. maximiliani* provide wildlife forage and cover, and *G. aristata* provides both (USDA, NRCS). *E. canadensis*, *E. trachycaulus*, and *S. airoides* provide wildlife forage and *P. smithii* provides erosion control (USDA, NRCS).

Our first objective was to identify which native plant species can tolerate salt impaction. Eight species were not affected (or were affected the least) by salt impaction. Most of these species exhibited moderate salt tolerance in the imbibition and germination experiments, similar to salt-tolerant non-halophytes. Most species had similar imbibition and germination in the soil solutions compared to deionized water. Our results are similar to previous research on roadway deicers that found *E. canadensis* exhibited high germination in salt concentrations (Harrington and Meikle 1992), and *E. trachycaulus* had consistent germination in high, medium, and low concentrations of roadway deicer salt solutions (Dudley et al. 2014). *P. smithii* exhibited high germination in salt concentrations when exposed to brine-induced salinity (Green 2019). However, *S. airoides* exhibited salt tolerance similar to halophytes, with imbibition in soil solutions similar to deionized water and germination higher in soil solutions. High germination of *S. airoides* in a similar study made it a recommended species for the restoration of saline/saline-sodic soils (Rock 2008). Imbibition studies involving the salt tolerance of the grass species (*E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides*) and imbibition and germination studies involving the salt tolerance of *A. speciosa*, *D. canadense, G. aristata*, and *H. maximiliani* could not be found in the literature, therefore these results are novel and provide essential information for the restoration and remediation of salt-impacted soil in the NGP.

Our second objective was to investigate if mechanical scarification was beneficial during imbibition and germination in salt-impacted conditions. We hypothesized that mechanical scarification would increase imbibition and germination. Several species responded positively to scarification in saline conditions. For example, 8 species responded to scarification for imbibition, 7 species for total germination, and 7 species for mean germination rate in saline conditions when scarified. However, responses to scarification decreased imbibition and germination in some conditions. Many of the seed performance responses were not consistent within species. For example, scarification decreased imbibition for *A. syriaca*, *S. airoides*, and *S. pectinata* in deionized water, *P. virgatum* for the low salt soil solution, and *E. trachycaulus* for the medium salt soil solution. Similar responses occurred for total germination and mean germination rate. Overall, response to seed treatment was not consistent across species. For example, seed treatment increased imbibition and germination rate but did not affect total germination for *A. speciosa.* However, seed treatment increased imbibition, total germination, and mean germination rate for *D. canadense*.

Imbibition or water uptake is the first of a chain reaction of cellular events that continue until radicle emergence, which signifies the end of germination. Therefore, we might expect a positive relationship between imbibition and germination. Surprisingly, we found species that imbibed more were not necessarily the species with higher germination. Interestingly, *S. coccinea*, the species with the highest mean imbibition across soil solutions was excluded from the germination analysis due to low germination. Additionally, *D. spicata*, a native grass species with saline soil tolerance (USDA, NRCS), had moderate imbibition across soil solutions and was also excluded from the germination analysis due to low germination. Overall, most species had similar imbibition between seed treatments and among soil solutions. Most had the highest imbibition in deionized water, with imbibition in the salt concentrations lower but with similar values. This could be due to lower water potential from salt ions, which disrupts water uptake and inhibits germination (Katembe et al. 1998).

Seed dormancy can prohibit imbibition and subsequent germination until optimal environmental conditions arise. To successfully restore salt-impacted areas, understanding the dormancy of the restoration species and effective methods to break dormancy are necessary. Based on the results of our study, mechanical scarification can be recommended as an effective practice. Additionally, the use of a scarifier for mechanical scarification was effective. As was found in one study, using a scarifier could be potentially beneficial for ecological restoration by breaking physical dormancy for native legumes, including *D. canadense* (Olszewski et al. 2010). Further, another study found that mechanical scarification (using a Forsberg seed cleaner) is more effective and feasible for commercial scarification than acid scarification of a legume, Ruby Valley pointvetch (*Oxytropis riparia* Litv.) (Hicks et al. 1989). The effectiveness of the Forsberg seed cleaner in this study, for scarifying other forbs and grasses, suggests it could be used for large-scale restoration efforts, including the restoration of salt-impacted areas. Responses to scarification varied among species and soil solutions; however, several species responded positively to scarification. Species *A. speciosa*, *D. canadense*, and *G. aristata* imbibition increased with scarification. *D. canadense* and *G. aristata* also responded positively to scarification for total percent germination. Interestingly, a similar study found that mechanical scarification of *D. canadense* with a scarifier damaged the seed (Olszewski et al. 2010). However, in our study, no seed damage was observed after scarification, and several species benefitted from scarification for imbibition and germination.

Some limitations for this study exist including the use of purchased seed and the lack of seed standards for native plant species (Cross et al. 2020). Some species had low or no germination even in the control deionized water nor with scarification suggesting that perhaps the seeds were not viable (although we did not test seed viability). Seeds were purchased from regional seed distributors therefore future studies have the opportunity to use field-collected seed to investigate if imbibition and germination differ. Currently, there are limited seed standards for native seeds whereas agricultural and forestry seeds have regulatory seed standards (Cross et al. 2020). Protocols for native seed handling for this project were informed by the best-known practices. Future studies might involve field-collected seed and recognized native seed standards.

Overall, we conclude that species response to seed treatment and soil solution was variable. Species response varied between seed treatments and among soil solutions. However, several species showed promise for salt-impacted soil remediation: *A. speciosa*, *D. canadense*, *E. canadensis*, *E. trachycaulus*, *G. aristata*, *H. maximiliani*, *P. smithii*, and *S. airoides*. Due to differences in salt tolerance, some species would be better suited for areas with lower salt concentrations whereas other species would be better suited for areas with higher salt concentrations. For example, *A. speciosa*, *D. canadense*, *E. canadensis*, *E. trachycaulus*, *G. aristata*, *H. maximiliani*, *P. smithii* might be better suited to revegetate areas with lower salt concentrations. These species tended to germinate quicker at medium or low soil solutions. *S. airoides* might be better suited to revegetate salt-impacted areas with higher salt concentrations. Total germination, mean germination time, and mean germination rate was greater for the soil solutions than the deionized water, especially with the high and medium soil solutions for *S. airoides*. Results from this study are important for land managers and producers to identify what species are suitable for the revegetation of salt-impacted areas. Additionally, results suggested that mechanical scarification increased imbibition and germination in saline conditions for some species. This further informs land management, making seeding of salt-impacted areas more effective.

Table 1. Seed distributors where seeds were purchased and the scarification time for eachspecies.

Scientific Name	Common Name	Seed Distributor	Scarification (sec)
Asclepias speciosa	Showy milkweed	Prairie Moon Nursery, Inc. (Winona, MN)	20
Asclepias syriaca	Common milkweed	Prairie Moon Nursery, Inc. (Winona, MN)	20
Desmodium canadense	Showy ticktrefoil	Prairie Moon Nursery, Inc. (Winona, MN)	60
Distichlis spicata	Inland saltgrass	Great Basin Seed (Ephraim, UT)	40
Elymus canadensis	Canada wildrye	Prairie Restorations, Inc. (Princeton, MN)	20
Elymus trachycaulus	Slender wheatgrass	Millborn Seeds, Inc. (Brookings, SD)	20
Gaillardia aristata	Blanketflower	Millborn Seeds, Inc. (Brookings, SD)	70
Helianthus maximiliani	Maximilian sunflower	Prairie Moon Nursery, Inc. (Winona, MN)	40
Panicum virgatum	Switchgrass	Prairie Moon Nursery, Inc. (Winona, MN)	20
Pascopyrum smithii	Western wheatgrass	Millborn Seeds, Inc. (Brookings, SD)	20
Solidago missouriensis	Missouri goldenrod	Prairie Legacy (Western, NE)	30
Spartina pectinata	Prairie cordgrass	Prairie Moon Nursery, Inc. (Winona, MN)	40
Sphaeralcea coccinea	Scarlet globemallow	Prairie Moon Nursery, Inc. (Winona, MN)	120
Sporobolus airoides	Alkali sacaton	Great Basin Seed (Ephraim, UT)	270
Symphyotrichum ericoides	White heath aster	Millborn Seeds, Inc. (Brookings, SD)	120
Trifolium fragiferum	Strawberry clover	Millborn Seeds, Inc. (Brookings, SD)	10

Table 2. F-values and p-values of seed treatment, soil solution, and their interaction on imbibition. Degrees of freedom (df) values = (variable, total). Bold p-values are significant to $p < 0.05$.

	Imbibition					
	Seed Treatment		Soil Solution		Seed Treatment x Soil Solution	
	$F_{(df)}$	p	$F_{(df)}$	p	$F_{(df)}$	p
A. speciosa	$78.87_{(1,56)}$	**<0.001**	$1.56_{(3,56)}$	0.210	$0.82_{(3,56)}$	0.487
A. syriaca	$7.86_{(1,56)}$	**0.007**	$21.07_{(3,56)}$	**<0.001**	$14.61_{(3,56)}$	**<0.001**
D. canadense	$72.16_{(1,54)}$	**<0.001**	$1.15_{(3,54)}$	0.339	$1.26_{(3,54)}$	0.296
D. spicata	$15.46_{(1,56)}$	**<0.001**	$3.12_{(3,56)}$	**0.033**	$0.174_{(3,56)}$	0.919
E. canadensis	$1.93_{(1,56)}$	0.170	$3.08_{(3,56)}$	**0.035**	$2.56_{(3,56)}$	0.064
E. trachycaulus	$4.46_{(1,56)}$	**0.039**	$1.55_{(3,56)}$	0.211	$3.54_{(3,56)}$	**0.020**
G. aristata	$18.48_{(1,56)}$	**<0.001**	$2.75_{(3,56)}$	0.051	$0.15_{(3,56)}$	0.926
H. maximiliani	$3.59_{(1,56)}$	0.063	$1.13_{(3,56)}$	0.346	$2.93_{(3,56)}$	**0.042**
P. virgatum	$1.38_{(1,56)}$	0.245	$1.46_{(3,56)}$	0.235	$6.12_{(3,56)}$	**0.001**
P. smithii	$0.30_{(1,56)}$	0.589	$1.72_{(3,56)}$	0.173	$1.02_{(3,56)}$	0.391
S. missouriensis	$0.75_{(3,56)}$	0.391	$4.23_{(3,56)}$	**0.009**	$7.17_{(3,56)}$	**<0.001**
S. pectinata	$0.20_{(1,56)}$	0.658	$7.64_{(3,56)}$	**<0.001**	$5.73_{(3,56)}$	**0.002**
S. coccinea	$10.68_{(1,56)}$	**<0.001**	$2.20_{(3,56)}$	**0.099**	$6.94_{(3,56)}$	**<0.001**
S. airoides	$0.08_{(1,54)}$	0.772	$1.18_{(3,54)}$	0.325	$2.84_{(3,54)}$	**0.046**
S. ericoides	$0.88_{(1,56)}$	0.353	$6.66_{(3,56)}$	**<0.001**	$2.69_{(3,56)}$	0.055
T. fragiferum	$25.19_{(1,55)}$	**<0.001**	$4.31_{(3,55)}$	**0.008**	$0.48_{(3,55)}$	0.695

Table 3. F-values and p-values of seed treatment, soil solution, and their interaction on the total percent germination. Degrees of freedom (df) values = (variable, total). Bold p-values are significant to p < 0.05.

	Total Germination					
	Seed Treatment		Soil Solution		Seed Treatment x Soil Solution	
	$F_{(df)}$	p	$F_{(df)}$	p	$F_{(df)}$	p
A. speciosa	$0.00_{(1,56)}$	0.949	$0.30_{(3,56)}$	0.823	$1.74_{(3,56)}$	0.169
A. syriaca	$12.68_{(1,56)}$	**<0.001**	$5.39_{(3,56)}$	**0.003**	$9.41_{(3,56)}$	**<0.001**
D. canadense	$255.63_{(1,56)}$	**<0.001**	$0.74_{(3,56)}$	0.532	$1.29_{(3,56)}$	0.285
E. canadensis	$2.15_{(1,56)}$	0.148	$2.10_{(3,56)}$	0.110	$6.88_{(3,56)}$	**<0.001**
E. trachycaulus	$2.78_{(1,56)}$	0.101	$1.86_{(3,56)}$	0.152	$2.40_{(3,56)}$	0.078
G. aristata	$10.99_{(1,56)}$	**0.002**	$4.91_{(3,56)}$	**0.004**	$2.64_{(3,56)}$	0.058
H. maximiliani	$0.03_{(1,56)}$	0.854	$1.46_{(3,56)}$	0.236	$0.45_{(3,56)}$	0.717
P. virgatum	$22.11_{(1,56)}$	**<0.001**	$10.49_{(3,56)}$	**<0.001**	$1.12_{(3,56)}$	0.349
P. smithii	$0.06_{(1,56)}$	0.802	$0.70_{(3,56)}$	0.559	$4.95_{(3,56)}$	**0.004**
S. missouriensis	$12.23_{(1,56)}$	**<0.001**	$28.26_{(3,56)}$	**<0.001**	$5.20_{(3,56)}$	**0.003**
S. pectinata	$53.49_{(1,56)}$	**<0.001**	$3.69_{(3,56)}$	**0.017**	$5.22_{(3,56)}$	**0.003**
S. airoides	$11.01_{(1,56)}$	**0.002**	$1.66_{(3,56)}$	0.186	$3.60_{(3,56)}$	**0.019**
S. ericoides	$2.01_{(1,56)}$	0.162	$4.50_{(3,56)}$	**0.007**	$8.72_{(3,56)}$	**<0.001**
T. fragiferum	$0.69_{(1,56)}$	0.411	$9.89_{(3,56)}$	**<0.001**	$11.87_{(3,56)}$	**<0.001**

Table 4. F-values and p-values of soil solution on the mean germination time. Mean number of days until germination concluded. Degrees of freedom (df) values = (variable, total). Bold p-values are significant to $p < 0.05$.

Mean Germination Time						
	Soil Solution		Mean Number of Days			
	$F_{(df)}$	p	DI Water	High	Medium	Low
A. speciosa	$18.29_{(3,56)}$	**<0.001**	2.20	5.93	3.11	3.00
A. syriaca	$21.76_{(3,56)}$	**<0.001**	4.22	8.75	11.17	3.82
D. canadense	$0.97_{(3,56)}$	0.413	5.69	6.90	6.75	5.47
E. canadensis	$7.21_{(3,56)}$	**<0.001**	4.78	8.06	8.41	7.27
E. trachycaulus	$3.42_{(3,56)}$	**0.023**	4.32	5.81	4.70	5.11
G. aristata	$17.56_{(3,56)}$	**<0.001**	1.79	3.37	5.75	5.63
H. maximiliani	$5.16_{(3,56)}$	**0.003**	3.33	4.90	4.09	3.04
P. virgatum	$13.96_{(3,56)}$	**<0.001**	5.77	10.91	18.79	3.52
P. smithii	$11.33_{(3,56)}$	**<0.001**	5.39	7.84	6.25	6.20
S. missouriensis	$6.56_{(3,56)}$	**<0.001**	14.53	8.60	9.02	6.44
S. pectinata	$6.48_{(3,56)}$	**<0.001**	15.11	14.37	22.67	15.39
S. airoides	$5.56_{(3,56)}$	**0.002**	1.92	3.23	2.62	4.43
S. ericoides	$10.05_{(3,56)}$	**<0.001**	6.12	12.41	8.73	9.65
T. fragiferum	$19.60_{(3,56)}$	**<0.001**	1.51	9.24	8.49	6.44

Table 5. F-values and p-values of seed treatment, soil solution, and their interaction on the mean germination rate. Degrees of freedom (df) values = (variable, total). Bold p-values are significant to $p < 0.05$.

	Mean Germination Rate					
	Seed Treatment		Soil Solution		Seed Treatment x Soil Solution	
	$F_{(df)}$	p	$F_{(df)}$	p	$F_{(df)}$	p
A. speciosa	$77.29_{(1,56)}$	**<0.001**	$88.75_{(3,56)}$	**<0.001**	$32.78_{(3,56)}$	**<0.001**
A. syriaca	$0.56_{(1,56)}$	0.447	$60.05_{(3,56)}$	**<0.001**	$17.69_{(3,56)}$	**<0.001**
D. canadense	$375.02_{(1,56)}$	**<0.001**	$20.99_{(3,56)}$	**<0.001**	$15.84_{(3,56)}$	**<0.001**
E. canadensis	$0.00_{(1,56)}$	0.960	$27.89_{(3,56)}$	**<0.001**	$38.58_{(3,56)}$	**<0.001**
E. trachycaulus	$99.31_{(1,56)}$	**<0.001**	$12.27_{(3,56)}$	**<0.001**	$9.01_{(3,56)}$	**<0.001**
G. aristata	$15.69_{(1,56)}$	**<0.001**	$92.10_{(3,56)}$	**<0.001**	$15.17_{(3,56)}$	**<0.001**
H. maximiliani	$1.06_{(1,56)}$	0.301	$9.13_{(3,56)}$	**<0.001**	$5.93_{(3,56)}$	**0.001**
P. virgatum	$0.65_{(1,56)}$	0.425	$23.79_{(3,56)}$	**<0.001**	$6.84_{(3,56)}$	**<0.001**
P. smithii	$29.90_{(1,56)}$	**<0.001**	$14.74_{(3,56)}$	**<0.001**	$5.90_{(3,56)}$	**0.001**
S. missouriensis	$1.70_{(3,56)}$	0.198	$14.34_{(3,56)}$	**<0.001**	$18.23_{(3,56)}$	**<0.001**
S. pectinata	$1.89_{(1,56)}$	0.175	$5.83_{(3,56)}$	**0.002**	$3.80_{(3,56)}$	**0.015**
S. airoides	$144.07_{(1,56)}$	**<0.001**	$13.81_{(3,56)}$	**<0.001**	$8.95_{(3,56)}$	**<0.001**
S. ericoides	$13.67_{(1,56)}$	**<0.001**	$18.08_{(3,56)}$	**<0.001**	$6.41_{(3,56)}$	**<0.001**
T. fragiferum	$2.51_{(1,56)}$	0.119	$80.03_{(3,56)}$	**<0.001**	$10.88_{(3,56)}$	**<0.001**

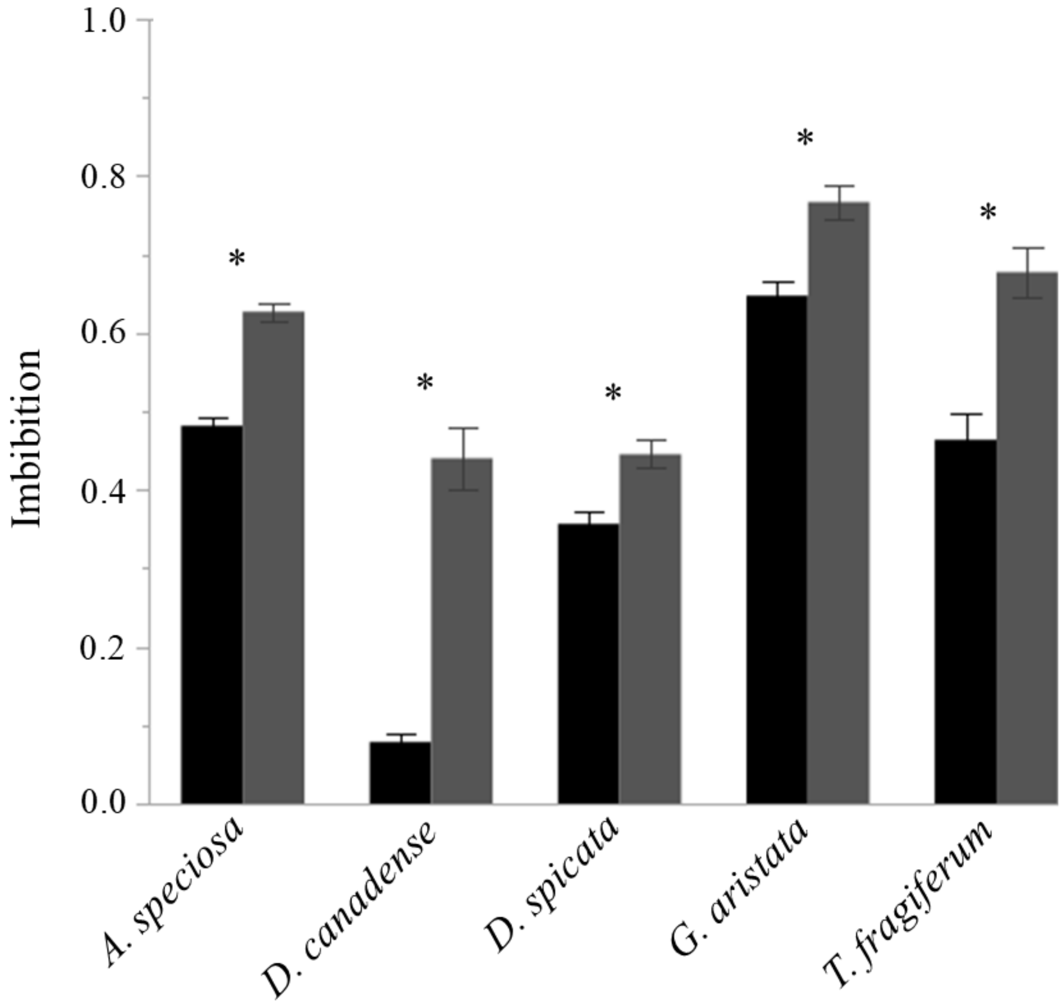

Figure 1. Imbibition (amount of water absorbed) of study species with significant responses to seed treatment only. Black bars = control seeds and gray bars = scarified seeds. Asterisks indicate significant differences in seed treatment response.

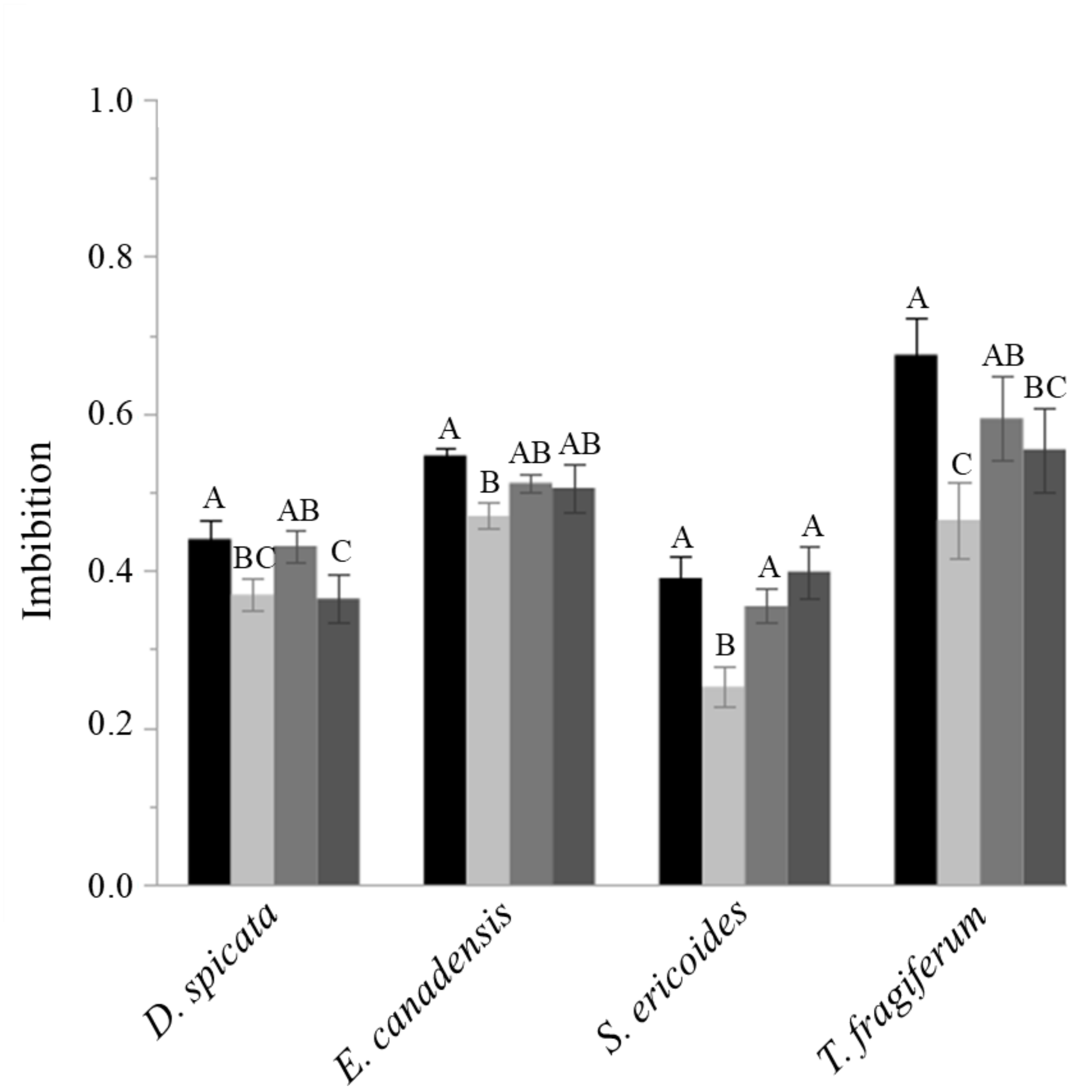

Figure 2. Imbibition (amount of water absorbed) of study species with significant responses to soil solution treatment only. Black bars = deionized water, light gray bars = high, medium gray bars = medium, and dark gray bars = low for the soil solutions. Letters indicate significant differences among soil solutions.

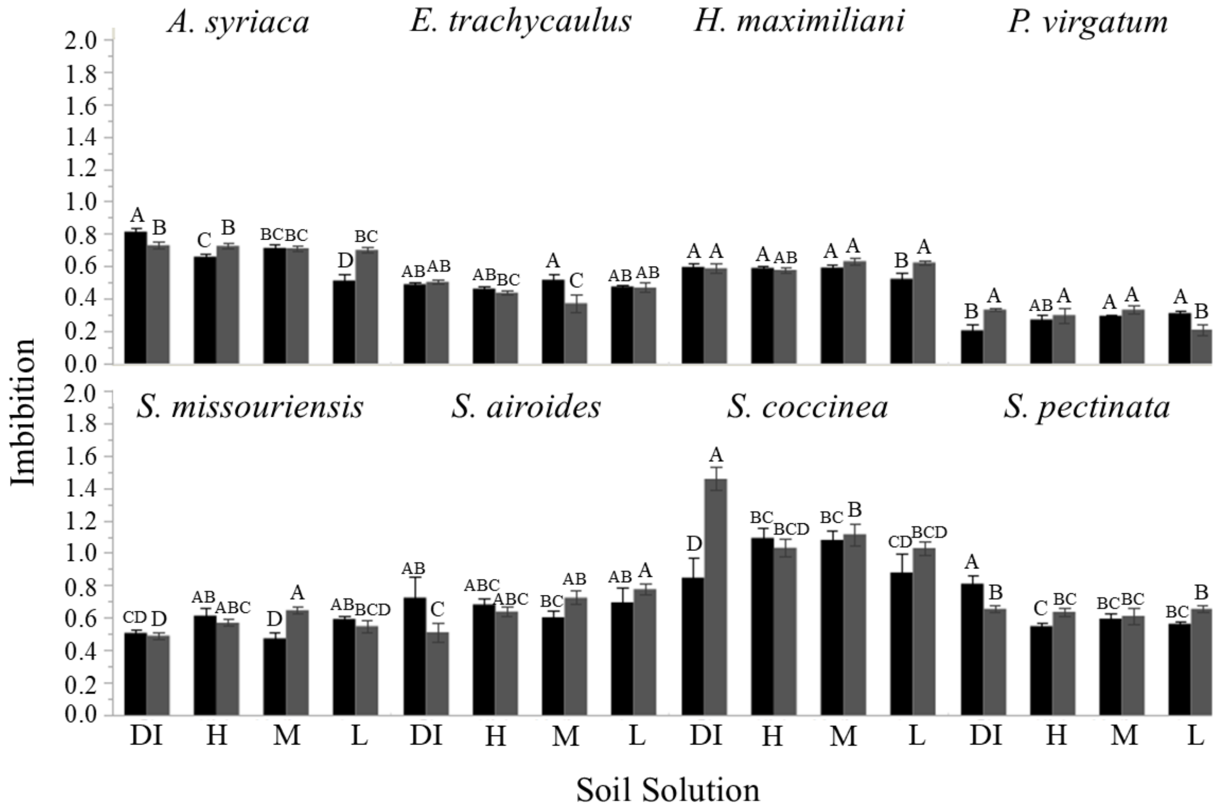

Figure 3. Imbibition (amount of water absorbed) of study species with significant responses to the interaction between seed treatment and soil solution. Black bars = control seeds and gray bars = scarified seeds. Soil solution is indicated by DI = deionized water, H = high, M = medium, and L = low. Letters indicate significant differences in interaction response for all species.

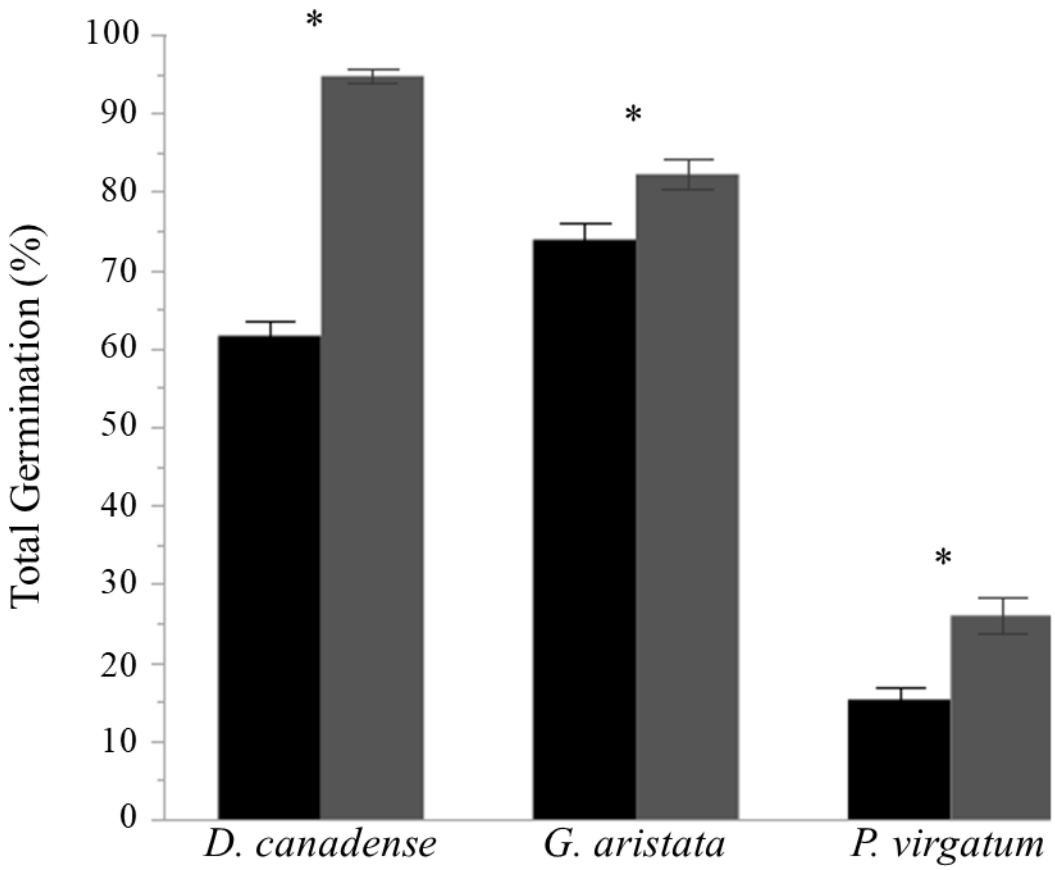

Figure 4. Total percent germination of study species with significant responses to seed treatment. Black bars = control seeds and gray bars = scarified seeds. Asterisks indicate significant differences between seed treatment response for all species.

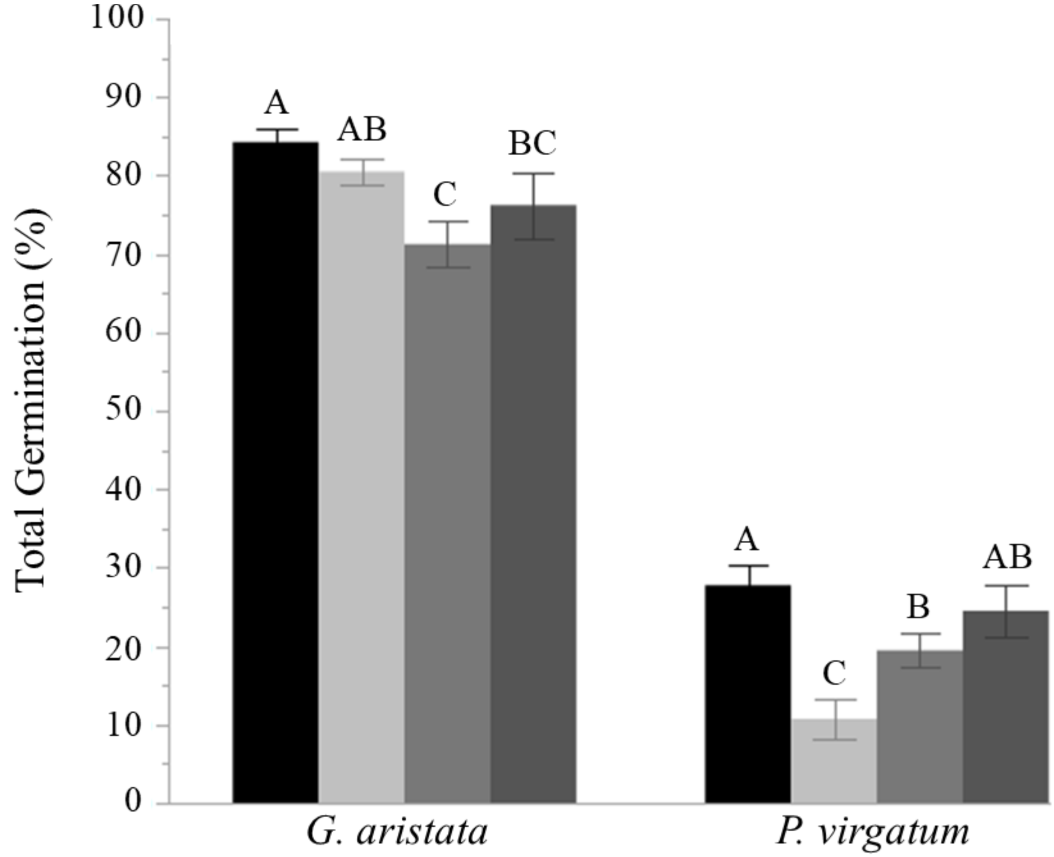

Figure 5. Total percent germination of study species with significant responses to soil solution. Black bars = deionized water, light gray bars = high, medium gray bars = medium, and dark gray bars = low for the soil solutions. Letters indicate significant differences among soil solutions for all species.

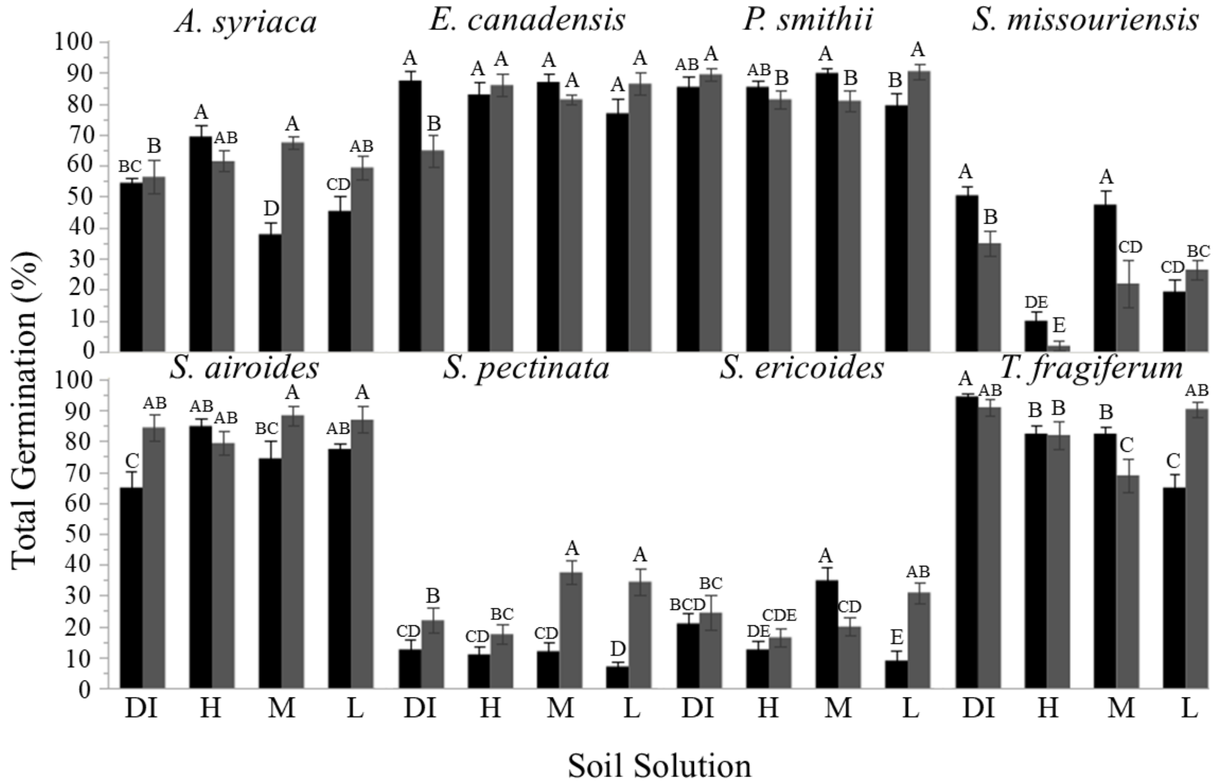

Figure 6. Total percent germination of study species with significant responses to the interaction between seed treatment and soil solution. Black bars = control seeds and gray bars = scarified seeds. Letters indicate significant differences in interaction response for all species.

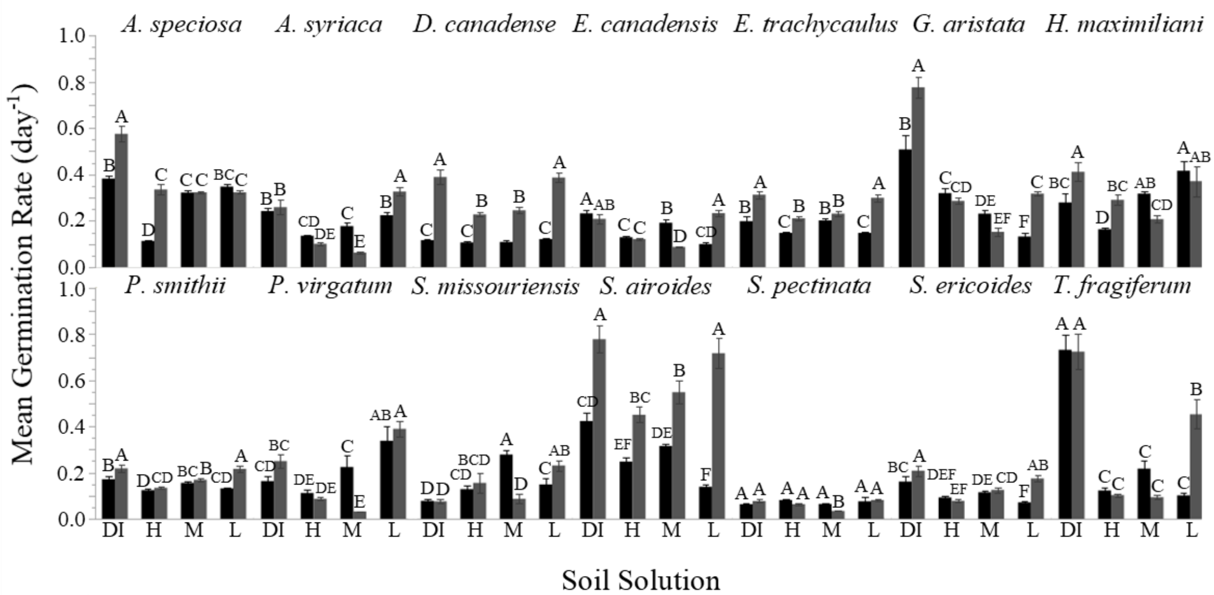

Figure 7. Mean germination rate of study species with significant responses to the interaction between seed treatment and soil solution. Black bars = control seeds and gray bars = scarified seeds. Letters indicate significant differences in interaction response for all species.

CHAPTER 3: REVEGETATION OF NATIVE PLANTS IN SALT-IMPACTED SOIL

Abstract

Salt-impacted soils are formed through anthropogenic or natural causes. In the northern Great Plains (NGP), salts naturally occur in the parent material and move upward through the soil profile. Common methods for remediating salt-impacted soil were created to remediate irrigated soils of the Southwestern U.S. Non-irrigated soils of the NGP are unaffected by these methods therefore new remediation strategies are necessary. The objective of this study was to determine which native plant species are better suited for revegetation. This study evaluated the survival and performance of eight native plant species in high, medium, and low salt concentrations. Survival was evaluated at mid-season and end-of-season sampling and performance variables (plant height, basal diameter, number of flowering heads, number of tillers/stems, and aboveground biomass) were evaluated at end-of-season sampling. Our results indicate that all species except *D. canadense* exhibited some salt tolerance and could be suitable for the revegetation of salt-impacted soil. Survival was highest in medium and low salt concentrations for most species; however, *S. airoides* was the exception, with greater survival as the salt concentration increased. Our transplant performance results mirrored survival, with most species, except *S. airoides*, exhibiting growth responses similar to salt-tolerant non-halophytes. *S. airoides* growth response was similar to halophytes, with increased growth in high salt concentrations. Overall, we suggest using *A. speciosa*, *G. aristata*, and *H. maximiliani* in minimally salt-impacted soils, *E. canadensis*, *E. trachycaulus*, and *P. smithii* in moderately salt-impacted soils, and *S. airoides* in highly salt-impacted soils to revegetate affected areas of the NGP.

Introduction

Soils are formed by the chemical and physical weathering of geological material and accumulation of organic material and contain inorganic and organic compounds, including salt (Jenny 1941). All soil types can be affected by salt (Rengasamy 2006) because although salt is a natural component of soil, high levels of salt lead to salt impaction. Salt-impacted soils occur due to anthropogenic or natural causes. Anthropogenic activities that contribute to salt impaction include the application of fertilizers and other soil amendments (Rengasamy 2010), irrigation with saline water (Maas and Grattan 1999), the application of roadway deicers (Dudley et al. 2014), and oil and gas production, where saltwater is unearthed during drilling (Merrill et al. 1990). Naturally occurring salt-impacted soils develop when salts accumulate in the soil through wind deposition, rain, seawater intrusion, or parent material (Maas and Grattan 1999). In the northern Great Plains (NGP), marine sediments in parent material have high salt concentrations. Salts are transported upward through the soil profile by capillary action as the water table rises (Rhoades and Halverson 1976; Seelig 2000; Carlson et al. 2016) due to increased precipitation and temperature (Lobell et al. 2010). After evaporation, salts remain near the soil surface where they can affect plant growth.

Common remediation methods for salt impaction include tile drainage, gypsum application, and salt leaching with low salt-concentrated water. Tile drainage improves soil drainage and helps leach salt from the soil. The application of calcium sources (i.e. gypsum and lime) helps counteract the dispersive properties of sodium in salt-impacted soil. Similar to tile drainage, the application of low salt-concentrated water helps leach salt from the soil (Seelig 2000; Carlson et al. 2013). Although these methods are beneficial in the arid, irrigated soils of the Southwestern U.S., they are ineffective in the semi-arid, non-irrigated soils of the NGP, possibly aggravating the problem due to differences in soil properties, gypsum concentration, and soil drainage (Birru et al. 2019). Because these methods are ineffective in the NGP, other methods are under investigation, including revegetation.

Revegetation can initiate the autogenic recovery of a salt-impacted site. Autogenic recovery is the process by which plants, through their growth and senescence, gradually improve conditions. For example, plants stabilize soil structure and improve water movement in the soil. Soil structure is an important part of ecosystem function, influencing water movement, soil processes, nutrient cycling, and productivity (Bronick and Lal 2005). Root growth, development (Lal 1991), distribution, and water uptake (Rampazzo et al. 1998, Pardo et al. 2000) are directly affected by soil structure. Salt-impacted soil has disrupted soil structure and poor aggregation since sodium ions act as a dispersive agent that breaks up aggregates. Plants can improve soil structure and water movement with root production. Plant roots enmesh soil particles and release compounds that help aggregate soil particles (Bronick and Lal 2005). Plant roots also create macropores that improve gas exchange and water movement through the creation of cycles of alternate wetting and drying. As roots decay, macropores are formed and new plants use the pores for root growth (Elkins et al. 1977). The revegetation of plants on salt-impacted soil can improve soil health, and consequently, be an effective method of remediating salt-impacted soils.

To establish plants on salt-impacted soil and begin autogenic recovery, plant species with salt tolerance need to be identified. Salt stresses plants in two ways: roots experience restricted water uptake and leaves accumulate salt causing salt toxicity (Ryan et al. 1975). Plant have varying tolerances to salt, with some using salt-specific physiological mechanisms to manage salt stress, including osmotic stress tolerance, sodium exclusion, and tissue tolerance (Munns and Tester 2008). Growth responses to salinity range from halophytes (that exhibit increased growth in soils with higher salt concentrations) or salt-tolerant non-halophytes (that maintain growth in salt-impacted soils) compared to salt-sensitive non-halophytes that do not maintain growth in salt-impacted soils (Barrett-Lennard 2002). Unfortunately, in some salt-impacted soils, salt-sensitive native species are replaced by non-native plants that are halophytes or salt-tolerant non-halophytes (Fischer 2001). For example, non-native species *Bassia scorparia* and weed *Hordeum jubatum* were abundant at the study site (personal observation), likely due to high salt tolerance since *B. scorparia* and *H. jubatum* are often found on saline/sodic soils (Ungar 1966). Therefore, investigating which native plant species exhibit salt tolerance will help inform revegetation practices necessary to remediate salt-impacted soil in the NGP without the negative ecological effects of non-native species or weeds (Santos et al. 2010).

The identification of native plant species suitable for the revegetation of salt-impacted soil in the NGP is important. In this study, we evaluated the response of eight native plant species to high, medium, and low salt concentrations at a field site with salt-impacted soil. Mid-season and end-of-season survival and end-of-season performance variables, including plant height, basal diameter, number of flowering heads, number of tillers/stems, and number of new tillers were measured, with aboveground biomass sampling occurring after senescence. Our objective was to determine which native plant species are better suited for revegetation.

Methods

Study Area

The study occurred in Clark County, South Dakota on private cropland previously managed in a conventional corn/soybean rotation. Surrounding cropland was primarily corn and soybeans, with some grass pasture for cattle grazing. Clark County is located in northeastern South Dakota, characterized by a temperate, continental climate with semi-humid summers and cold, dry winters. Average annual temperatures include a high of 11.9°C and a low of 0.0 °C. The average annual precipitation is 571 mm, with June - October experiencing 60% of the precipitation (U.S. Climate Data). During the field season, from June – October 2019, the total precipitation was over 584 mm, 13 mm higher than the average annual precipitation of Clark County (National Oceanic and Atmospheric Administration) making it an unusually wet season. The soil was primarily Cavour-Ferney loams, which are characterized by moderately good drainage and a water table depth of 1 to 1.5 meters below the soil surface. The maximum salinity in the soil profile is slight to moderate salinity for Cavour (4.0-10.0 dS/m) and moderate to strong salinity for Ferney (8.0-16.0 dS/m) (Soil Survey Staff).

Transplants

Based on the previous germination study, eight perennial plant species (*A. speciosa* (Asclepiadaceae), *D. canadense* (Fabaceae), *E. canadensis, E. trachycaulus*

(Poaceae), *G. aristata, H. maximiliani* (Asteraceae)*, P. smithii,* and *S. airoides* (Poaceae)) were chosen. Seeds were planted in 2.54 x 16.10 cm (66 ml) Ray Leach Pine Cell Cone-Tainers (Stuewe & Sons, Inc., Tangent, Oregon) filled with potting media (Miracle-Gro potting mix). Seeds were planted in each tube and were thinned to one individual plant per tube. Seeds were misted twice daily until germination and subsequent establishment occurred. Transplants were then watered twice daily, to ensure adequate moisture throughout the tube. Greenhouse temperature fluctuated between 10-25 °C with ambient lighting. Two weeks before planting in the field, transplants were moved outside for hardening.

Before planting, existing vegetation was mowed and Dewitt woven ground cover was placed onto the 10 x 120 m plot over the three landscape positions: high, medium, and low salt concentrations (which correspond to the footslope, midslope, and summit, respectively). Electrical conductivity was 7.90 dS/m (high salt), 3.22 dS/m (medium salt), and 0.32 dS/m (low salt). Six strips per landscape position were designated for planting with surrounding unplanted buffers for walking and data recording. Slits were cut into the ground cover in 1 x 1 ft spacing. A total of 2,016 transplants were planted. The placement of transplants was predetermined using a random number generator, with 84 transplants per species per landscape position. Transplants started in the greenhouse (March 2019) were transplanted in the field (June 2019) with one plant per slit. A soil core was used to make an approximately 16 cm deep hole. Light watering during planting was the only assistance given to the transplants for the duration of the study.

Mid-season (July 2019) and end-of-season survival (October 2019) were recorded and end-of-season performance was assessed with plant height (cm), basal diameter (cm), number of flowering heads, and number of tillers or stems. Additionally, aboveground biomass (g) sampling occurred after plant senescence and end-of-season data recording occurred (November 2019). Biomass samples were dried until a constant weight was achieved and weighed. Due to the Covid-19 pandemic and restricted travel, transplant survival and performance could not be recorded the following year (2020).

Statistical Analysis

Statistical analysis for mid-season and end-of-season survival was conducted using logistic binomial regression, with mid-season and end-of-season survival as response variables and species and salt concentration as explanatory variables. Initial analysis for mid-season survival indicated that species (χ^2= 592.92, df = 7, $p < 0.001$) and salt concentration (χ^2 = 157.98, df = 2, $p < 0.001$) were statistically significant. Initial analysis for end-of-season survival indicated that species (χ^2 = 781.70, df = 7, $p < 0.001$) and salt concentration (χ^2 = 81.43, df = 2, $p < 0.001$) were statistically significant. Statistical analyses for transplant performance were conducted using ANOVA, with end-of-season performance variables (plant height, basal diameter, number of flowering heads, number of tillers or stems, and aboveground biomass) as response variables, and species and salt concentration as explanatory variables. Of the 2,016 transplants, 13 were misplanted, therefore statistical analysis was conducted on 2,003 transplants. Initial analysis indicated that species was significant for plant height (F = 15.52, df = 2, $p < 0.001$), basal diameter (F = 55.88, df = 7, $p < 0.001$), and aboveground biomass (F = 22.14, df = 7, $p < 0.001$); therefore, subsequent analysis was conducted separately for each species, except for number of flowering heads and number of tillers or stems. Salt concentration was not statistically significant for those two performance variables: number of flowering heads (F = 1.23, df = 2, p = 0.282) and number of tillers or stems (F = 2.06, df = 2, p = 0.128). Plant height (p = 0.05) and aboveground biomass (p = 0.880) met the assumptions of normality but basal diameter (p = 0.008) did not. However, basal diameter could not be transformed to meet the assumptions of normality or equal variance; therefore, a non-parametric test, Kruskal-Wallis, was run. The post-hoc test, Student's t-test, was performed to determine differences in explanatory variable effects. RStudio (RStudio Team 2020, PBC, Boston, Massachusetts, USA) and JMP (JMP Pro, Version 14, SAS Institute Inc., Cary, NC, USA) software were used for statistical analysis.

Results

Transplant Survival

One thousand and fourteen (51%) transplants survived to mid-season (July 2019). By end-of-season sampling (October 2019), 288 more transplants died resulting in an overall transplant survival of 35% (701 transplants) among all salt concentrations. Mid-season survival was significantly ($p < 0.05$) affected by salt concentration for all species whereas end-of-season survival was significantly affected by salt concentration for all species except *H. maximiliani* (Table 1, Figure 1). Transplants of all the grasses (*E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides)* survived in all salt concentrations for mid-season and end-of-season sampling (Figure 1). Mid-season survival for the forb transplants resulted in two species (*A. speciosa* and *D. canadense)* with surviving transplants in all salt concentrations and the other two species (*G. aristata* and *H. maximiliani*) with surviving transplants in the medium and low salt concentrations. For end-of-season sampling, *A. speciosa*, *G. aristata*, and *H. maximiliani* had surviving transplants in the medium and low salt concentrations and *D. canadense* had surviving transplants in the low salt concentration only (Figure 1).

Transplant Performance

Transplant performance variables plant height, basal diameter, and aboveground biomass had significant responses to salt concentration ($p < 0.05$) for all species except *D. canadense*, which did not have surviving transplants for analysis. Only *A. speciosa*, *P. smithii*, and *S. airoides* had a significant response to salt concentration for plant height (Table 2). Mean plant height was lower (cm) in the medium salt concentration ($\mu = 12.31$, SE = 3.20) than the low salt concentration ($\mu = 28.97$, SE = 3.38) for *A. speciosa*. Plant height also increased as salt concentration decreased for *P. smithii*: high salt ($\mu = 19.48$, SE = 1.78), medium salt ($\mu = 27.27$, SE = 1.39), and low salt ($\mu = 30.15$, SE = 1.45). *S. airoides* plant height (cm) was lowest in the high salt concentration ($\mu = 47.03$, SE = 2.48) and highest in the medium salt concentration ($\mu = 59.60$, SE = 2.66), with plant height in the low salt concentration ($\mu = 55.79$, SE = 3.23) in-between. All species except *E. trachycaulus* and *H. maximiliani* had a significant response to salt concentration for basal diameter (cm), with basal diameter decreasing as salt concentration increased (Table 2, Figure 2). Only one species, *G. aristata*, had a significant response to salt concentration for aboveground biomass (Table 2). Mean aboveground biomass (g) increased from the medium salt concentration ($\mu = 2.38$, SE = 4.29) to the low salt concentration ($\mu = 12.37$, SE = 1.85).

Discussion

Four of our study species, *E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides,* showed promise as candidates for the revegetation of salt-impacted soils based on their survival and performance in the field. Three species, *A. speciosa*, *G. aristata*, and *H. maximiliani,* also showed promise as candidates for revegetation, but only for areas with medium to low salt impaction. *D. canadense* did not have great survival or field performance and therefore cannot be recommended. Along with their ability to survive transplanting into salt impacted soils, *E. canadensis*, *E. trachycaulus*, and *S. airoides* provide wildlife forage and *P. smithii* is beneficial for erosion control (USDA, NRCS). For our forb species with the ability to survive transplanting into moderately salt-impacted soils, *A. speciosa* provides pollinator forage and habitat, *H. maximiliani* provides wildlife forage and cover, and *G. aristata* provides both (USDA, NRCS).

Our objective was to determine which native plant species are better suited for revegetation. Our survival results suggest that all species, except *D. canadense*, exhibited some salt tolerance and could be suitable for revegetation. *E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides*, survived in all salt concentrations, with *E. canadensis*, *E. trachycaulus*, and *P. smithii* survival significantly higher in the medium and low salt concentrations compared to the high salt concentration. The salt tolerance of these species makes them suitable candidates for all salt concentrations, especially for medium to low salt concentrations. *E. canadensis* exhibited high survival and germination in an experiment studying the suitability of native vegetation to roadway deicers (Harrington and Meikle 1992). *E. trachycaulus* and *P. smithii* exhibited salt tolerance and weed control when used seeded into invaded saline soils to control salt-tolerant weeds *H. jubatum* and *Bromus tectorum* (Steppuhn et al. 2017). *E. trachycaulus* also responded positively to salt impaction in germination studies, with consistent germination in high, medium, and low concentrations of roadway deicer salt solutions (Dudley et al. 2014). *S. airoides* survival increased as the salt concentration increased, which was the only species to exhibit higher survival in higher salt concentrations. Therefore, the salt tolerance of *S. airoides* makes it a suitable species for areas with high salt impaction. Interestingly, one study found that *S. airoides* transplanted into non-salt-impacted soil had low survival 1-year post-planting (Abella et al. 2012). High survival in our study for *S. airoides* could be due to a reliance on salt impaction, similar to halophytes.

A. speciosa, *D. canadense*, *G. aristata*, and *H. maximiliani* survival was more affected by salt concentration. Most survived only in the medium and low salt concentrations. No forb species survived in the high salt concentration at end-of-season sampling and of the *A. speciosa* and *D. canadense* transplants that survived in the high salt concentration at mid-season sampling, both only had a few individuals. The salt tolerance of *A. speciosa*, *G. aristata*, and *H. maximiliani* made them suitable candidates for areas with medium to low salt impaction. *G. aristata* exhibited similar salt tolerance to our field study under greenhouse conditions (Niu and Rodriguez 2006). Studies involving the salt tolerance of *A. speciosa* and *H. maximiliani* could not be found in the literature.

Salt-tolerant non-halophytes are expected to maintain growth in salt-impacted soil and halophytes are expected to perform better in salt-impacted soil compared to normal (non-salt-impacted) soil (Barrett-Lennard 2002). Transplant performance (plant height, basal diameter, and aboveground biomass) results indicate that most of our species had growth responses similar to salt-tolerant non-halophytes, except *D. canadense*, which had growth responses similar to salt-sensitive non-halophytes and *S. airoides*, which had growth responses similar to halophytes. For the remaining species, the response of plant height, basal diameter, and aboveground biomass to salt impaction could classify those species as salt-tolerant non-halophytes. This result is similar to previous research that examined the relative growth rate of *Distichlis spicata*, a salt-tolerant species, compared to the growth rate of *P. smithii* (Aschenbach 2006). These results suggested that the relative growth rate of *P. smithii* was greater than *D. spicata* in all experimental salt concentrations, making it a comparable restoration candidate to *D. spicata* for salt-impacted areas (Aschenbach 2006). Our study yielded similar results, with *P. smithii* survival and performance making it a suitable candidate for salt-impacted soil revegetation.

S. airoides survival increased as the salt concentration increased and performance (plant height, basal diameter, and aboveground biomass) was among the greatest among salt concentrations compared to the other species, a response expected of halophytes. This result agrees with previous research that examined the growth responses of a *S. airoides* cultivar to salt impaction in drylands (Pessarakli et al. 2017). Results indicated high salt tolerance and suitability as a revegetation candidate in a dryland system (Pessarakli et al. 2017), similar to the results of our study in a temperate to semi-arid system. Further, *S. airoides* promise as a suitable restoration candidate increases with demonstrated invasion resistance. Populations of *S. airoides* were assessed for lineages with and without historic invasions and found that the lineage with historic invasions demonstrated invasion resistance, with greater germination and plant growth (Sebade et al. 2012). For the NGP, the salt tolerance and potential invasion resistance of *S. airoides* make its restoration suitability even more promising.

Compared to the forb species, our grass species had greater survival and growth responses to salt concentration, which indicates that these grass species could be more suitable for the revegetation of salt-impacted soils, even in high salt concentrations. In another study looking at the effects of roadway deicers on forb and grass germination, results indicated that their selected forb species (*Linum lewisii*) and (*Penstemon strictus*) germination was least affected by the high salt concentrations (Dudley et al. 2014). However, these forb species were selected due to their mixed elevation tolerance giving them a broad ecological niche and perhaps an increased salt tolerance. Interestingly, *E. trachycaulus* was also selected for this study due to its mixed elevation tolerance and was one of the species least affected by high salt concentrations as well. Increased *S. airoides* survival in higher salt concentrations makes its revegetation ability especially promising. Perennial plant cover is recommended as a management strategy to lower the water tables of saline soils within the NGP (Black et al. 1981). All species selected for this study were perennial. In particular, perennial grasses have more expansive root systems than perennial forbs, possibly lowering the water table or allowing grassroots to reach soils lower in the soil profile with lower salt impaction.

Some limitations for this study exist, including the above-average precipitation, uneven salinity throughout the plot, and the use of ground cover. Our field season experienced above-average precipitation. In the footslope landscape position (high salt concentration), water would pool, potentially affecting the salt concentration and subsequently transplant survival and performance. Future studies could extend the study over multiple seasons to examine transplant survival and performance across time and season. Salt-impacted soil is not consistent across the landscape and salt concentrations vary throughout the plot. Future studies could use field-collected soil to grow plants in controlled salt concentrations although natural environmental conditions are more ecologically informative. Ground cover was used to minimize *B. scorparia* and *H. jubatum* growth and their competition with the study species; however, it could have affected transplant survival and performance. Future studies could use other weed prevention or no weed prevention to better simulate natural environmental conditions.

Overall, we can conclude that almost all species selected for this study are suitable for the revegetation of salt-impacted soil via transplants, particularly *E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides*. Responses to salt impaction were species-specific, with some species having greater salt tolerances than other species. In general, the grass species (*E. canadensis*, *E. trachycaulus*, *P. smithii*, and *S. airoides*) had greater survival and performance across salt concentrations than the forb species (*A. speciosa*, *G. aristata*, and *H. maximiliani*). *D. canadense* showed little suitability for the revegetation of salt-impacted soils because of low survival and growth responses similar to salt-sensitive non-halophytes. All remaining species, besides halophytic *S. airoides,* had similar growth responses to salt-tolerant non-halophytes. Therefore, *A. speciosa*, *G. aristata*, and *H. maximiliani* can be recommended for minimally salt-impacted soils, *E. canadensis*, *E. trachycaulus*, and *P. smithii* can be recommended for moderately salt-impacted soils, and *S. airoides* can be recommended for highly salt-impacted soils. We suggest using these species to revegetate salt impacted areas and continuing research to find other native species to revegetate salt-impacted soils in the NGP.

Table 1. Chi-Square values and p-values of the salt concentrations at mid-season and end-of-season survival. Bold p-values are significant to $p < 0.05$.

	Survival			
	Mid-Season		End-of-Season	
	$\chi^2_{(df)}$	p	$\chi^2_{(df)}$	p
A. speciosa	$67.82_{(2)}$	**<0.001**	$28.12_{(2)}$	**<0.001**
D. canadense	$72.81_{(2)}$	**<0.001**	$15.27_{(2)}$	**<0.001**
E. canadensis	$38.84_{(2)}$	**<0.001**	$53.66_{(2)}$	**<0.001**
E. trachycaulus	$54.50_{(2)}$	**<0.001**	$85.97_{(2)}$	**<0.001**
G. aristata	$70.42_{(2)}$	**<0.001**	$27.20_{(2)}$	**<0.001**
H. maximiliani	$18.23_{(2)}$	**<0.001**	$4.26_{(2)}$	0.119
P. smithii	$12.07_{(2)}$	**0.002**	$20.33_{(2)}$	**<0.001**
S. airoides	$14.93_{(2)}$	**<0.001**	$31.39_{(2)}$	**<0.001**

Table 2. F-values, Chi-Square values, and p-values of salt concentration on end-of-season performance variables plant height, basal diameter, and aboveground biomass. Bold p-values are significant to $p < 0.05$.

	End-of-Season Performance					
	Plant Height		Basal Diameter		Aboveground biomass	
	$F_{(df)}$	p	$\chi^2_{(df)}$	p	$F_{(df)}$	p
A. speciosa	$12.78_{(1)}$	**0.001**	$10.10_{(1)}$	**<0.001**	$2.46_{(1)}$	0.129
D. canadense	0	0	0	0	0	0
E. canadensis	$0.57_{(2)}$	0.570	$6.51_{(2)}$	**0.039**	$1.41_{(2)}$	0.249
E. trachycaulus	$0.77_{(2)}$	0.463	$5.81_{(2)}$	0.055	$2.65_{(2)}$	0.074
G. aristata	$1.10_{(1)}$	0.302	$6.18_{(1)}$	**0.013**	$4.57_{(1)}$	**0.041**
H. maximiliani	$0.28_{(1)}$	0.623	$1.23_{(1)}$	0.268	$0.11_{(1)}$	0.759
P. smithii	$11.08_{(2)}$	**<0.001**	$23.94_{(2)}$	**<0.001**	$2.23_{(2)}$	0.111
S. airoides	$6.29_{(2)}$	**0.002**	$7.18_{(2)}$	**0.028**	$0.31_{(2)}$	0.734

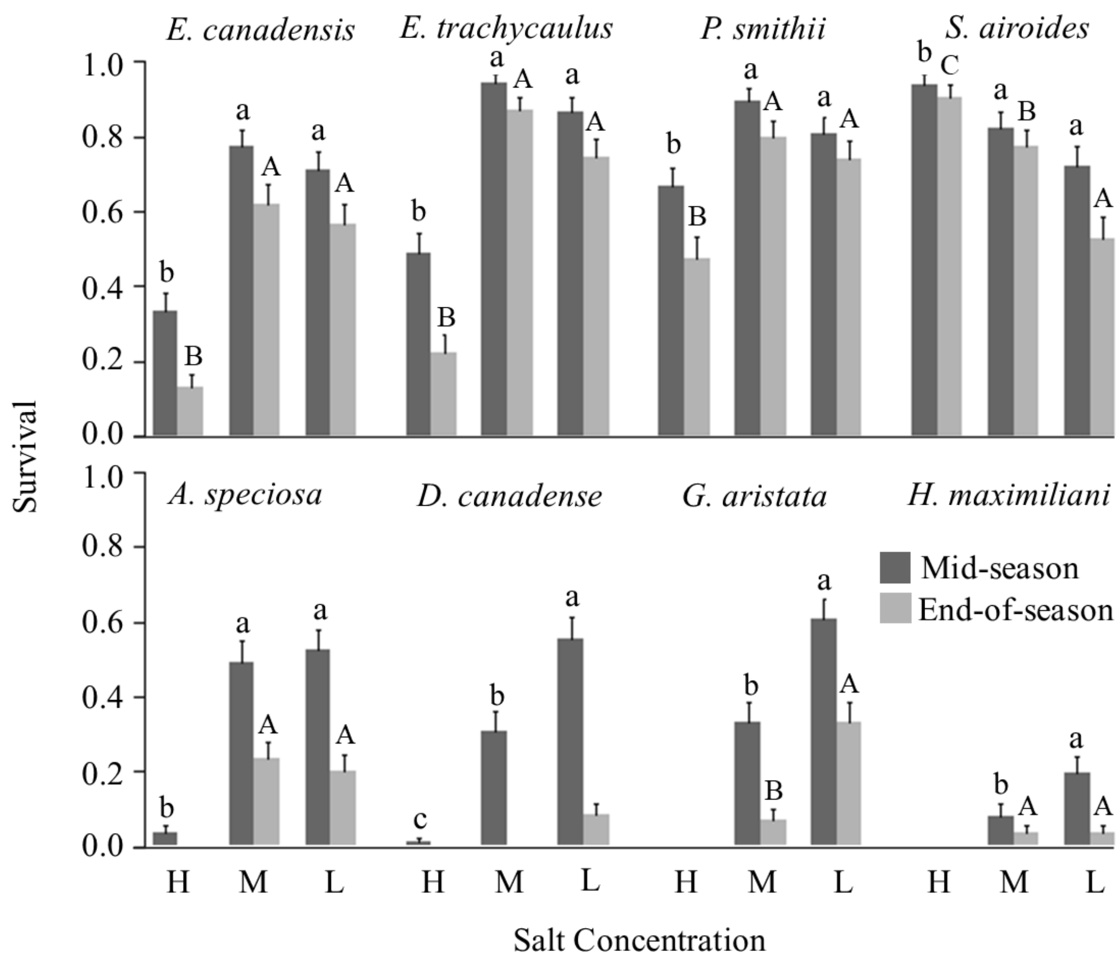

Figure 1. Mid-season and end-of-season survival based on salt concentration. Bars indicate standard error. Salt concentration is abbreviated H = high, M = medium, and L = low. Significance is based on Student’s t-test by salt concentration and within species (mid-season significance is indicated by lowercase letters and end-of-season significance is indicated by uppercase letters).

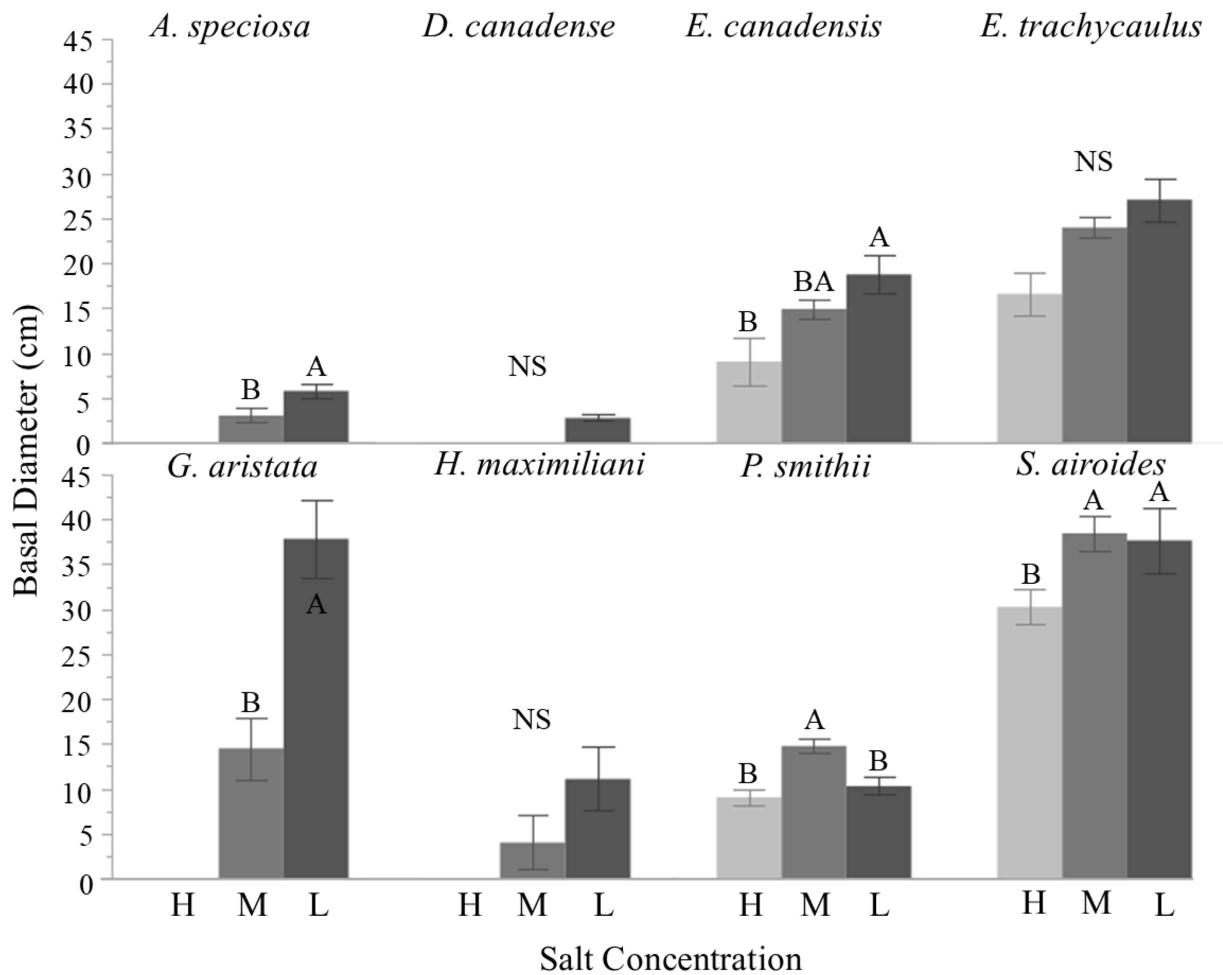

Figure 2. Mean basal diameter of the species based on salt concentration. Bars indicate standard error. Salt concentration is abbreviated H = high, M = medium, and L = low. Significance is based on Student's t-test by salt concentration and within species.

CONCLUSION

The overall purpose of our research was to identify suitable native plant species to revegetate salt-impacted soils of the NGP. Our specific research objectives included identifying native plant species that could tolerate salt impaction during imbibition and germination, assessing the effectiveness of mechanical scarification during imbibition and germination in saline conditions, and determining native plant species that are suitable for the revegetation of salt-impacted soil via transplants. We identified eight native plant species that could tolerate salt impaction during imbibition and germination and of those eight, seven species that were suitable for the revegetation of salt-impacted soil via transplants. Additionally, we determined that mechanical scarification was an effective strategy.

Seed responses to soil solutions and mechanical scarification were species-specific as were plant responses to salt concentrations. Of the eight species selected for salt tolerance from the imbibition and germination studies, seven were moderately salt tolerant and one was highly salt tolerant. Of those eight species, six species exhibited moderate salt tolerance and one species exhibited high salt tolerance as transplants in salt-impacted soil. *A. speciosa*, *E. canadensis*, *E. trachycaulus*, *G. aristata*, *H. maximiliani*, and *P. smithii* would be best suited for moderately salt-impacted soils and *S. airoides* would be best suited for revegetation in highly salt-impacted soils. We cannot recommend *D. canadense* due to poor survival and transplant performance in salt-impacted soils.

From our results, we suggest revegetating salt-impacted soils of the NGP using our recommended species and continuing research to find other suitable native plant species. Additionally, we suggest using mechanical scarification when seeding salt-impacted soils. With a better understanding of which native species are suitable in salt-impacted soil, land managers in the NGP can make more informed decisions.

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