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Identifying and Addressing Soil Property Issues Affecting Roadside Vegetation Establishment

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Identifying and Addressing Soil Property Issues Affecting Roadside Vegetation Establishment

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Disclaimers

Abstract

Attaining adequate vegetation cover along highways is important for NDOR to comply with EPA's stormwater regulations. However, low plant cover is a common problem on shoulders (first 16 feet off the pavement) of many highways in Nebraska. The ultimate goal of this study is to identify cost-effective engineering solutions that assure adequate seed beds (i.e., soil conditions) for establishment of selected seeding mixtures. The objectives of this study are to (1) characterize the soil properties along roadsides where vegetation stands have not developed well, and (2) verify the effects of select soil property parameters on plant germination and establishment.

Sampling occurred at multiple locations along the highways near Beaver Crossing and Sargent, NE. At each location, soil samples were collected from a transect of multiple landscape positions, perpendicular to the highway. The soil physical properties measured included cone index, sorptivity, and aggregate stability, while the soil chemical properties measured included EC, pH, organic matters, Na, and Ca. Results show that the soils near the edge of the highway pavement were highly compacted. Also, the soils had higher pH, lower organic matter, and higher salt levels than optimal conditions. In the subsequent greenhouse studies, a factorial design was used to test three factors: soil compaction (i.e., 1.5, 1.7, and 1.9 g cm^{-3} soil compaction levels as well as sand as control), timing of salt stress (2 pulses of salt treatment applied pre-germination and post-germination as well as no-salt control), and plant species (buffalo grass, tall fescue, and western wheat grass). Results from the greenhouse studies showed that the three plant species exhibited different germination and early survival responses to the soil compaction and salt treatments. Tall fescue is better suited for site re-vegetation especially if salt is present in the soil prior to germination. Statistical analysis show that salt treatment had the most impact on species performance.

Finally the project recommends a few engineering remediation strategies for plant establishment. Creating microsites on compacted soil surfaces could potentially alleviate the soil compaction issue by creating local environmental conditions favorable to plant establishment at microsites. To remediate the high salt levels in soil, it is recommended to consider alternative de-icing agents and amend zeolites and organics in soil.

Chapter 1 Introduction

1.1 Overview

Establishing vegetation quickly on roadsides is an important task of the Nebraska Department of Roads (NDOR). A roadside is the strip of land of variable width, extending from the edge of pavement to the right-of-way (ROW) marker. Roadside vegetation performs ecosystem functions and benefits people and their environment in many ways. First, well-established vegetation on highway roadsides can reduce erosion and stabilize slopes as it helps remove water in the subgrade of roadways, a factor that strongly affects pavement life and serviceability (Cedergren 1974). Second, vegetation on highway shoulders provides hazard-free zones for errant vehicles and reduces blowing and drifting snow onto highway. Third, attaining adequate vegetation cover along roadways could help NDOR comply with EPA's stormwater regulations, because effective roadside vegetation could remove pollutants such as chemical oxygen demand and total phosphorus from highway runoff (Kaighn and Yu 1996). Finally, roadside vegetation provides habitat and corridors to wildlife and scenic beauty to roads users (Akbar *et al.* 2003). However, several Nebraska highways have segments where vegetation cover failed to establish despite repeated seeding efforts. Shoulder areas that are bare or have limited surface cover can be critical sources of water erosion and degradation of soil and environmental quality. Preliminary studies suggest poor soil conditions were the underlying reason. There is a critical need to identify and address specific soil property issues that cause vegetation establishment failure.

A number of soil factors could affect plant establishment: (1) soil compaction (bulk density and penetration resistance), (2) inherent fertility and presence of contamination of heavy metals, (3) pH, (4) texture as related to moisture, nutrient-holding capacity, cation exchange capacity, and erodibility, (5) exchangeable and soluble salts, (6) soil structural stability (aggregate size and stability), (7) organic matter content, and (8) soil hydraulic properties (water infiltration, water retention, soil porosity, pore-size distribution, and saturation capacity). The following physical and chemical properties are particularly relevant to Nebraska Highways.

Typical roadside soils are often highly disturbed. Their original soil horizons are usually destroyed and finished slopes are designed to quickly remove water runoff from the sites rather than infiltrate into the soil profile where it is available for plant use. Imported soil and gravel substrate are often used as roadside soils after road construction, however they lack the stratified layers typical of undisturbed soils (Forman *et al.* 2003).

Roadsides can also produce microclimates with unique characteristics such as low humidity due to poor vegetation growth and high temperature due to the heat stored in the road's pavement, which is released to the atmosphere at night, creating heat islands along the roadside (Whitford 1985). The low humidity and high temperatures can contribute to reduce seedling establishment (Forman *et al.* 2003). Dust pollution and emissions from vehicular traffic and use of de-icing salts can also impede vegetation growth. De-icing salts suppress native vegetation and facilitate development of invasive species (Haan *et al.* 2012). Soluble salts lower the osmotic potential of the soil water and reduce water uptake by roots from the soil (Brady and Weil 2010). In some cases, de-icing salts can also increase soil pH. Increased levels of soil pH can drastically reduce nutrient availability in the soil (Haan *et al.* 2012).

Roadside soils, especially within shoulder areas, are compacted by road construction and maintenance equipment. The compaction can be detrimental to seedling establishment as well as to water infiltration (Berli *et al.* 2003). On urban construction sites, Gregory *et al.* (2006) reported that construction activity and associated compaction reduced infiltration rates by 70 to 99 percent and increased cone index in the 20 to 30 cm soil depth. A compacted soil has greater bulk density and less pore space than non-compacted soil (Brady and Weil 2010). Traffic can increase soil bulk density by as much as was 60% (Vora 1988). Compaction can also degrade soil structure. Aggregate stability is an indicator of soil structural quality and is often used as a parameter to assess soil physical condition (Marquez *et al.* 2004). On an agricultural field, Barik *et al.* (2014) reported that aggregate stability decreased by about 23% and soil porosity by about 10% due to traffic operations. Similarly, on a controlled traffic cropland experiment in Kansas, wheel traffic increased bulk density from 1.16 to 1.38 Mg m^{-3}, cone index from 1.78 to 3.10 MPa, and reduced both cumulative water infiltration from 109 mm to 6 mm and the volume of >50-μm pores by 2.7 times after 8 years (Blanco-Canqui *et al.* 2010). These studies indicate that compacted soils can have adverse soil properties than the surrounding undisturbed or non-compacted soil.

In the central Great Plains, native warm-season grasses are adapted to soil water fluctuations, wide range of pH, low nutrient availability, and low organic matter levels. The short grasses (e.g., buffalo grass and blue grama) and mid-grasses (e.g., western wheat grass) of central and western Nebraska generally are better adapted to poor growing conditions than the tall grasses of eastern Nebraska. Some tall grasses, such as sideoats grama and little bluestem, are known to establish more readily on poor soils than the other tall grasses. There are less common grasses that are particularly tolerant of nutrient poor conditions or alkaline/acid soils. For example, alkali sacaton and inland saltgrass are very tolerant of salinity and can form monocultures or simple mixtures on saline soils. There also are numerous forbs (a.k.a., wildflowers) that are tolerant of extreme soil conditions. A mixture of warm-season native grasses, however, can tolerate the range of nutrient and pH levels found on most roadside soils. The effect of poor soil conditions is seen primarily in low cover establishment rates and poor cover of roadside seedings (Figure 1-1). With the unfavorable growing environment in roadside soils, mixtures of seeded perennial grasses may not establish or persist, leading to weed problems and bare soil that may cause erosion.

Figure 1-1. Problematic sites on Nebraska Highway 34, 41, and 275 (left to right).

1.2 Objectives

The goal of this study is to identify cost-effective solutions that can assure adequate seed beds (i.e., soil conditions) for establishment of selected seeding mixtures. One important step toward this goal is to determine soil factors that have the most profound effects on roadside vegetation establishment. The specific objectives of this project are:

Objective 1: Identify soil properties critical to rapidly establishing roadside vegetation covers.
Objective 2: Test seed mixtures for vegetation establishment in suboptimal soil.
Objective 3: Test soil remedial methods for vegetation establishment in suboptimal soil.

1.3 Organization of the Final Report

This final report is organized into the following chapters. Chapter 2 is focused on the experimental materials and methods used in the project. Chapter 3 and Chapter 4 present the results from the field work and the greenhouse study, respectively. Chapter 5 recommends engineering remediation methods that could potentially address the roadside vegetation problem. Chapter 6 lists conclusions drawn from the entire project.

Chapter 2 Materials and Methods

2.1 Description of the Study Sites

This study was conducted at two Nebraska highway segments: L80E (40.79 N, 97.29 W) near Beaver Crossing, NE in southeastern Nebraska and US-183 (41.65 N, 99.38 W) near Sargent, NE, in central Nebraska. These two highway segments were selected because their shoulders had limited or no vegetative cover. The Beaver Crossing site has an average annual precipitation of 743 mm and annual average maximum temperature of 15.9 ^{o}C. Soils in the area are predominately Hasting silt loam (Fine, smectitic, mesic Udic Argiustolls), Crete silt loam (Fine, smectitic, mesic Pachic Udertic Argiustolls), and Fillmore silt loam (Fine, smectitic, mesic Vertic Argialbolls). Soil properties of these series are, in general, very deep, silty soils with a clayey subsoil, and nearly level to gently sloping (<1% slope). The Sargent site receives an average annual precipitation of 661 mm and annual average temperatures of 16.4 ^{o}C. Soils in the area are predominantly Valentine fine sand (Mixed, mesic Typic Ustipsamments) with <21% slope, Elsmere loamy fine sand (Sandy, mixed, mesic Aquic Haplustolls) with <1% slope, and Tryon loamy fine sand (Mixed, mesic Typic Psammaquents) with 2% slope. Soil properties of these series are generally deep, nearly level to moderately steep, and sandy soils formed in alluvium or eolian sand of the Sandhills.

2.2 Design of Study Locations along Roadsides

Field measurements and soil sampling were conducted at six separate locations along the L80E highway segment at the Beaver Crossing site and six separate locations at the US-183 at the Sargent site (Figure 2-1). At the Beaver Crossing site, field measurements and soil sampling were done at every 3.2 km for a total of six locations along a 17.7-km segment of the highway (Figure 2-1, Figure 2-2). At the Sargent site, field measurements and soil sampling were done at every 1.6 km for a total of six locations along a 14.5-km highway segment (Figure 2-1). Each sampling location at both sites was further segmented into six to seven positions with distance from the edge of pavement. These landscape position were summit (S1), shoulder (SH), sideslope (SS), ditch (D), backslope (BS), and summits (S2, S3, Figure 2-1). At each landscape position, a 40-m long transect was sampled at every 10 m intervals (Figure 2-1).

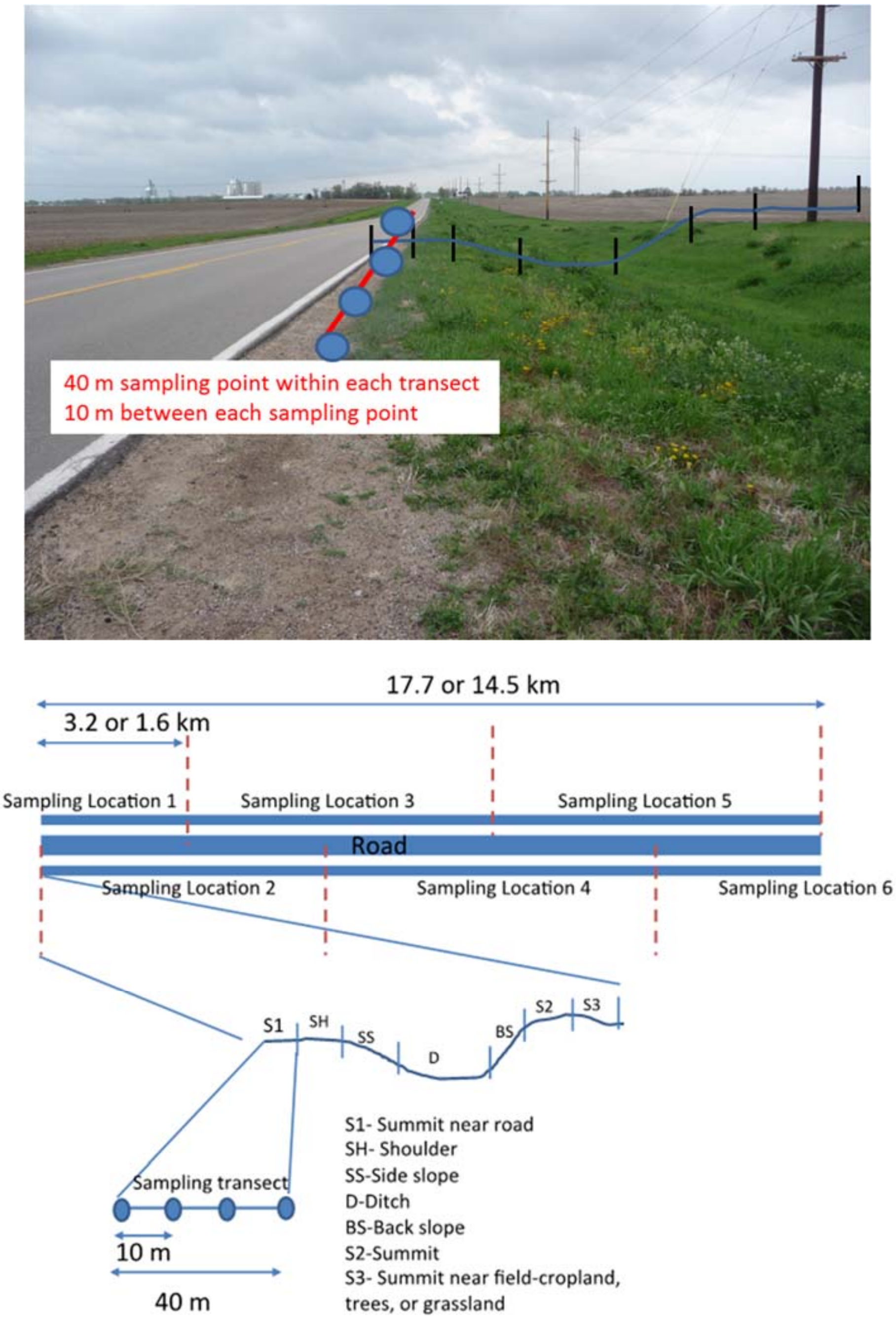

Figure 2-1. Field sampling design at the Beaver Crossing and Sargent sites.

Figure 2-2. Photos taken during soil sampling at the Beaver Crossing site.

2.3 Field Measurements and Soil Sampling

Soil physical and chemical properties were determined for each site. Physical properties included water content, bulk density, penetration resistance, sorptivity, and wet aggregate stability, while chemical properties included pH, electrical conductivity (EC, Figure 2-3), and concentrations of organic matter (OM), Na, and Ca. Intact soil cores were taken for the determination of soil water content, bulk density, and soil chemical properties for the 0 to 20 cm soil depth. The soil cores were collected from each of the seven landscape positions. Each soil core was taken with a zero contamination sleeve soil sampler (2 cm diameter and 20 cm long). On landscape positions, primarily S1 and SH positions, where the soil was too compact to use the sleeve soil sampler, a hammer driven soil core sampler equipped with stainless steel liners was used instead of the sleeve soil sampler. Soil cores were transported to the laboratory in a cooler, sliced into 0-10 cm and 10-20 cm depths, and stored at -4 ^{o}C until analysis. For each soil sampling depth, soil water content by the gravimetric method and bulk density by the core method were determined using the soil cores (Grossman and Reinsch 2002). A fraction of the soil sample from the cores was air-dried and analyzed for soil chemical analyses including pH, EC, and concentrations of OM, Na, Ca, and heavy metals using standard protocols.

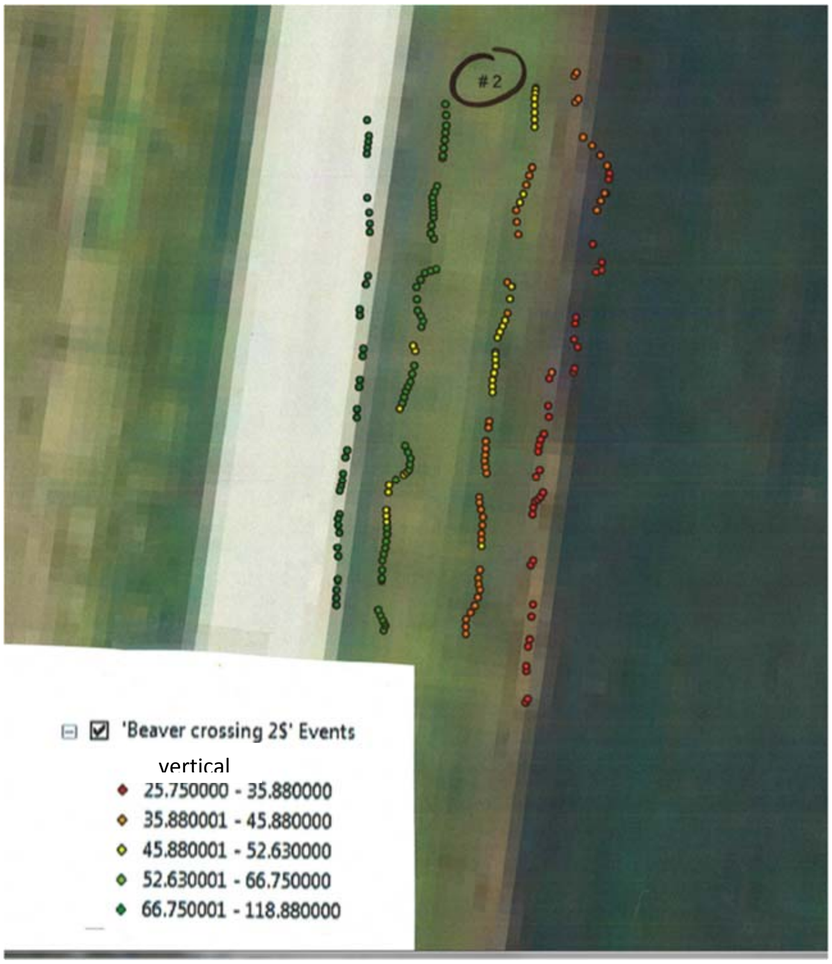

Figure 2-3. Apparent electrical conductivity (EC) mapped using EM38 at the Beaver Crossing site. Map presented is for sampling location #2 only.

2.4 Wet Aggregate Stability

At the time of collection of intact soil cores, bulk soil samples were collected for the determination of wet soil aggregate stability. The bulk samples were taken from each landscape position from the 0-10 cm and from the 10-20 cm depths. The bulk samples were air-dried for 72 h and passed through sieves with 8 mm openings. The wet soil aggregate stability was determined by the wet sieving method (Nimmo and Perkins 2002). A portion of the air-dry sieved soil was placed on top of the two sieves with 4.75 mm and 0.25 mm openings, saturated by capillarity for 10 min, and then sieved in water using a wet sieving apparatus for another 10 min (Figure 2-4. Mechanical sieving equipment (top) and sieves (bottom) used for the determination of wet soil aggregate stability in the laboratory.). Soil aggregates remaining in each sieve were transferred to pre-weighed beakers and dried at 105°C for 24 h. Samples were weighed and then treated with sodium exametaphosphate for 24 h and washed through 0.053 mm sieves to correct for sand content (Nimmo and Perkins 2002). The sand-free fraction of soil aggregates were then used to calculate the fraction of macroaggregates (>0.25 mm aggregates) and microaggregates (<0.25 mm aggregates).

Figure 2-4. Mechanical sieving equipment (top) and sieves (bottom) used for the determination of wet soil aggregate stability in the laboratory.

2.5 Cone Index and Sorptivity

Penetration resistance was measured for the 0-10 cm and the 10-20 cm depths with a static hand cone penetrometer (Bradford 1986). The penetrometer was pushed downward steadily and vertically at about 1 cm s^{-1}. Because penetration resistance measurements are correlated with changes in soil water content, the measured values were adjusted to a common water content following the procedures by Busscher (1990). The cone index in MPa was determined by dividing the penetrometer reading with the base area of the cone (1 cm^2).

Sorptivity, which is the early stage of water infiltration, was measured as described by Smith (1999). Rings (10.5 cm high and 9.8 cm diam.) were driven into the soil surface approximately to 2.5 cm depth (Figure 2-5). Any debris or plant material was removed without disturbing the soil surface. If the soil surface developed a crack during the insertion of the ring, the ring was removed and reinserted in another spot. Seventy five milliliters of tap water was poured into the ring and the amount of time (t) required for the water to infiltrate was recorded. Sorptivity was then calculated as per Eq. 1.

$$\text{Sorptivity (cm } s^{-1/2}) = H/t^{1/2} \qquad \text{Eq. 1}$$

where H (cm) is the head of water computed from the volume of water and the ring diameter.

Figure 2-5. Measurement of initial water infiltration at the Beaver Crossing site.

2.6 Preliminary Greenhouse Experiment

Based on the results from the field tests, the team identified two soil properties, bulk density and sodium level, as key environmental factors that had limited plant establishment along the highway segments in Beaver Crossing and Sargent. Before a full-scale greenhouse experiment was conducted, a preliminary greenhouse experiment was performed.

The preliminary experiment was conducted in May and June 2015 to determine (1) if soil surface treatment on compacted soil is necessary for seed germination, and (2) which grass species can germinate and grow on various soil surfaces. In this preliminary greenhouse study, three grass species were included to test their tolerance to soil compaction and salt treatment: buffalo grass (*Bouteloua dactyloides* Nutt.; BG), tall fescue (*Schedonorus arundinaceus* Schreb.; TF), and western wheat grass (*Pascopyrum smithii* Rydb.; WW). In addition to the three soil compaction levels (i.e., 1.4, 1.6, and 1.8 g cm^{-3}), two controls (i.e., greenhouse mix and sand) were also included. Another purpose of the preliminary experiment was to optimize the watering procedure in the greenhouse. In this preliminary greenhouse experiment, 18 pots were prepared.

The protocol that was developed to compact soils to the target bulk densities of 1.4, 1.6, and 1.8 g cm^{-3} started with the selection of ID Schedule 40 pressure-rated PVC pipes. The pipes had an interior diameter of 15.25 cm (i.e., 6 inch). The pipe was cut into sections with a height of 10 cm (i.e., 4 inch). Only 7.5 cm of the height would be occupied with soil resulting in a volume of 1390.6 cm^3 into which the soil would be compacted.

The first step with the soil preparation was to take a portion of field-moist soil and dry it at 105°C to determine the water content of the soil and make corrections for the desired final water content. The remaining field-moist soil was passed through a sieve with 19 mm openings to break down large clods and obtain uniform material prior to compaction. Having smaller clods (<19 mm) was critical for achieving uniform compaction of the soil in the pots particularly at the 1.4 and 1.6 g cm^{-3} bulk densities.

The amount of soil (corrected for water content) needed for each bulk density was weighed into a plastic bag. The amount of water needed to bring each sample to field capacity (-33 kPa matric potential) was calculated and then added to soil by misting on the soil sample. The soil was mixed and stored in the plastic bag for 12-24 hours to allow the soil to adsorb water through capillary action and achieve uniform water distribution before compacting the soil.

The moistened soil was loaded into the pot and compacted by hand before a hand-operated hydraulic press was used to compact the soil to the final volume (Figure 2-6). The hand compaction was necessary to uniformly distribute the soil in the pot and prevent the soil from ribboning out of the bottom and top of the pot. The pot was then placed into the hydraulic press and pressed until reaching the desired depth (7.5 cm) or volume (1390.6 cm3). After compaction, the pots were placed in plastic bags to prevent the soil from air drying and stored until planting. It is important to note that the volume of the tested soil material can change with moisture content due to shrinking and swelling. The photos in Figure 2-6 show the hydraulic press and the pots with soil.

Figure 2-6. The hand-operated hydraulic press used to compact soils (left). Soil before and after compaction (right).

2.7 Full-Scale Greenhouse Experiment

Based on results from the preliminary experiment, a full-scale greenhouse experiment was initiated in July 2015 at the UNL Agronomy and Horticulture greenhouses. A factorial design included three treatment factors: plant species (buffalo grass, tall fescue, and western wheat grass), soil compaction (i.e., 1.5, 1.7, and 1.9 g cm^{-3} soil compaction levels as well as sand as control), and timing of salt stress (2 pulses of salt treatment applied pre-germination and post-germination as well as no-salt control). Germination and plant performance (height, weight, specific leaf area, chlorophyll content, salt content, carbon isotopes) were investigated under the three treatment factors.

Soil compaction treatment consisted of Aksarben silty clay loam, acquired from the Nebraska Department of Roads (NDOR), compressed into pots using the same method as described above. Aksarben silty clay loam was compressed into the pots at three bulk density levels: 1.5, 1.7, and 1.9 g/cm^3. Uncompressed sand was used as a control. Three NaCl salt treatment levels were applied at seeding (pre-germination, July 15th 2015) and germination (post-germination, August 3rd 2015), and no salt addition as a control. Salt applications took place over two consecutive days, applying half the total amount of salt on each day. The germination threshold was a stand count of at least 3 plants out of 10 seeds planted per pot in controls. Salt concentration varied, corresponding to the bulk density of the pots. The total salt concentrations applied corresponding to the bulk density of the pots were:

- 1.5 g/cm^3 → 5.2 g per application (total 10.4 g)
- 1.7 g/cm^3 → 5.85g
- 1.9 g/cm^3→ 6.55g
- Sand (Uncompacted) → 2.5g

The experiment was designed as a randomized block, with 7 replications per each treatment combination. Plants were grown under day:night temperature of 30:20 °C and 16-hr photoperiod. Three replications were harvested for plants and tissue analysis in August and September of 2015.

2.8 Plant Physiology Measurements

Germination rates and live/dead stand counts were recorded on a daily basis following seeding, and plant height was measured weekly from germination. Chlorophyll content - which is a direct measure of greenness and an indirect measure of the health of the photosynthetic system as impacted by compaction and salt - was determined on all seedlings on a regular basis using a CCM300 (Opti-Sciences, Inc. NH, USA). Carbon isotope ratio ($\delta^{13}C$ ‰), and tissue chloride content which are indicative of water status and stress were determined on plant materials after harvest. Plants were harvested on two separate dates: replications 2, 4, and 6 were harvested on August 21, 2015, while replicates 1, 3, 5, and 7 were harvested on October 10, 2015. At harvest, the number of live plants, number of dead plants, and leaf area of live plant material (using an LI-3100, Lincoln, NE) were recorded. The harvested plant materials were oven dried and weighed. Dried and weighed materials were then sent to the UNL Water Sciences Laboratory for carbon and chloride content analysis.

2.9 Data Analyses

Data from the field test were analyzed using the PROC MIXED model in SAS (SAS version 9.3) where highway segment was used as whole plot treatment and landscape position as split plot. Data from the greenhouse study were analyzed using the mixed model procedure in SAS, where plants were considered random effect and treatments fixed effects.

Chapter 3 Field Test Results

3.1 Overview

Locations on the highway segments had no significant effect, but landscape position had a large and significant effect on soil physical properties including cone index, wet aggregate stability, and sorptivity. Site × landscape position interaction was not significant. Thus, data were averaged across the six locations to study the effect of landscape positions on the soil properties for each site.

3.2 Cone Index

Concerning the Beaver Crossing site, the penetration resistance was the highest at S1 (0 m from the road), particularly at the 0 to 10 cm depth. Similar trends were observed for the 10 to 20 cm depth except at one location on the highway. The maximum penetration resistance value at Beaver Crossing was 10 MPa. It ranged from 5 to 10 MPa across S1 for the 0-10 cm depth. These cone index (CI) values, however, gradually decreased with an increase in distance from the road, ranging from about 10 to 1 MPa. The CI values at the S3 (cropland) ranged from 1 to 2 MPa. In landscape position P2 and P3 the 10 – 20 cm depth had a higher CI value than the 0 - 10 cm depth across all locations, usually having a 1 MPa difference.

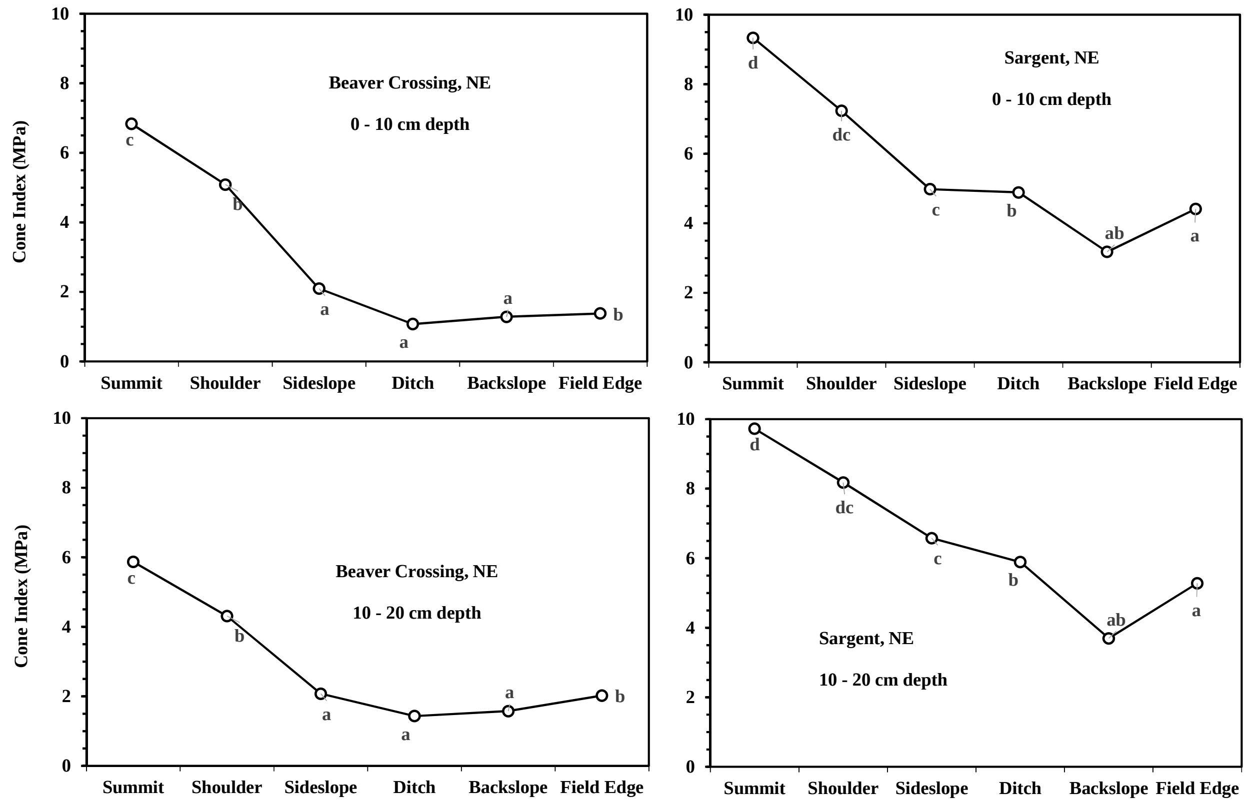

Figure 3-1. Cone index with distance from the road for the 0-10 cm and the 10-20 cm depth along two highway segments near Beaver Crossing and Sargent, NE. Summit was the closest position (0.5 m) from the edge of pavement. Means followed by different lowercase letters are significantly different.

Concerning the Sargent site, similar penetration resistance trends were found with a few exceptions. Like at Beaver Crossing, the roadside CI value had a maximum of 10 MPa. The CI range across S1 for the 10 cm depth was 10 MPa to 5 MPa. However, instead of the values increasing again at S2 (summit near cropland) and S3 (cropland) positions, the penetration resistance increased at D (ditch) positions with a maximum of 9.8 MPa at the 10 cm depth. The CI value again gradually decreased with the range of 9.8 MPa at D to 2 MPa at S3 position.

At Beaver Crossing, the S2 and S3 positions were located in fields all of which experienced tillage operations. It has been reported that plowing operations can result in subsoil compaction (Bradford 1986). This study proves that the subsoil compaction at 10 – 20 cm was expected due to the effects of tillage operations. On the other hand, the high compaction near the roadside occurred at the 0-10 cm depth. The topsoil was compacted by heavy machinery after road construction and was unable to resist compaction, whereas the subsoil showed fewer signs of compaction (Berli *et al.* 2003). It is noted that the maximum allowable CI value for croplands is about 2 MPa. In our study, the CI values greatly exceeded the threshold. This means that vegetation growth can be impaired or reduced, as seen by the current lack of vegetation on the roadside.

3.3 Sorptivity

Sorptivity assesses the soil's ability to rapidly capture water (Smith 1999). Surface soil sorptivity (S) was measured using the cumulative infiltration in the early stage in which gravity effect is negligible, rather than measuring the infiltration flux for a long initial period (Smith 1999). For all three Beaver Crossing locations, sorptivity measurements were at or below 0.05 cm $s^{-1/2}$ at the first landscape positions. Sorptivity measurements peaked at SS (Side Slope), the third landscape positions and decrease again at D (Ditch) the 4th and BS (Back Slope) the 5th landscape position (Figure 3-2). The Sargent site follows similar trends in the data with low sorptivity at transect positions S1 and steadily increase as landscape positions are farther away from the road (Figure 3-2).

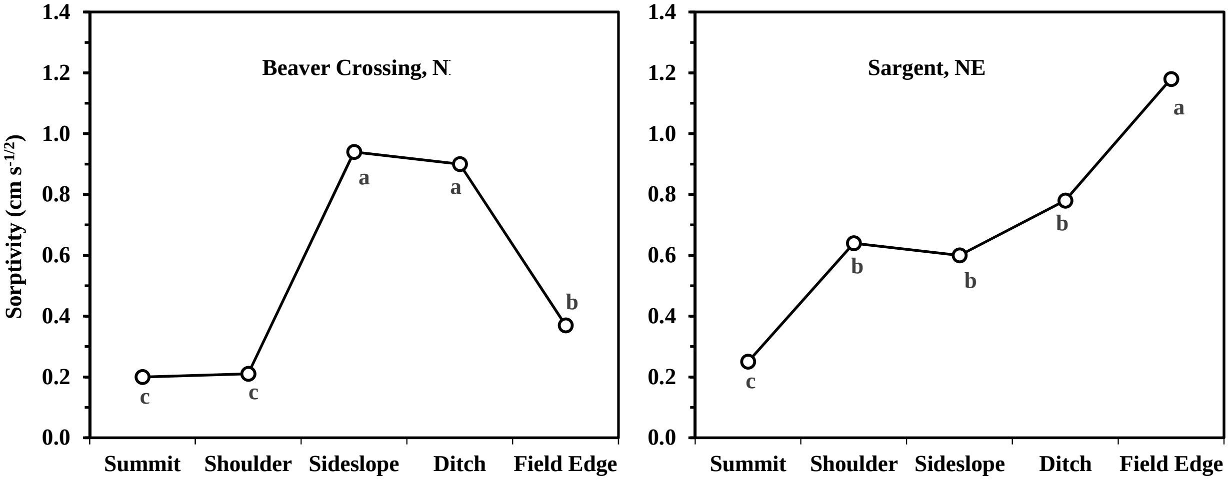

Figure 3-2. Changes in soil sorptivity (initial infiltration) with distance from the road along two highway segments near Beaver Crossing and Sargent, NE. Summit was the closest position (0.5 m) from the edge of pavement. Means followed by different lowercase letter are significantly different.

In general, for both sites the rate of infiltration near the road was low and increased until the ditch, where generally sorptivity increased due to compaction that happened under wet soil conditions. The sorptivity and cone index values were inversely related: the rate of infiltrations was low at locations where the cone index was high. Thus, the sorptivity rate would be low where the soil compactions is high.

3.4 Aggregate Stability

Water stable aggregates (WSA%) are the amount of aggregates that do not slake upon wet sieving (Marquez *et al.* 2004). WSA% is used in order to measure the stability of macroaggregates and microaggregates. Figure 3-3 shows the macroaggregates values as a function of the distance from the road. The macroaggregates exhibited a positive correlation between WSA% and distance from the road. In contrast, the microaggregates exhibited a negative correlation between WSA% and distance from the road. So while macroaggregates will have a low WSA% at 0 m, microaggregates will have a high WSA% at 0 m. For macroaggregates, the average WSA% at 0 m was 22.75 for the four locations at the Beaver Crossing site, while for microaggregates the average WSA% at 0 m was 77.25.

Measurements of macroaggregate stability have been found to be negatively correlated with soil erodibility (Bajracharya *et al.* 1992). It has also been suggested that disintegration of the soil macroaggregates into microaggregates is the first step in the loss of soil structure (Abusharar *et al.* 1987). This suggests that better soil health is found farther away from the road. Our data shows few water stable macroaggregates near the road where soil erodibility is high. The microaggregates had a high number of water stable aggregates near the pavement's edge, suggesting that the less stable highly disturbed soil is located near the road.

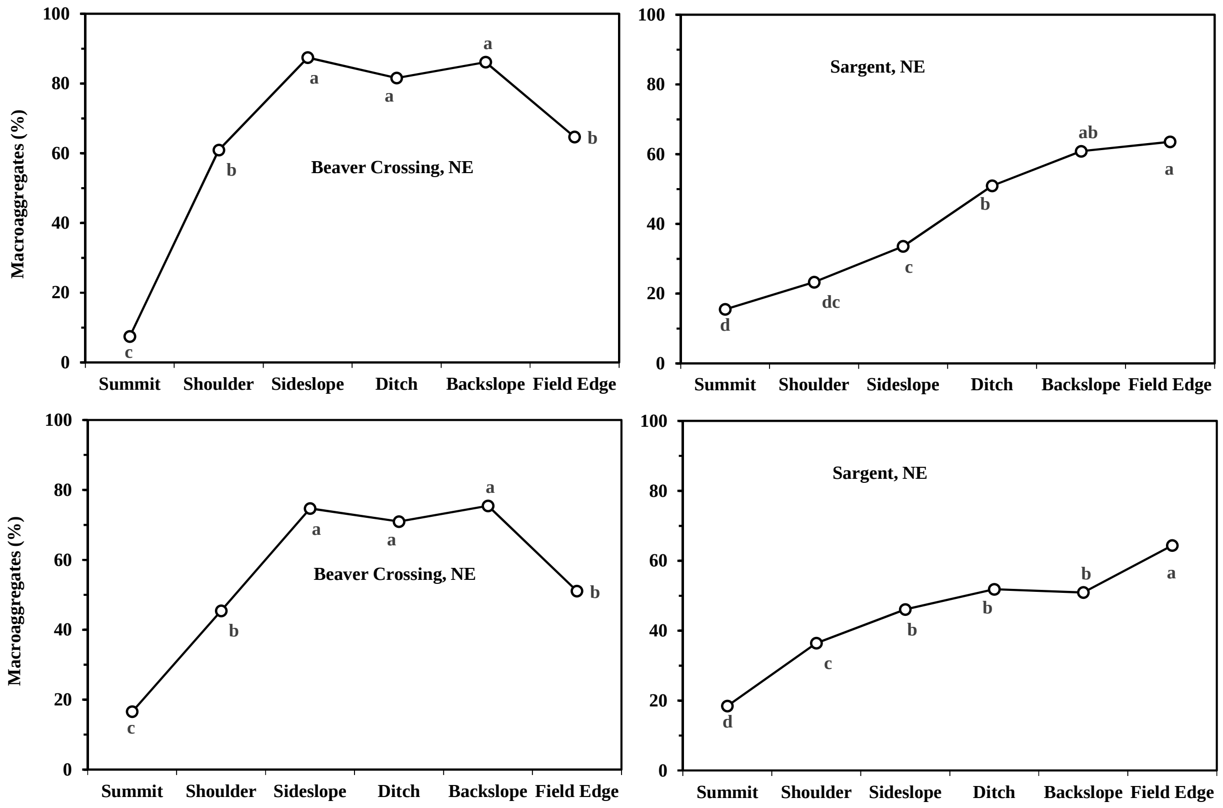

Figure 3-3. Soil macroaggregate distribution with distance from the edge of pavement for the 0-10 cm and 10-20 cm soil depths along two highway segments near Beaver Crossing and Sargent, NE. Summit was the closest position (0.5 m) to the edge of pavement. Means followed by different lowercase letters are significantly different.

3.5 Chemical Properties

Soil samples were sent into the Ward Laboratories and analyzed for pH, organic matter (OM), electrical conductivity (EC), Na, and Ca content (Figure 3-4). The pH was very basic with an average of 8.3 at 0-m from the edge of pavement. As distance from the road increased, pH decreased to an average of 7.4 at 6-m. The OM% and landscape positions were positively correlated. OM% increased as the distance from the road increased. The values ranged from 2.3 OM% at 0-m to 3.2 OM% at 6-m. EC had relatively high values at 0-m of 3.3 dS m^{-1}, which gradually decreased farther away from the road. Sodium content was negatively correlated when comparing sodium in soil and the landscape position. The average sodium level was 1600 mg Na Kg^{-1} at 0-m from the road, whereas it was 200 mg Kg^{-1} at 6-m from the road. The Ca in soil exhibited the exact opposite trend from that of Na in soil. The average Ca level was 2,950 mg Ca Kg^{-1} at 0-m from the road, whereas the average Ca level was 3,400 mg Ca Kg^{-1} at 6-m from the road.

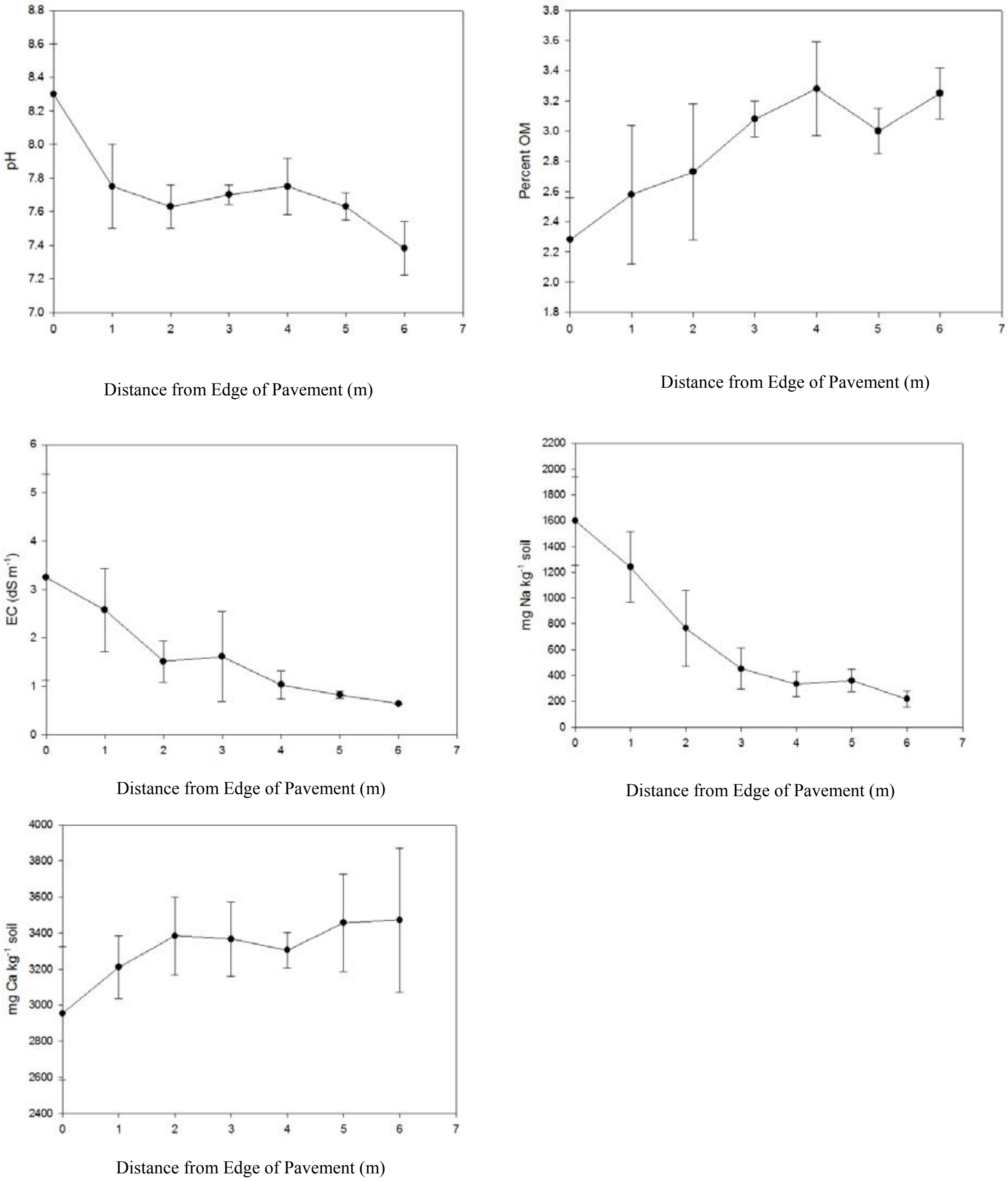

Figure 3-4. The values of pH, OM, EC, Na, and Ca as functions of distance from the edge of pavement.

The optimum soil pH level for vegetation germination and growth is between 6.5 and 7.5. The pH values of at most of the positions in the transects were above the optimum range except at 6-m from the edge of pavement. Because alkaline pH occurred across the transects and plants grew at some positions of the transects, high pH did not appear to affect vegetation at the study locations. Pure water is a poor conductor of electricity, however its electrical conductivity increases when salt dissolves in water. The EC for a normal soil is less than 4 dS m^{-1}. Soils that are high in salts can lower the osmotic potential of the soil water, making it difficult for roots to remove water from the soil (Brady and Weil 2010). The soils near the side of the road had EC values less than 3.3 dS m^{-1}. Hence, EC alone was likely not the reason for impaired vegetation growth.

Na levels show similar trends as EC. The high Na in roadside soils is most likely due to de-icing agents used in the winter, which in turn raises the pH and the EC. Na is also a dispersing agent of soils. High Na levels can lead to elevated level of microaggregates. The levels of Na and microaggregates were the highest by the edge of pavement and then decreased with distance away from the road. The trend of Ca was the opposite to the trends of Na and EC, and was similar to the trend of macroaggregates. This is most likely because Ca is a binding agent, it encourages the formation of macroaggregates.

Chapter 4 Greenhouse Study Results

4.1 Preliminary Experiment

Table 4-1 summarizes the results from the preliminary experiment. The results show that when sufficient water was provided, a large percentage of the seeds planted were able to germinate, irrespective of plant species, soil compaction ratio, and soil surface treatment. This was critical to guide the design of the full-scale greenhouse experiment, since seeds from various species needed to germinate under most of the treatment combinations in order to determine the significance of the treatment factors tested. Low or zero germination rates (i.e., negative results) would not have allowed the determination of effects of those treatment factors.

Table 4-1. Germination rates of three grass species under three soil compaction treatments, and two controls (sand and fill soil) under greenhouse conditions.

Treatment	**Tall Fescue**	**Western Wheat Grass**	**Buffalo Grass**
1.4 g/cm^3			
Compacted fill (NDOR) soil only	50%	45%	40%
Compact with sand surface	63%	60%	67%
Compact with fill (NDOR) soil surface	97%	73%	60%
1.55 g/cm^3			
Compacted fill soil only	40%	60%	50%
Compact with sand surface	67%	40%	60%
Compact with fill soil surface	87%	53%	53%
1.7 g/cm^3			
Compacted fill soil only	85%	30%	55%
Compact with sand surface	57%	63%	57%
Compact with fill soil surface	77%	73%	57%
Sand control	73%	30%	77%
Fill soil control	47%	63%	50%

4.2 Full-Scale Test

Germination and early survival results showed significant species*salt*soil compaction interaction. Buffalo grass showed the highest germination rate relative to the other two species in control and in control*pre-germination salt treatment. Germination was impacted in buffalo grass in response to compaction >1.7, and application of salt prior to germination inhibited germination except in control (sand) for this species. We believe seeds were able to germinate in control due to salt leaching in pots with sandy soil in response to watering.

Germination and early survival in tall fescue were not impacted by soil compaction or post-germination salt treatment. Although, pre-germination salt application severely impacted germination in this species, tall fescue was the only species that exhibited some germination in this treatment albeit at very low rate (<1.3%).

Western wheatgrass seed germination and early plant survival were the lowest relative to the other two species. Similar to tall fescue soil, compaction did not significantly impact germination. Neither did post-germination salt treatment. We did not record any germination in pots receiving salt prior to germination except in control.

Several buffalo grass plants died after germination (tissue analysis is underway). The plants that survived remained very small. We were only able to measure chlorophyll in western wheatgrass and tall fescue, preliminary results showed little difference between the two species.

Overall, based on our results from this study, we believe that tall fescue is better suited for site re-vegetation especially if salt is present in the soil prior to germination.

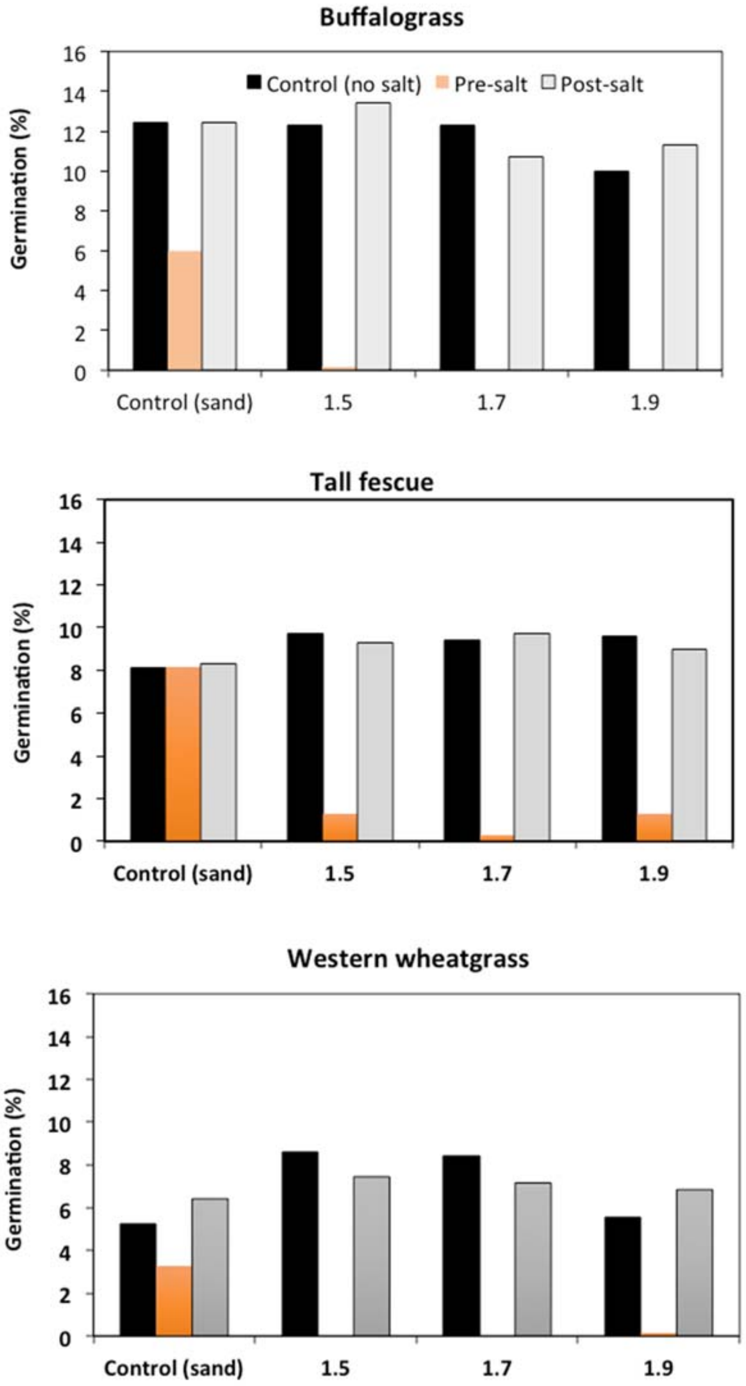

Figure 4-1. Germination rate and survival of select grass species in response to soil compaction (1.5, 1.7, 1.9, and control) and salt treatments (pre-germination, post-germination, and no-salt control).

Statistical analysis has shown that salt treatment had the most impact on species performance (Figure 4-2). With the exception of buffalo grass, which had higher leaf count under sand control, soil from NDOR provided a better medium for species germination and establishment regardless of soil compaction. This observation is somewhat counter intuitive, and more in-depth future studies need to be performed to confirm this observation.

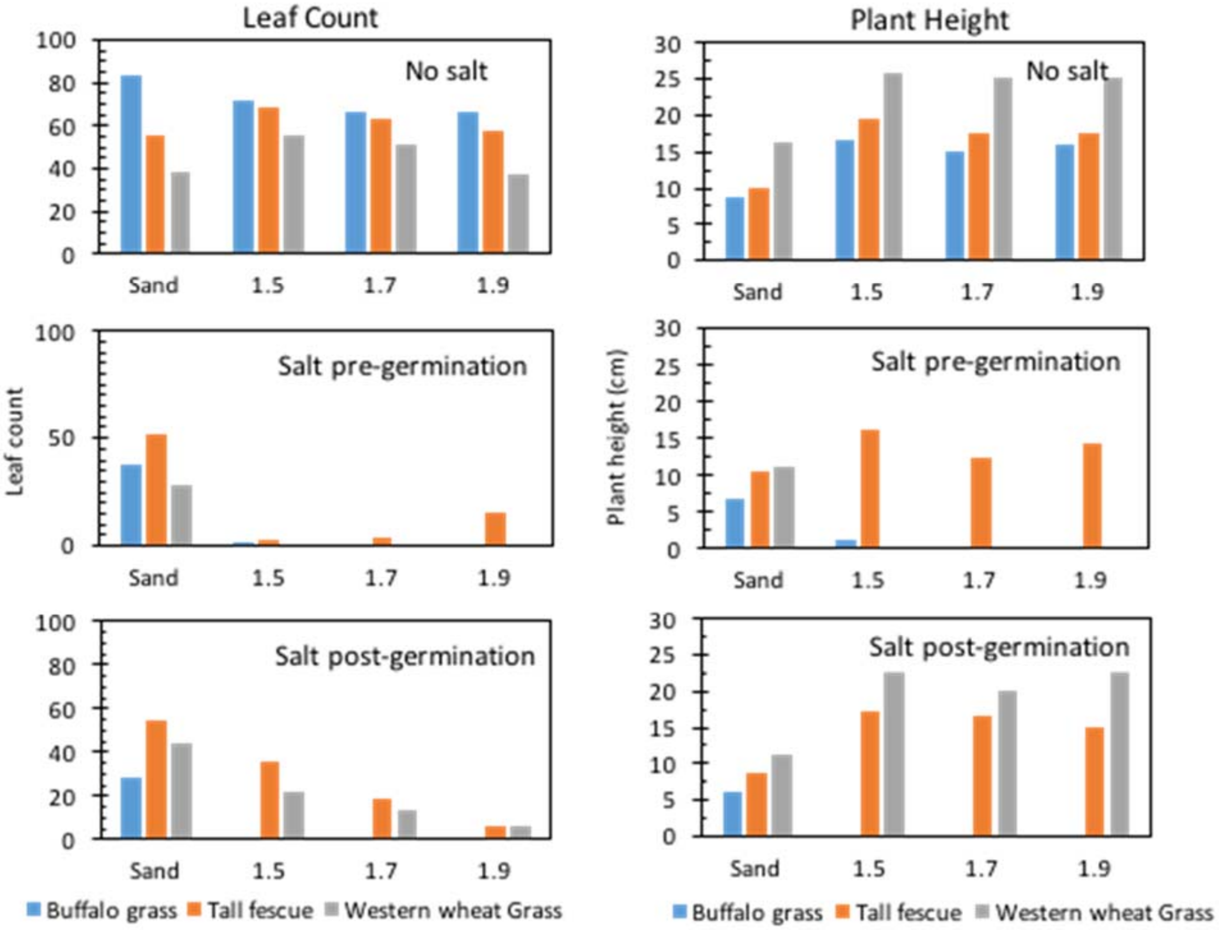

Figure 4-2. Leaf count and plant height (cm) of three grass species under four soil compaction levels (g/cm^3) and salt treatment (pre-germination, post-germination, and no salt).

Species displayed differences in dry weight and leaf area. Buffalo grass displayed the highest weight to leaf area ratio (i.e., specific leaf weight; Figure 4-3), a characteristics of this species. The other two species, tall fescue and western wheat grass, showed higher investment in leaf area versus weight (i.e., higher specific leaf area; Figure 4-3). Tall fescue in general showed more plasticity in responding to soil density and salt treatment and was the only species that maintained some productivity under salt treatment. In general, salt application at pre- or post-germination was less detrimental for plants in control sand than in NDOR soils. Tall fescue in NDOR soils was less impacted by salt application after germination than at seeding time, which indicates that once established, tall fescue can withstand soil compaction and salty runoff. However, seeding on soils with high levels of salt will result in failure in germination except in sandy soils. This observation will need to be confirmed in future studies under field conditions.

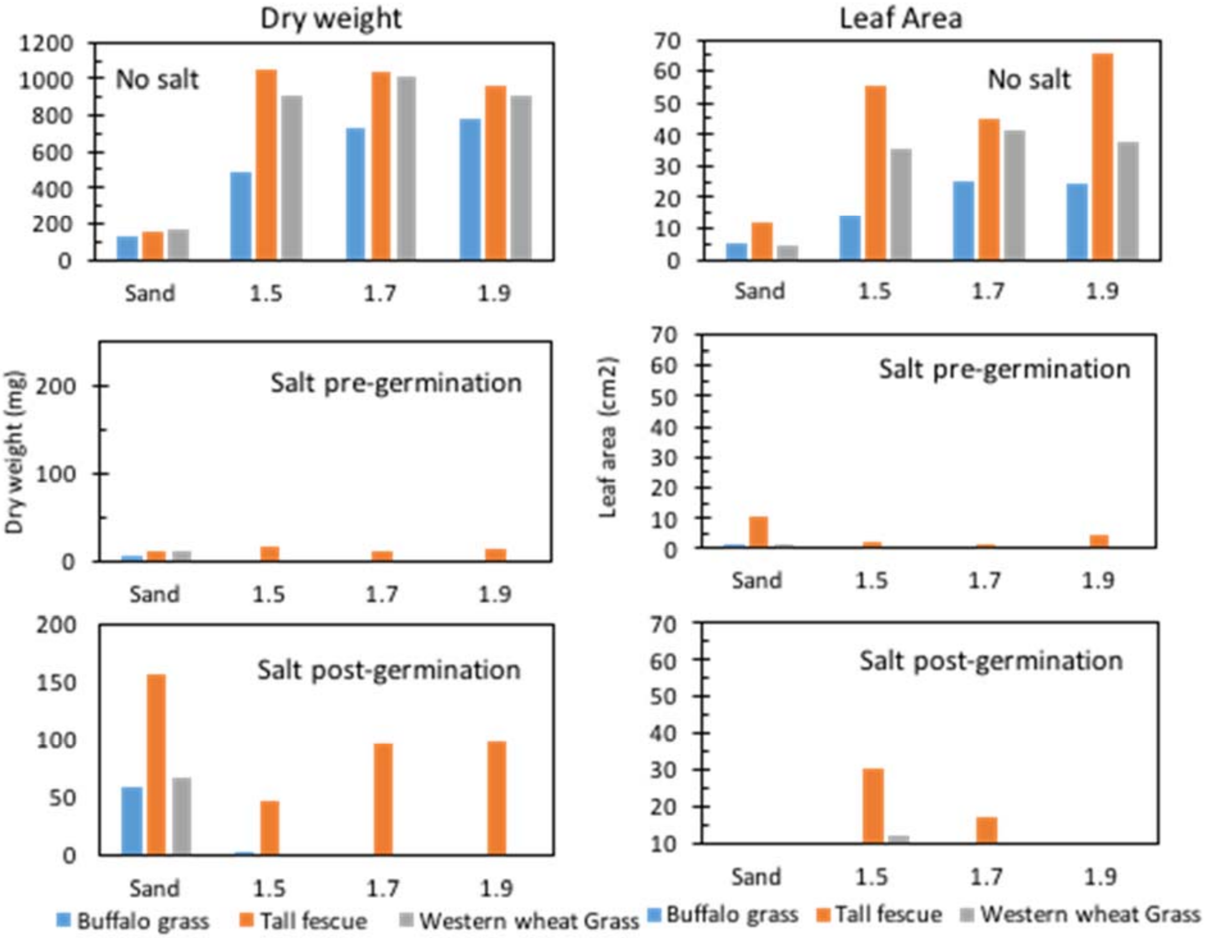

Figure 4-3. Above ground plant dry weight (mg) and total leaf area (cm^2) for three grass species under three soil density levels (g/cm^3), and salt treatment applied at seeding or after germination, and in control (sand medium).

Carbon isotope ratio is indicative of water use efficiency (Figure 4-4). Analyses of carbon isotope ratio showed that buffalo grass tissues were the most enriched (less negative) among the three species tested. This is consistent with buffalo grass being a C4 and a warm season plant, which is more efficient in water use compared to tall fescue and western wheat grass, both of which are C3 or cool season plants. We did not observe any change in tissue signatures in response to soil density or salt treatments. Difference were only associated with functional groups (i.e., C4 vs C3 photosynthetic system). Salt accumulated the least in tissue of plants in sand, likely due to salt leaching. Buffalo grass tissues accumulated the most, which could be the reason behind its poor performance.

Leaves had to be big enough to fit into the clip for the chlorophyll content measurement. Hence, we were only able to measure chlorophyll in tall fescue and western wheat grass. Measurement results showed that chlorophyll content was not impacted by density but post-germination salt treatment resulted in 40% reduction in chlorophyll content.

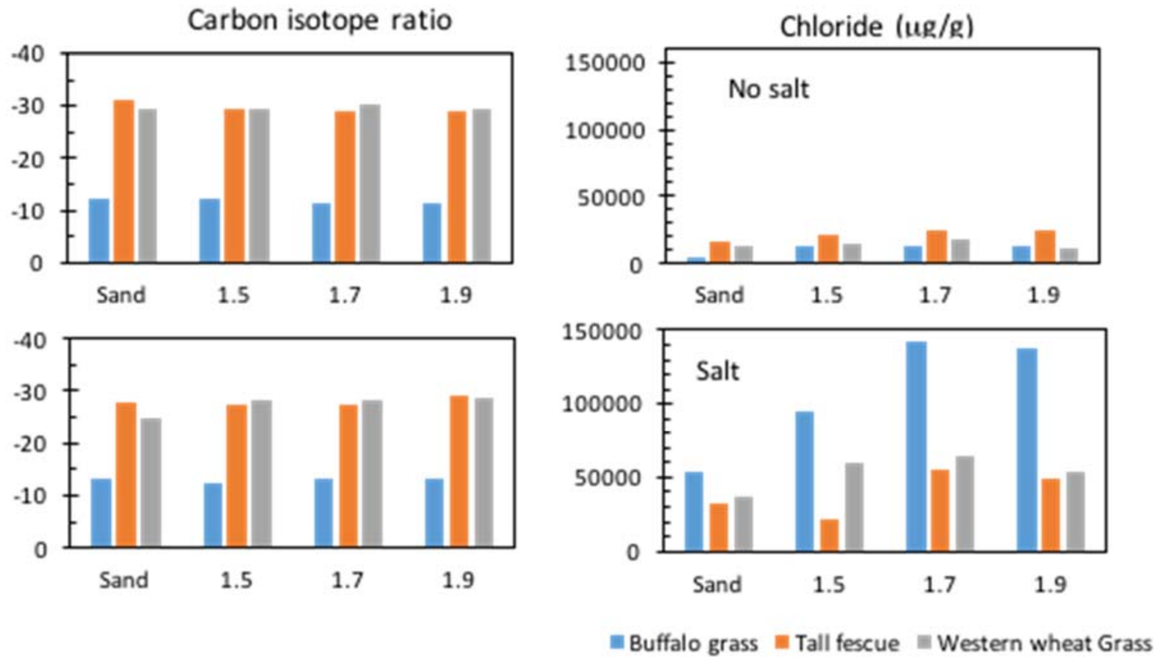

Figure 4-4. Carbon isotope ratio ($\delta^{13}C$, ‰) and leaf chloride content (µg/g), for three grass species under three soil density levels (g/cm^3), and salt treatment applied at seeding or after germination, and in control (sand medium).

Chapter 5 Engineering Approach

Selecting proper seeding mixture composition and improving soil conditions could be two effective approaches to address the roadside vegetation problem facing NDOR. In this project, three commonly used plant species were tested for their tolerance of high soil compaction and high salt content in soil. In this chapter, we will explore engineering options that can be used to improve soil conditions by addressing problems such as low fertility and high compaction.

5.1 Remedy for Soil Compaction

From the literature as well as from the field and the greenhouse tests in the project, it is clear that high compaction of soil is a major cause of poor plant establishment on highway shoulders. However, studies designed to address the soil compaction issue in revegetation are very limited in the literature. One possible solution to the soil compaction issue is to create microsites on compacted soil surfaces (Montana Watercourse 2012). Microsites are grooves on the soil surface (Figure 5-1), and can be created using machinery such as dozers. The local environmental conditions at the microsites, such as soil moisture, nutrient availability, soil physical characteristics, are often different from the rest of the soil surface. For example, compared to the rest of the soil surface, microsites can better maintain moisture after rainfall events. Soil moisture is critical to the germination and growth of plants. Also, compared to smooth soil surfaces, the microsites make the soil surface rough, creating larger contact areas between seeds and soil. This can help plants to extract nutrients from soil during growth.

Figure 5-1. Plant germination (left) and establishment (right) in the microsites created on roadside (Montana Watercourse 2012).

The microsites can be created on the existing compacted soil surface. If the chemical properties of the existing soil is poor, topsoil can be added to the top of the low-quality soil. Then, the topsoil may be compacted to meet engineering specifics, and microsites can be created on the surface of compacted topsoil. To avoid the growth of undesired species, amendment of topsoil is recommended just prior to seeding. According to the study on Montana Watercourse, the creation of microsites should occur after seeds are broadcast on a compacted soil surface. Following seeding and the creation of microsite, compost can be applied to the seeding area to provide nutrients for plant growth.

According to the construction code, the soil on shoulders needs to be compacted as much as possible. The idea of creating microsites could be adopted to address the soil compaction issue at problematic highways in Nebraska. With respect to the engineering characteristics of the roadside, the microsites would unlikely affect the integrity of the roadside soil, hence would not affect driver safety. In the meantime, it can help establish plants on roadside and manage storm water runoff to meet EPA regulations.

The choice of top soil could also be a potentially important factor in establishing plants. Top soil hosts a vast amount of microbes. It is estimated that there are 2×10^9 cells per gram of top soil (Whitman *et al.* 1998). These soil microbes play a crucial role in establishing and maintaining the productivity of soil. They interact with plant roots, and form symbiotic relationships with plants (Dodd and Ruiz-Lozano 2012). For example, phosphate solubilizing bacteria are one type of plant growth-promoting bacteria, such as *Enterobacter agglomerans* and *Erwinia herbicola*, They can enhance the bioavailability of phosphorus to plants, and therefore benefit plant growth. Such bacteria likely exist in top soil but are absent in subsoils. By adding top soil back to the shoulders after construction, these beneficial bacteria will be introduced back to the site. There are other microbes that are indigenous to the construction site. They can be particularly beneficial for re-establishing plant species that occurred prior to construction (Li *et al.* 2008). Hence, when top soil is extracted from the construction site at the beginning of a project, the top soil should be saved and re-used at the end of the project for revegetation on the roadsides.

The actual benefits of microsites on compact top soil need to be tested experimentally. Unfortunately, greenhouse experiments are not suitable to test this engineering approach. When rainfall occurs in the field, water flow through the surface of the roadside into the ditch next to the highway. Small amounts of water may remain in microsites, but water won't accumulate over the entire surface of the roadside soil. Such flow patterns are difficult to simulate on the pots in greenhouse studies. When pots are watered in greenhouse, water cannot flow away due to pot walls and would sit on the top of the soil for an extended period of time. The sitting water would soak into soil and cause soil expansion, lowing the bulk density of the soil. We observed this phenomenon in one of our preliminary experiments. Instead of greenhouse studies, pilot studies in the field would be a more suitable option.

5.2 Alternative De-icing Agents

Our greenhouse experiment showed that exposure of seeds to high salt levels in soil could greatly impede seed germination. One significant source of the salt in soil is the de-icing agents. De-icing agents reach roadside following the melt of snow and ice in winter. When seeds are applied to roadsides in spring, they are exposed to high salt levels. Compared to sodium chloride, alternative de-icing salts and agents, such as calcium chloride and acetate-, formate- and molasses-based organic substances, are often less corrosive and have fewer negative impacts on roadside soils. Compared to sodium, calcium and magnesium ions can moderately improve soil structure and fertility without impairing water quality. Acetate- and formate-based de-icing agents are efficient and environmentally friendly with little corrosive effects. For example, the aggressiveness of magnesium acetate is 3 times lower than that of calcium chloride and 2 times lower than that of magnesium chloride. However, due to the cost, organic de-icing agents are used only for certain places such as bridges and tunnel pavement. Organic materials can also be used to reduce road slipperiness. One such material, also known as molasses, is an agricultural byproduct from the sugar production process. The patented name of this material in Europe is Safecote. In the US this product is known as Geo-Melt.

5.3 Use of Zeolite

Zeolites are mixtures of microporous minerals consisting of aluminosilicates of sodium (Na), potassium (K), calcium (Ca), and barium (Ba). Zeolites may be mined naturally or produced synthetically. They have many unique properties that make them good soil amendments. The microporous structure on zeolite surfaces can accommodate a variety of cations. Because these cations are only loosely held, they can be readily placed by other cations, such as heavy metals lead (Pb) and cadmium (Cd). Hence, zeolites have been used successfully to reduce the bioavailability of heavy metals in soil and improve crop growth in contaminated soils (Castaldi *et al.* 2005). Pitcher *et al.* found that synthetic zeolite performs considerably better than naturally occurring zeolites when they are used to absorb heavy metals from the environment (Pitcher *et al.* 2004). In addition, the amendment of zeolites in soil can benefit plants by gradually conveying agrochemically useful substances (e.g., sodium, potassium, calcium and others) to soil, ensuring a proper level of cation exchange capacity (0.9-1.5 g-eqv./g) and encouraging the propagation of beneficial microorganisms (Baltrėnas and Kazlauskienė 2007). Finally, as a soil amendment Zeolite can also add the following characteristics to soil: reducing soil trampling effects, aerating the soil and plant roots, improving water permeability, retaining the optimum amount of water, and reducing fertilizer run-off to the environment.

However, while the addition of zeolites to high salinity soil can increase plant biomass, it is noticed that in some cases high zeolite content may cause negative effects on plant growth. Baltrėnas *et al.* reported that plants grown in soils with 20% zeolite content had shorter above-ground parts as well as less phytomass than the plants grown in soil with 10% zeolite (Baltrėnas and Kazlauskienė 2007). Hence, when amending zeolites to soil, preliminary tests may be necessary to determine the optimal dose for a particle soil.

5.4 Amendment of Organics

Amendment of organic materials such as mulch, manures and composts have been investigated for their effectiveness in soil remediation (Tejada *et al.* 2006). El-Shakweer *et al.* demonstrated that adding organic matters can accelerate sodium leaching in saline soils and decrease the exchangeable sodium percentage and electrical conductivity (El - Shakweer et al. 1998). The amendment of organics can also increase water infiltration, water-holding capacity and aggregate stability (El - Shakweer *et al.* 1998). Studies show that organic amendments can increase soil microbial biomass and certain soil enzymatic activities (Blagodatsky and Richter 1998). The increase of microbial biomass is caused by microbial growth associated with the organics and with improved plant growth as a result of organic amendment.

Tejada and co-authors reported the positive effects two organic amendments, cotton gin crushed compost and poultry litter, on the physical, chemical, biological properties of soil (Tejada *et al.* 2006). At the end of this 5-year study, the authors reported an 80% plant cover in treated saline soil under dryland conditions versus an 8% plant cover in the control soil. Compared to poultry litter, cotton gin crushed compost resulted in more pronounced improvement in the soil physical properties (i.e., 23% increase in bulk density compared to the control soil) and in soil chemical properties (i.e., 50% decrease in exchangeable sodium percentage compared to the control soil). In contrast, compared to cotton gin crushed compost, poultry litter led to more substantial improvement in water soluble carbohydrates and enzymatic activities. When organics used for soil amendment, the heavy metals associated with organics may also be introduced to soil and cause toxic effects to plants and soil microbes. So, organic materials with low levels of heavy metals are recommended for amendment.

Chapter 6 Conclusions

Analyses of the soil samples collected from the field revealed that the physical and chemical properties of soil changed as function of the distance from the edge of pavement. Although several soil properties measured were not within the optimal ranges for plant growth, two parameters appeared to stand out: soil compaction and sodium level. The Cone index, an indicator of soil compaction, of the soil at the summit (i.e., closest position from the edge of pavement) was as high as 10 MPa at the 10-cm depth of the two sites included in the study. This is much higher than the optimal cone index, 2 MPa, for plant growth. The high level of compaction of the top soil likely resulted from the use of heavy machinery on the highway shoulders after road construction. The second parameter is the sodium level. The average sodium level was 1600 mg Na Kg^{-1} at the edge of pavement, whereas it was 200 mg Kg^{-1} at 6-m from the edge of pavement where plants could grow well. The high level of sodium by the edge of pavement likely contributed to the poor vegetation establishment.

During the greenhouse study, the effects of the two soil properties identified were further verified for their effects on the germination and growth of three plant species (i.e., tall fescue, western wheat grass, and buffalo grass). Among the three plant species tested, tall fescue showed the most promising results. Neither soil compaction nor post-germination exposure to high sodium levels appeared to affect the germination and early survival of tall fescue. However, pre-germination exposure to high sodium levels severely impacted the germination of tall fescue. Western wheat grass seed germination and early plant survival were the lowest relative to the other two species. This greenhouse experiment proved that soil compaction and high salt levels were two environmental conditions that could severely impeded the germination and early growth of plants.

In the meantime, it was also learned from the greenhouse experiment that growing plants in pots could not satisfactorily simulate all the environmental conditions that plants encounter in the field. It was recommended that future studies should be conducted in the field. If future studies are to be conducted in the field, a few approaches are recommended to remediate the soil compaction and sodium issues. In order to remediate the soil compaction issue, microsites (i.e., grooves) can be created on the soil surface using machinery such as dozers. Compared to compacted soil surfaces, microsites are expected to better retain moisture after rainfall and create larger contact area between seeds and soils. To avoid the buildup of high sodium levels, alternative de-icing agents can be used in the winter and soil amendments such as zeolites and organics may be added to the soil during the compaction of the road shoulder.

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