SALT AFFECTED SOILS AND THEIR RELATIONSHIPS WITH PLANT COMMUNITIES ON RECLAMATION WELL SITES

by

Laura Bony

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Department of Renewable Resources

University of Alberta

ABSTRACT

Salt affected soils are common around the world from natural causes or anthropogenic activities. Over 1030 million hectares of land worldwide are affected by salt or at risk of being affected. In Alberta, saline and sodic soils may occur with oil and gas production, increasing the risk of salinization on well sites due to waste water production. Those salts can have detrimental impacts on soil structure and impede vegetation growth and development. Land reclamation on these well sites follows provincial regulatory requirements that include thresholds for electrical conductivity (EC) and sodium adsorption ratio (SAR) to measure success. However, EC and SAR are not always representative of soil and vegetation recovery. This research assessed whether EC and SAR are the most scientifically appropriate indicators for salt affected soil reclamation.

Well sites were assessed in Dry Mixed Grass and Central Parkland ecoregions of Alberta. Soil was sampled from 0 to 1.5 m depth and analyzed for EC, SAR, pH, and individual ions including sodium, chloride, sulfate, calcium, magnesium, and potassium. Vegetation assessments included ground and canopy cover and diversity. Relationships between soil parameters and those between soil parameters and vegetation variables were determined using correlations, non-metric dimensional scaling, linear mixed model, hierarchical partitioning, and redundancy analysis.

Although EC and SAR gave good information on general soil health, they were not sufficient measures to determine salt impacts in reclaimed plant communities and to assess salt affected soils. EC and SAR did not always represent ion concentrations in the soil well, and were not a satisfactory measure to predict plant survival or general condition. Sodium, chloride, and sulfate, the most toxic salts for plants, are not always represented by EC and SAR. Magnesium and potassium were significantly impacting vegetation parameters, and are recommended to be added to reclamation criteria when EC and SAR do not meet criteria, but vegetation is healthy and productive. The upper 0.45 m depth influenced the most vegetation parameters in both ecoregions; thus reclamation criteria is recommended to focus salt remediation at that depth.

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CHAPTER I: BACKGROUND

1. INTRODUCTION

Salt affected soils occur naturally, or may be anthropogenically produced, such as during oil and natural gas extraction and production. Over 1030 million hectares of land worldwide, and approximately 20 million hectares (30 %) of agricultural land in Canada is considered salt affected, or at risk of salinization (Bertrand et al. 2020). Oil and gas production can lead to the release of highly saline waste water, which can contaminate the environment without appropriate management. Landowners and industries are required by government regulations to remediate salt affected soils as part of land reclamation requirements after oil and gas operations (Alberta Government 2019a). For successful reclamation, soil in many jurisdictions must satisfy provincial guidelines for salinity and sodicity.

Western Canada holds a large quantity of oil and natural gas in various stages of production. The Alberta land base that contains oil and gas reserves is currently estimated to have approximately 172,000 active wells, 91,000 inactive wells, 73,000 abandoned wells, and over 433,000 km of pipelines (Alberta Government 2020). Many of these sites are located in natural salt affected soils. During oil and gas production, soil contamination with saline waste water is frequent. These waste waters usually contain chloride salts such as sodium chloride, calcium chloride, or potassium chloride. Changes in salt composition due to oil and gas production are affected by soil properties and geomorphological sites.

In Alberta, salinity is measured by electrical conductivity (EC), and sodicity is measured by sodium adsorption ratio (SAR). Since plant community reestablishment can be influenced by soil salinity and sodicity, EC and SAR have been considered measurements that are critical to understand and facilitate reestablishment of functioning soil and plant communities during reclamation. Regulatory requirements include the Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guideline (Alberta Government 2019b). Many other jurisdictions have similar regulatory requirements that must be followed during reclamation.

Although using EC and SAR to determine reclamation success has been a long standing practice, these parameters may not be the most appropriate metrics for salt contaminated soils. For example, cut-off measurements of specific ions, soil structural properties, or plant community composition may be used as indicators of detrimental salt conditions, or indicators of the ability of the ecosystem to recover from oil and gas extraction.

2. LITERATURE REVIEW

2.1. Salt Affected Soils

Salt affected soils can develop naturally through weathering, or with anthropogenic activities, such as oil and gas well site development and operation and saline water spills. Salt contaminated soils are those that impede normal plant growth (Pirasteh-Anosheh et al. 2015, FAO 2016, Shin et al. 2016). They are classified into three categories: saline, saline-sodic, and sodic, depending on salt concentration, type of salts, concentration of sodium, and soil alkalinity (Paz et al. 2020).

Salt affected soils contain many salts in the soil solution. These salts come from several sources including in situ weathering, saline water bodies (cyclic salts), atmospheric deposition, sedimentary rocks (fossil salts), and anthropogenic activities (Essington 2005). The most common salts are non-hydrolyzing cations, also called base cations. They include calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and some anions such as chloride (Cl^{-}) and sulfate (SO_4^{2-}) (Essington 2005). Smaller quantities of other salts found in soils include potassium (K^{+}), nitrate (NO_3^{-}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^{-}). (Allison et al. 1954). In western Canada, sodium chloride is the most common salt in saline waste water (Alberta Environment 2001). Chloride ions do not bind to soil particles, and easily leach in soils, often reaching ground water. Sodium molecules bind to soil particles leading to clay dispersion and structure breakdown.

In primary weathering, the soil environment contains unstable minerals. Mineral dissolution is promoted by carbonic acid and soluble organic compounds. After primary weathering is complete, secondary minerals appear and form ions such as bicarbonate (HCO_3^{-}), carbonate (CO_3^{2-}), chloride (Cl^{-}), and sulfate (SO_4^{2-}). These are solubilized and remain in the soil solution (Essington 2005). An arid or semiarid region has limited leaching with a pH of approximately 8 to 10. These regions usually contain calcite, and since the ions are not leached through the soil profile, water-logging develops and generates sodic systems. The elevated concentration of HCO_3^{-} and CO_3^{2-} in these ecosystems, combined with high pH results in precipitation of calcium (Wojtowicz 2001) and magnesium carbonates (Doner and Pratt 1969). This reaction leaves a significant amount of sodium on the soil exchange complex. Salts can also infiltrate the soil through irrigation waters and through sedimentary rock dissolution (fossil salts). While fossil salts exist as a primary salt source, salinization is a secondary and anthropogenic process (Essington 2005). Salt quantity brought up by surface and ground water is based on amount of salt in the material that water has been in contact with. Other factors contributing to soil salinization are water deficit, topography, salt content in parent material, and hydrology (Wiebe et al. 2007).

Salt is quite motile and can move easily in the soil profile with water (Scianna 2002). Cation exchange reactions affect mobility; positive ions are generally less mobile than negative ions (Alberta Environment 2001). Soluble salts generally move downwards; however, with leaching, they can move in any direction by capillary action. This capillary action migrates salt upward with pore water from a high water table into the plant root zone (Landsburg 1981, Shin et al. 2016). The amount of capillary rise in soil and depth to water table influence salinization of the root zone (Finlayson 1993). Chemical diffusion generally occurs within 30 cm above the soil and saline interface. Anthropogenic activity can, however, influence salinization (Jordán et al. 2004).

Soil salinization may arise from both irrigated water and poor drainage when poorly managed (Pirasteh-Anosheh et al. 2015). Dissolved salts may be found in irrigation waters, which results in additional salts released by mineral weathering. In arid and semiarid regions, salts may appear at the surface of soils due to more evapotranspiration than precipitation (Pirasteh-Anosheh et al. 2015). Sometimes salts from the irrigated water do not percolate to the ground water and instead stay in close proximity to the soil surface (Essington 2005). Poor drainage results in accumulation of salts at the soil surface and in the ground water. The type and amount of salt present in the soil or in the irrigated water influences soil physical and chemical properties. An excessive quantity of sodium is associated with high soil pH, poor soil structure due to slaking of aggregates, and swelling and dispersion of clay, which further impede root penetration leading to poor conditions for plant growth (Essington 2005).

Saline soils are usually defined by pH less than 8.5 and may be referred to as white alkali soils because of the visible salts at the soil surface (Allison et al. 1954, Brady and Weil 2008). Sodic soils typically have pH 8.5 to 10.0 because of the ability to form sodium hydroxide (NaOH) and increase hydrolysis. They are referred to as black alkali soils since there is a visible accumulation of organic matter at the soil surface (Allison et al. 1954, Brady and Weil 2008). Saline soils usually have EC greater than 2 dS m^{-1}, SAR greater than 4, and exchangeable sodium percentage less than 15 (Jordan et al. 2004).

2.2. Effects Of Salts On Soil Physical And Chemical Properties

Salt contamination can affect the environment and ecological processes, including degrading soil chemical properties, impairing vegetation, degrading soil physical properties by excess sodium, degrading surface water or ground water quality, and reducing soil strength with increased salinity and temperature (Hivon and Sego 1995). If sodium dominates the soil solution, as in sodic soils, it takes over calcium and magnesium adsorption sites (Allison et al. 1954). Since sodium is a monovalent cation, it causes dispersion of soil particles, due to its low valency that increases diffusion of double layer thickness and forces soil particles away from each other (Quirk 2001). This induced dispersion results in soil structure issues such as swelling, surface crusting, and hard setting (Qadir and Oster 2004).

The decrease of water infiltration and air movement into and within the soil profile reduces plant available water. It can increase runoff and erosion due to the clay particle swelling that causes large pores to decrease and results in dispersion and movement of clay platelets, further blocking soil pores (Shainberg 1990). Soil dispersion affects hydraulic conductivity; the water does not pass through soil as easily and the upper layer of soil can swell and become waterlogged. This causes anaerobicity which can reduce organic matter decomposition rates. The repetition of wet and dried cycles on soil can enhance clay dispersion, that then reforms and solidifies into cement like crusts (Warrance et al. 2016).

Soil physical properties are affected not only by salt but by soil water salinity, which can cause fine soil particles to bind together or flocculate into aggregates (Warrance et al. 2016). Soil aggregation and stabilization are positively affected by increasing soil solution salinity; however, at high levels, it can have negative effects on several plant species. Calcium and magnesium contribute greatly to salinity and tend to cluster close to clay particles. Both usually keep the soil flocculated since they compete for the same spaces as sodium to bind to clay particles. Therefore, larger amounts of calcium and magnesium in the soil reduce the amount of sodium induced dispersion in a soil (Scianna 2002). The effects of salts and sodium on soils can be determined by the ratio of salinity EC to SAR (Warrance et al. 2016). Salinity promotes soil flocculation and sodicity promotes soil dispersion. The swelling factor, which is the amount of soil that will likely swell with different salinity and sodicity ratio, predicts whether there will be sodium induced dispersion or salinity induced flocculation (Warrance et al. 2016).

2.3. Salt Impacts On Plants

Salts have inhibitory effects on plant growth since they accumulate outside the roots and inside plant cells, causing osmotic and ionic stress (Orozco-Mosqueda et al. 2020). The effect of salts on plants and soils is generally linked to toxicity level, which is based on bioavailability and solubility. Plant physiological processes, such as photosynthesis, might be inhibited by salts (Orozco-Mosqueda et al. 2020). Macro and micro nutrients, such as salts, influence interactions with the surrounding environment, can be found in the plant rooting zone, and are regularly transported into plant roots when in aqueous solution (Warrance et al. 2016). Salts such as sodium are easily transported, and others such as chloride are not; their concentrations fluctuate with changes in water sources, drainage, evapotranspiration, solute availability, and hydrostatic pressure (Volkmar et al. 1998).

Salt stresses from salinity are due to ion composition and concentration in the plant. The more salt ions in the soil, the harder it is for water and nutrients to move in and out of root membranes and into the plant due to osmosis. Osmotic stress is therefore expressed by dehydration (Orozco-Mosqueda et al. 2020). However, even if water and solute uptake are slower, it does not cease (Maas and Grattan 2015). Plants affected by salinity have nutrient imbalances which are expressed differently between species (Maas and Grattan 2015). Affected plants are stunted due to slower growth, have smaller leaves that might be thicker than those not affected, and leaves are usually darker green (Bernstein 1975). Nutrient uptake and distribution in plants result in physiological damage due to competitive processes between nutrients and major salts. For instance, high amounts of sodium lead to potassium and calcium deficiency, and chloride reduces NO_3 uptake (Maas and Grattan 2015). Salt crust can inhibit germination and leave bare ground (Bernstein 1975).

Calcium is inhibited by sodium due to sodium's effect on calcium distribution in the plant (Maas and Grattan 2015). Potassium is also affected by sodium. Since potassium is involved in photosynthesis, its deficiency can be expressed by reduction of chlorophyll, leading to yellowish stripes along leaf margins (DeTurk 1941). Salt ion transport rate is an important factor in plant salt tolerance and is linked to plant growth. When salt gets into the plant, it is transported to the leaves, which may result in ion toxicity (Munns and Termaat 1986). When salt gets into the leaves, it crosses the plasma membrane and accumulates in the cell vacuoles. This results in mature leaves dying first due to salt accumulation, showing signs of salt ion toxicity. Photosynthesis is disrupted, leading to decreased carbohydrate production needed to support continued growth (Munns 1993). Therefore, salt toxicity is observed through its effect on leaves.

Plant species called halophytes naturally tolerate high concentrations of salts in soils (Redmann and Fedec 1987). Halophytes are often considered weeds, as they are undesirable plants that can impact production of desired crops and plants. More than 50 % of halophytes are in the Chenopodiaceae family, which includes common weeds such as *Bassia scoparia* (L.) (kochia), *Salsola pestifer* A. Nels. (Russian thistle), and chenopodium (goosefoot species (Glenn et al. 1999). Other species from other plant families such as Poaceae, Fabaceae, and Asteraceae represent a high proportion of common halophytes, in spite of less than 5 % of the species in each of these families being halophytes.

2.4. Salt Impacts On Microorganisms

Microbial diversity affects abiotic and biotic factors including pH, temperature, humidity, nutrients availability, soil type, and salinity (Orozco-Mosqueda et al. 2020). Many microorganisms can be favourable to plant growth. However, they can be highly affected by salt contaminated soil if they are not adapted to it. The microbial community is affected by high concentrations of salts from the increase of osmotic pressure potential, which may lead to withdrawal of water from microbial cells, and can be killed by plasmolysis (Yan et al. 2015). Some adaptation can be observed on salt resistant organisms. For instance, these organisms counter osmotic stress by production of osmolytes, which allows maintenance of cell turgor and metabolism (Yan et al. 2015). Producing osmolytes has a downside, such as the energy cost of making it, which reduces growth and activity of these microorganisms. Reduction of osmotic potential leads to decreased spore germination, hyphae growth, and change in morphology (Juniper and Abbott 2006), and altered gene expression, leading to formation of spores with thicker cell walls (Mandeel 2006). Bacteria are generally more resistant to saline stress than fungus (Wichern et al. 2006). Microbial biomass is reduced in high salinity (Wong et al. 2008). High respiration rates occur in soils with low salinity. Low microbial biomass affects amino acid capture and protein synthesis and respiration, which increase and decrease carbon and nitrogen mineralization (Wichern et al. 2006).

Ecological functions and fertility are highly affected if salt contamination is found in the upper centimeters of soil. Plant nutrient availability is regulated by microbial activity (Orozco-Mosqueda et al. 2020). Therefore, its reduction in the topsoil impacts nutrient availability and plant growth. The most important microbial process that affects plant growth is nitrogen cycling. Nitrification is inhibited by salinization (Sethi et al. 1993) and sodium chloride can reduce nitrogen immobilization, nitrification, and mineralization. This leads to accumulation of ammonium nitrogen, which has an important role on nitrogen dynamics and availability for plants. Organisms are more sensitive to sodium chloride if they assimilated nitrate since it reduces nitrogen immobilization, nitrification, and mineralization (Azam and Lfzal 2006).

Survival of many species is dependent on mycorrhizae, and may be used as a pre-inoculant for plants in revegetation of salt affected soils. The effect of sodium chloride contamination on five species of mycorrhizal fungi (two basidiomycetes, three ascomycetes), ascomycetes are more tolerant to salt stress than the others (Bois et al. 2005). The mechanisms of salt transport and resistance differed for each species. For instance, *Rhizophagus irregularis* (N.C. Schenck & G.S. Sm.) (arbuscular mycorrhizal fungus) showed great potential to develop in saline solutions, with different tolerance for isolated individuals (Campagnac and Khasa 2014).

2.5. Salt Impacts On Plant Enzymatic Activities

Enzymes play a significant role in soil ecosystems. Reactions like organic residue decomposition, nutrient cycling, and organic matter formation in soil are catalyzed by enzymes (Frankenberger and Bingham 1982). These organisms are sensitive to salinity and may be from plants, animals, or microorganism sources. Thus, salinity negatively impacts soil enzyme activity.

The decrease of enzyme activity in saline soils may be attributable to osmotic dehydration of microbial cells (Orozco-Mosqueda et al. 2020), which release intracellular enzymes that make it susceptible to attack by soil protease. It results in the decrease of enzyme activity, inhibition of dehydrogenase activities, and mildly inhibited hydrolase. Addition of salt modifies the effect of ionic conformation of the protein enzyme site, including specific ionic toxicity that generates a nutritional imbalance for microbial growth and subsequent enzyme synthesis. Other enzymes have reduced capacity due to salinity, including urease, alkaline phosphatase, B-glucosidase, and microbial respiration (Ghollarata and Raiesi 2007, Yan et al. 2015).

Stress caused by salt increases ethylene production leading to poor plant growth and damages including leaf yellowing, organ senescence, abscission of leaves, and others (Orozco-Mosqueda et al. 2020). Carbon and nitrogen mineralization and enzyme activities can decrease in a highly saline environment (Amini 2015).

2.6. Regulatory Framework

In Alberta, legislation governing reclamation is the Environmental Protection and Enhancement Act (EPEA) (Alberta Government 2019a). Remediation of salt affected soils must meet EPEA criteria to be considered reclaimed. The management of contaminated sites should prevent pollution, protect human health and the environment, and return land to productive use. This may be done by following criteria or guidelines, or by a site specific approach consisting of an evaluation of exposure potential and hazard to receptors and resulting risk to receptors. The Alberta tier 1 and 2 for soil and ground water remediation provide comprehensive remediation guidelines for equivalent land capability ((Alberta Environment and Parks (AEP) 2019a).

The Tier 1 guideline (Alberta Environment and Parks (AEP) 2019a) were first developed to protect sensitive sites and they can be used without modification at most contaminated sites in Alberta. The guideline determines remediation of contaminated soil by the mean of numerical values based on identification of receptors to be protected under various land uses, applicable exposure pathways, and parameters that permit conservative predictions of risks. These assessments of contaminated sites must follow specific requirements. This guideline may be used with additional government documents including landfill disposal or remediation of sulfur containing soils, salt contamination assessment and remediation, and drilling waste disposal. Topsoil guidelines must be applied to L, F, H, O, and A horizons for EC and SAR, and subsoil guidelines must be applied for horizons below A.

Land use is an important factor for Tier 1 guidelines (Alberta Environment and Parks (AEP) 2019a), and affects potential receptors and their exposure to soil contaminants. This guideline was developed for natural areas, agricultural, residential and parkland, and commercial and industrial lands. EC and SAR are used to determine whether sites are successfully reclaimed according to the 2010 reclamation criteria for well sites and associated facilities for native grasslands (Alberta Government 2013a), cultivated lands (Alberta Government 2013b), and forested lands (Alberta Government 2013c).

Tier 2 guidelines (Alberta Environment and Parks (AEP) 2019b) are reliable for sites that are based on site specific conditions and on Tier 1 guidelines potential for human or ecological exposure to the specific parameter being assessed. Tier 1 approaches may be unacceptable if specific conditions increase risks, and is thus based on sensitivity of the site being assessed. Tier 2 guidelines may be more or less restrictive and both differ in the site specific information required for their use (Alberta Environment and Parks (AEP) 2019b).

Salt contamination assessment and remediation guidelines (Alberta Environment 2001) repeat Tier 1 soil quality guidelines. Soil quality criteria relative to disturbance and reclamation are the primary guidelines for assessing salt and sodium of salt contaminated soils (Alberta Agriculture 1987). The criteria were developed to provide physical, chemical, and biological guidelines for evaluating soil suitability for reclamation. Three regions in the province have guidelines, including the plains region with the central plains and Peace River plains, with a predominantly agricultural land use; the eastern slopes region includes the lower and upper foothills and the Rocky Mountains to the British Columbia border; the northern forested region includes the remainder of the province. This document provides soil standards for EC and SAR for topsoil and subsoil. For unrestricted land use EC is considered good at 2 dS m^{-1}, fair 2 to 4 dS m^{-1}, poor 4 to 8, and unsuitable greater than 8 dS m^{-1}. For subsoil, the range is 3, 3 to 5, 5 to 10, and greater than 10 dS m^{-1} for these categories. In the same category SAR topsoil and subsoil are ranked good, fair, poor, and unsuitable with less than 4, 4 to 8, 8 to 12, and greater than 12, respectively.

Variation in these standards may occur. For instance, certain plant species are sensitive to salts at EC lower than 2 dS m^{-1}, and a soil texture of sandy loam or coarser with percent saturation lower than 100, with SAR 12 to 20 can be ranked as poor. EC has some restriction when it is for commercial and industrial soils and cannot be greater than 4 dS m^{-1} and SAR not higher than 12 (CCME 1999). If a site is reclaimed, but the land use is changed for commercial or industrial, the standards for this specific land use have to be met, and therefore might require additional remediation. Commercial or industrial sites should have a maximum EC of 4 dS m^{-1}, and agricultural and residential sites with a maximum EC of 2 dS m^{-1} and SAR of 5.

In other provinces in Canada, criteria for salt remediation vary. British Columbia is considering sodium and chloride concentrations under the Contaminated Sites Regulations (Government of British Columbia 2015). They have a regulation for soil standards that includes wildland, agricultural, urban park, residential low and high density, commercial, and industrial land for human health and environmental protection. The maximum toxicity thresholds of chloride ion are 350 mg kg^{-1} for wildland, agricultural, and urban park and 2500 mg kg^{-1} for commercial and industrial land. The maximum toxicity threshold for sodium ion is 200 mg kg^{-1} for wildland, agricultural, and urban park, and 1000 mg kg^{-1} for commercial and industrial lands (Government of British Columbia 2015).

The province of Saskatchewan assesses salinity contamination by a range of values for EC and SAR (Saskatchewan Petroleum Industry and Government Environmental Committee 2009). Sites may differ due to differences in crop variety, salt composition, climate factors, and soil properties. Therefore, since crop response to salinity varies, the reclamation criteria are taking into account specific land use like crop variety, and site specific factors such as meteorological factors and soil textures. Soil remediation criteria are specific to agricultural, residential, forest, and subsoil and have ranges of EC and SAR that are acceptable. They are divided by unconditional use, moderately tolerant crop, and tolerant crops. The EC is not good over 2 dS m^{-1} for unconditional use, 3 to 5 dS m^{-1} for moderately tolerant crops, and 6 to 8 dS m^{-1} for tolerant crops, for agricultural, residential, and forested; and subsoil ranges are higher with 8 dS m^{-1} for unconditional use and 9 to 12 dS m^{-1} for moderate tolerant and tolerant crops (Saskatchewan Petroleum Industry and Government Environmental Committee 2009). For SAR, unconditional use is 5 and conditional use is 6 to 8 for agricultural, forested, and residential, and subsoil is 8 for unconditional use and 9 to 13 for conditional use.

2.7. Oil And Natural Gas Drilling Procedures

For a considerable period of time the most common of the various techniques to harvest oil and gas was fracking. Currently two different drilling methods, onshore and offshore, have transformed drilling sites that are uneconomic into profitable drilling sites. Onshore drilling applies to drilling deep holes under the surface of the earth, and offshore drilling refers to drilling underneath the seabed (Richard 2013). Both of these techniques are performed to extract natural resources such as oil and gas.

Typically, onshore drilling uses equipment including exploratory equipment, waste water and oil separators, pumps, pipelines, and storage tanks (Richard 2013). Onshore drilling rigs use classic equipment that comes in many sizes and strengths. The drilling rigs are usually classified by their maximum drilling depth and mobility (Richard 2013). The petroleum industry typically uses conventional land rigs that cannot be moved as a whole unit, although there are also mobile rigs that are mounted on wheeled trucks, including jackknife and portable mast that can be moved to various sites as needed (Richard 2013).

The subsurface area that one well can drain is called a spacing unit. In Alberta, the spacing unit for oil wells is one well per quarter section of land, and for natural gas it is one well per section of land (AER 2011). However, a common practice in Alberta is to reduce spacing and conduct directional drilling; meaning that inside the spacing unit, the target area is where the well bottom should end. The target area thus prescribes subsurface location for a well instead of a surface location of a well (AER 2011).

Salt domes are a pile or column of salt that has forced its way upwards into overlying sediments (Bayram and Bektasoglu 2020). They can be formed in a sediment basin with a thick layer of salt covered by younger sediments and can rise hundreds of meters above the initial layer of salt. Oil and natural gas may be trapped under salt domes, which are impermeable, and often mined as a source of salt and sulfur. The salt dome grows and the cap rock above it curves upwards serving as an oil or natural gas reservoir (Bayram and Bektasoglu 2020). To get to the oil and natural gas, salt domes or layers can be injected with fresh or sea water to leach the salt, and the resulting salt water will be produced at the surface (Anger-Soehne 2014). The cap rock that covers the salt dome can contain a great amount of elemental sulfur.

In oil and natural gas production, another fluid may be found on sites. Drilling mud or drilling fluid is a heavy, viscous fluid mixture that is used to transport rock cuttings up to the surface and lubricate and cool the drill bit (Lan et al. 2020). This fluid is known to prevent collapse of unstable strata into the borehole in addition to encountering the intrusion of water from water bearing strata by hydrostatic pressure (Lan et al. 2020).

Water based fluid can be from fresh and sea water, or natural or prepared brines. Water based fluids are used for less demanding, medium depth, drilling of conventional vertical wells. Water based fluids are made of clay, generally bentonite, which makes up the viscosity that carries cutting chips to the surface, minerals like barite (barium sulfate), that increase weight of the column that stabilizes boreholes calcium carbonate (chalk) or hematite (Rabia 1996). Smaller quantities of other ingredients may be added, including caustic soda (sodium hydroxide) that increases alkalinity and reduces corrosion, salts such as potassium chloride that decreases water infiltration from drilling fluid into rock formation, and petroleum derived drilling lubricants. Other thickeners influencing viscosity such as xanthan gum, guar gum, glycol, carboxymethylcellulose, polyanionic cellulose, or starch (Rabia 1996) can be added. Deflocculates to reduce viscosity of clay based mud may be used, including anionic polyelectrolytes, acrylates, polyphosphates, lignosulfonate, or tanic acid derivatives.

Oil and gas production yields salt water as a by-product and should be disposed on a regular basis on a well site (Pinnergy 2018). Therefore, waste disposal is a necessity and can be found on sites. One of the disposal techniques include injection of produced salt water and other oil and gas wastes into injection zones, which can be from naturally occurring formations. Injection zones require well isolation by an impermeable strata, confining injected fluids to the permitted zone (Pinnergy 2018). Zones may be using permanent surface tanks to accumulate oil and gas wastes and separate contaminants. This is done with a high pressure pump that injects waste into the permitted injection zone using a disposal well.

3. RESEARCH OBJECTIVES AND THESIS ORGANIZATION

The goal of this research is to address the identified knowledge gap of whether electrical conductivity and sodium adsorption ratio are the most scientifically appropriate indicators of salt affected sites and potential negative impacts on soil and plants. The research will address what their relationship is to plant community composition, health, and diversity across a range of land use of salt affected sites, and the relationship to alternative or complementary measures of salinity and sodicity, namely total salt concentrations and specific ion concentrations.

Specific research objectives are as follows.

- To assess salinity and sodicity on sites based on EC, SAR, pH, individual salts, and ion concentrations, and determine the relationships among these measures.
- To assess impacts of salinity and sodicity on plant communities and species of interest.
- To determine salinity and sodicity measures that most influence remediation and reclamation.
- To determine preliminary ranges of values for salinity and sodicity measures that may be acceptable as part of a scientifically based criteria for salt affected sites.

The thesis is organized into four chapters to address the above research objectives. Chapter I provides some of the background and rationale for the research. Chapter II focuses on soil properties and the relationships between EC, SAR, pH, and individual salt ions. Chapter III focuses on the relationships between soil (EC, SAR, pH, individual ions) and vegetation properties (ground cover, species canopy cover). Both Chapters II and III include discussions around suitability of current criteria to determine reclamation and remediation success using EC, SAR, and pH. Chapter IV summarizes the research, then study limitations, applications and potential future research are discussed.

CHAPTER II. SALT AFFECTED SOILS AND THEIR SALINE ION RELATIONSHIPS

1. INTRODUCTION

Salt affected soils originate through both natural and anthropogenic events. Worldwide, most important land degradation processes in agricultural areas come from soil salinization and alkalization (Wang et al. 2020). Over 900 million hectares of land are estimated to be contaminated with salts (Shin et al. 2016), with salinity and sodicity varying greatly across locations due to parent material, landscape position, climatic conditions, and human activities (Aldabaa et al. 2015).

Western Canada is known to hold a large quantity of oil and natural gas. In Alberta, there are over 336,000 wells sites and over 433,000 km of pipelines which contain oil and gas reserves (Alberta Energy Regulator 2020). Several production sites are located in natural salt affected soils, and further soil contamination with saline waste water is frequent during oil and gas production. These waste waters usually contain chloride salts such as sodium chloride (NaCl), calcium chloride (CaCl), and/or potassium chloride (KCl). Changes in salt composition are affected by geomorphology. The most prevalent salt for saline waste water in western Canada is sodium chloride (Alberta Environment 2001). As chloride molecules do not bind to soil particles, they easily leach in soils and are more likely to reach ground water. Sodium ions attach to soil particles leading to clay dispersion and soil structure breakdown. Excess sodium can result in high soil pH and poor soil structure due to aggregate slaking and swelling and clay dispersion, which further impedes root penetration leading to poor conditions for plant growth (Essington 2005). Salinity promotes soil flocculation while sodicity promotes soil dispersion.

In Alberta landowners and industries are required by government regulation to remediate anthropogenic salt affected soils as part of land reclamation requirements (Alberta Government 2019a). For successful reclamation, soil must satisfy provincial guidelines for salinity and sodicity. Salinity is measured by electrical conductivity (EC), and sodicity by sodium adsorption ratio (SAR). Since plant community reestablishment can be influenced by soil salinity and sodicity, EC and SAR have been considered critical measurements to assess and facilitate establishment of functioning soil and plant communities. Regulatory requirements include the Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guideline.

Other Canadian provinces, such as British Columbia have sodium (200 mg kg^{-1}) and chloride (350 mg kg^{-1}) concentrations in their reclamation criteria (Government of British Columbia 2015). In

Saskatchewan, EC and SAR ranges are used to assess site salinity; these ranges vary for different climates, soil properties, crop varieties, and salt compositional properties (Saskatchewan Petroleum Industry and Government Environmental Committee 2009).

There is some concern among industry, scientists, and regulators that EC and SAR may not be the most appropriate metrics for assessing salt contaminated soils. Upper limit specific ions, soil structural properties, and/or plant community composition may be more effective indicators of detrimental salt conditions or of the ability of the ecosystem to recover from oil and gas extraction and production activities. These more extensive indicators would be potentially important if vegetation was in good condition, but regulatory levels of EC and SAR were not met.

2. RESEARCH OBJECTIVES

The overall objective of this research was to address whether EC and SAR are the most scientifically appropriate indicators of salt affected sites and their potential negative impacts from a remediation criteria perspective. Specific research objectives were to assess salinity and sodicity on sites based on EC, SAR, pH, and individual salt and ion concentrations and determine their relationships.

3. MATERIALS AND METHODS

3.1. Research Sites

A list of potential oil and gas well sites in Alberta with saline issues was obtained from oil and gas companies and municipalities (Canadian Natural Resources Limited, Perpetual Energy, City of Medicine Hat, Orphan Well Association). Phase I and II reports for each site were used to locate saline areas, to provide detailed site diagrams with historic work areas such as well head, above ground storage tank, flare pit and drilling waste disposal area, that could be sources of salinity; and to provide information on whether any spill occurred, what contaminants were released on site, and any contaminant remediation techniques and timelines. Well sites selected for study required a saline issue that had been addressed in some way, revegetation at least a year old, a reclamation certificate applied for, received or not yet been applied for, and accessibility by four wheel drive truck or by walking a short distance.

Twenty-two sites were selected for study, 16 located in the Dry Mixed Grass and 6 in Central Parkland ecoregions (Appendix). Sites had four different land uses: grazed native forage (13 sites), grazed non-native forage (4 sites), ungrazed cultivated (4 sites), and ungrazed non-native forage (1 site). Sites were drilled between the years 1951 and 2003, most in the 1970s. Wells produced for 1 to 36 years (median 23 years), and one never produced. Wells were abandoned between 1970 and 2014. Documented spills were infrequent, with most salt affected soil resulting from regular production activities near the well centre, flare pits, drilling waste disposal areas, and/or storage tanks. There was little documentation on what reclamation had occurred, although most sites had some soil remediation, mainly contaminated soil removal and replacement with clean topsoil in highly contaminated areas. Cultivated and non-native forage sites were seeded. Soil was fine textured for 17 sites, coarse textured for four, and a mix for one.

3.2. Soil Sampling

The four corners of each site were marked with pegs every 10 m. An EM38-MK2 ground conductivity meter (Geonics Canada) was used to survey the sites. The readings were taken in areas previously identified as having high EC and/or SAR, usually in production areas (well centre, drilling waste disposal area, above ground storage tank, flare pit), and in areas with evidence of poor revegetation such as high bare ground and visibly stressed vegetation. Areas where EC was >2 or between 1.5 and 2 with poor vegetation were marked on the site diagram. One to three of these poorly reclaimed areas were randomly selected for soil sampling.

At each selected area, a hole was augered, then two more holes were augered approximately 1 to 2 m from the first. Each hole was marked with a pin flag and GPS location recorded. Sampling was conducted with a hand auger when possible. A percussion auger (Cobra PRO, TT, TT-AWD, 2010) was used to sample depths that could not be hand augered. At cultivated sites, all augering was done by hand to avoid damaging the crops. After each hole the auger was cleaned by removing excess soil with a knife and wiping with isopropanol. Augering was done to 1.5 m by 15 cm increments. When 1.5 m could not be reached due to compaction, the sample was taken as deep as possible. Ziploc bags were labeled with site, auger hole ID, and sample depth. If sufficient soil could not be obtained from one hole, another hole was augered next to the first one. Samples were stored in buckets during the field trips at ambient temperatures.

After every field trip, soil samples were sent to a commercial laboratory in Edmonton Alberta for analyses. Analyses were conducted according to Carter (2007) unless otherwise noted. Soil pH was determined using a pH meter in a 1:2 extraction with 0.01M $CaCl_2$ solution (CSSS 16.3). Conductivity saturation paste was used to determine EC by meter (CSSS 15.2.1, 15.3.1), and SAR was calculated (CSSS 15.4.4). Saturation paste analysis using Inductively coupled plasma optical emission spectrometry to determine concentrations of sodium (CSSS CH15, EPA 6010B), calcium (CSSS CH15, EPA 6010B), magnesium (CSSS CH15, EPA 6010B), potassium (CSSS CH15, EPA 6010B), chloride (colourimetry CSSS 15.2.1, ALPHA 45000-Cl E), and sulfur (CSSS CH15, EPA 6010B and converted to sulfate).

3.3. Data Analyses

Statistical analyses were conducted in R version 1.1.456 (RStudio 2020) All data were tested for normality and homogeneity using density and residual plots. Data were non-normal and non-homogeneous. Spearman correlation analysis, which does not assume normality of data, was used to determine if variables were correlated using PerformanceAnalytics package (Peterson 2020) and R and p-values <0.05 were obtained. R values above 0.7 were considered strongly correlated. Permutational analysis of variance using adonis was used from the ecodist package (Goslee and Urban 2007), followed by pairwise comparison using RVAideMemoire package (Hervé 2020) to determine how to combine multiple depths and to assess significant differences between ecoregions, land uses, soil textures, and years the wells were drilled.

Non-metric multidimensional scaling (NMDS) was used to determine similarity and dissimilarity based on soil parameters. This method does not assume normality, dimensionality, and linearity (Kruskal 1964), and uses a system of ranking for dissimilarity (Legendre and Gallagher 2001). NMDS has a stress parameter that assesses inadequate fit between object distances and measures dissimilarities among objects in the ordination space (Paliy and Shankar 2016). Stress values <0.05 show excellent representation, <0.1 fair, <0.2 good, and <0.3 poor (Clarke 1993). Since soil variables had different units, data were log transformed to weight them the same and reduce skew (Quinn and Keough 2002). To obtain a stable configuration, metaMDS from the Vegan package (Oksanen et al. 2019) was used to perform several runs to get the lowest dissimilarity between ordinations. Bray-Curtis distance matrix was selected for final models since it deals with dissimilarities instead of distance (Legendre and Gallagher 2001). It is a good distance matrix when data are not unimodal or linear, and is good for community data since it deals with zeros or absence of data (Legendre and Gallagher 2001). The length of vectors in NMDS is proportional to its R-value (Fensham et al. 1999).

Two regression models were used to determine which of sodium, chloride, or sulfate predicted the best response variable; a generalized mixed model and hierarchical partitioning since they complement each other (Gavier-Pizarro et al. 2010). The generalized linear regression model was used to obtain a subset of models that explain the best response variable using the best glm package (McLeod et al. 2020). Hierarchical partitioning is a multivariate regression model that joins all possible regression combinations to identify best causal factors (Chevan and Sutherland 1991, Nally 1996). It does not account for multicolinearity, since it assumes all measures are independent and estimates predictor variables, therefore being a good analysis in ecology (Nally 2002). Hierarchal partitioning predictor significance was calculated from randomization testing with negative log likelihood (n=1000) (Emilson et al. 2017) using hier.part package (Walsh et al. 2003). Those two regressions together showed the percent variability explained by a variable and frequency of best model.

4. RESULTS

4.1. Soil Parameters

Depth increments 0.0-0.15, 0.15-0.30, 0.30-0.45, and 0.45-0.60 m were statistically different and below 0.60 m depths were similar (Table 1). Hence, they were grouped for further analyses.

Soil parameters differed with ecoregion. Dry Mixed Grass and Central Parkland sample locations show dissimilarities in soil salinity parameters relationships (Figure 1). EC and SAR increased with depth in both Dry Mixed Grass and Central Parkland ecoregions (Table 2). Values for EC were highly variable in the upper 0.15 m in Dry Mixed Grass. All studied ions had higher concentrations in Dry Mixed Grass than in Central Parkland. Notably, mean sulfate concentration ranged from 294 to 1804 mg kg^{-1} and 44 to 133 mg kg^{-1} in Dry Mixed Grass and Central Parkland, respectively (Table 2). Lowest sodium, chloride, and sulfate occurred in the upper 0.15 m, with variability and concentration increasing with depth in Dry Mixed Grass. In Central Parkland highest sulfate values were found in the upper 0.3 m, decreasing with depth; sodium and chloride were lowest in the upper 0.3 m, increasing with depth. In Dry Mixed Grass, concentrations of calcium, magnesium, and potassium also increased with depth, but with less variability (Table 2). In Central Parkland, calcium, magnesium, and potassium concentrations decreased with depth from 0 to 0.6 m; highest concentrations were below 0.6 m depths. Variability of pH was low throughout depths and ecoregions (Table 2). Soil parameters also differed with land use but due to highly uneven numbers of sites in each land use, that difference was not focused on.

4.2. EC And SAR Relationships

Across ecoregions, mean EC ranged from 1.0 to 8.4 dS m^{-1}, and mean SAR from 0.7 to 9.1 (Table 2). For the 0.15 to 0.45 m depths, EC was strongly correlated with SAR (Table 3). However, when all parameters were assessed in an NMDS (Figure 1), EC and SAR did not show any relationship as they were forming a 90 degree angle.

In Dry Mixed Grass, EC and SAR were correlated from 0 to 0.6 m depths (Table 4), and in Central Parkland, EC and SAR were correlated from 0.15 to 0.45 m depths (Table 5). In Dry Mixed Grass, from 0 to 0.45 m, SAR significantly contributed to 13 to 16 % of the variation in EC; from 0 to 0.3 m EC significantly contributed to 16 to 26 % of the variation in SAR (Table 6). In Central Parkland, EC and SAR did not contribute to each other (Table 6).

4.3. EC And Ion Relationships

Across ecoregions, EC was generally strongly correlated with all measured ions (sodium, chloride, sulfate, calcium, magnesium, potassium) at every depth (Table 3). However, when all parameters were assessed together in the NMDS, EC was most strongly correlated with sulfate above 0.3 m and with magnesium below that depth (Figure 1).

In Dry Mixed Grass, EC was significantly correlated with all ions above 0.6 m (Table 4). When all variables were assessed together in the NMDS, EC and sulfate were most closely correlated above 0.3 m; and EC, magnesium, and calcium at lower depths (Figure 2). In Central Parkland, EC was correlated with chloride and magnesium at all depths and calcium at most depths (Table 5). When all variables were assessed together in the NMDS, EC was not closely correlated with any one ion above 0.3 m, but was closely correlated with chloride and potassium from 0.3 to 0.45 and below 0.6 m (Figure 3). At most depths and in both ecoregions, sulfate (18.4 to 41.8 %) and chloride (19 to 51 %) were significant contributors to EC (Table 6).

4.4. SAR And Ion Relationships

SAR was significantly correlated with most ions, strongly with sodium at all depths and sulfate under 0.15 m, when both ecoregions were combined (Table 3). When all variables were assessed together in the NMDS, SAR was most strongly correlated with sodium at all depths, and sulfate and/or pH at increasing depths (Figures 1, 2, 3). In Dry Mixed Grass, SAR was correlated with sodium and sulfate at all depths, strongly with sodium, and was correlated with chloride above 0.3 m (Table 4). In Central Parkland, SAR was correlated with pH above 0.3 m, and with sodium at all depths below 0.15 m (Table 5). In Dry Mixed Grass, sodium (27.7 to 43.8 %) and sulfate (11.5 to 16.8 %) significantly explained the variation in SAR, and in Central Parkland only sodium explained that variation (32.8 to 80.2 %) (Table 6).

4.5. PH And Ion Relationships

When data were pooled across ecoregions, pH was significantly correlated with all ions (Table 3). However, within ecoregions significant correlations varied with depth. In Dry Mixed Grass, pH was correlated with sodium between 0.15 to 0.6 m depths, sulfate from 0 to 0.6 m, magnesium 0 to 0.45 m, and calcium 0 to 0.3 m (Table 4). In Central Parkland, pH was correlated with sodium, sulfate, and calcium in the upper 0.15 m; and sodium, sulfate, and potassium from 0.15 to 0.3 m (Table 5). Soil pH was not corelated with any ions below 0.3 m (Table 5). In the NMDS, pH did not show any consistent relationships with ions (Figures 1, 2, 3). Sodium (23.87 and 24.7 %) and SAR (47.8 and 57.2 %) from 0.45 to 1.5 m in Dry Mixed Grass significantly contributed to the variation in pH (Table 6a). In the Central Parkland, SAR (35.6 %) significantly contributed to pH from 0.15 to 0.3 m, and chloride (30.3 %) from 0.45 to 0.6 m (Table 6b).

4.6. Ion Relationships

Across ecoregions, sodium was correlated with sulfate, chloride, and magnesium throughout all depths (Table 3). Calcium, magnesium, and potassium were correlated for all depths (Table 3). Similar results were observed in Dry Mixed Grass with the exception that chloride did not show a significant correlation with sodium below 0.3 m, and magnesium with potassium above 0.15 m (Table 4). In Central Parkland, the strongest correlation was between calcium and magnesium (Table 5). Sodium was correlated with chloride to 0.3 m and sulfate to 0.45 m.

In Dry Mixed Grass, when all variables were assessed together in the NMDS, sodium and sulfate, chloride and potassium, and calcium and magnesium were closely correlated below 0.3 m (Figure 2). In the NMDS for Central Parkland, calcium and magnesium were strongly correlated at all depths, and sodium and sulfate below 0.6 m (Figure 3).

4.7. Sodium, Chloride, Sulfate Indicators

As sodium, chloride, and sulfate are the most toxic salts for plants, they were assumed to also have adverse effects on soil properties. A comparison of generalized linear regression and hierarchical partitioning was performed to better understand the relative importance of salinity parameters in explaining these ion presences and concentrations. In Figures 4 and 5, black columns show the % variation in sodium, chloride, and sulfate explained by other salinity variables; the grey columns show the frequency of these variables being included in the best linear models to potentially predict sodium, chloride, and sulfate. In Dry Mixed Grass sodium appears to be most dependent on EC, SAR, and sulfate; chloride dependent on EC and sodium; and sulfate dependent on sodium (Figure 4). In Central Parkland sodium was most dependent on SAR, and chloride and sulfate on EC (Figure 5). However, the two approaches were not always in agreement. Based on results from both ecoregions, sodium was most dependent on SAR, and chloride on EC, suggesting EC and SAR would be appropriate measures for these ions.

5. DISCUSSION

5.1. Ecoregion And Soil Type Variation

Differences observed between ecoregions in the studied soil properties were as expected. Dry Mixed Grass and Central Parkland ecoregions have distinct climate differences, influencing soils and vegetation. Dry Mixed Grass consists of undulating semi-arid prairies, coulees, and valleys, dominated by brown chernozemic and solonetzic soils, and drought tolerant vegetation (Natural Regions Committee 2006). Central Parkland consists of agricultural lands, northern forests, and dry prairies, with black and dark gray chernozems and solonetzic soils dominating.

Soil properties and/or type influence land use decisions (grazing, crops). Thus, differences in soil properties with land use and ecoregion were likely more inherent to location than from the well site disturbances, since most land uses depend on the type of soil at that location.

A lack of significant differences associated with time since the wells were drilled was unexpected, as well site construction and reclamation differed considerably between 1951 and 2003. This implies that reclamation regulatory requirements and methods of drilling and reclamation were not the main drivers for expressed EC, SAR, and ions at the time of the study.

Differences in soil properties with depth were expected. Soil properties change with depth, and are manifested as specific horizons for the different types of soils. A main difference between Black, Dark Brown, and Brown Chernozems is the climate they developed under. Chernozemic soils are characterized by a Chernozemic A horizon (Ah/Ahe/Ap) of at least 10 cm, with a C:N ratio less than 17, and with calcium as the dominant exchange cation (Soil Classification Working Group 1998, Pennock et al. 2011). Solonetzic soils form on saline parent material (Soil Classification Working Group 1998). Southern Alberta soils are known to have high sulfate and calcium concentrations (Chang et al. 1983). Therefore, reclamation criteria could be adapted for those soils to best determine reclamation success. For instance, criteria at those locations could be based on background measures.

The water table, precipitation, evapotranspiration, capillary action, plant rooting depth, and microorganisms also affect soils (Aldabaa et al. 2015, Yan et al. 2015). Soluble salts usually leach downwards; however, capillary action or chemical diffusion can move salts upwards. Therefore, movement up or down in the soil profile may be expected (Landsburg 1981). Soil microorganisms change throughout the soil profile, affecting soluble nutrient concentrations (Lavahun et al. 1996, Treonis et al. 2010). All of these factors likely had a stronger effect on soil properties than well site construction and reclamation.

Ecoregions and soil types should be taken into consideration in reclamation criteria. For instance, Soil Quality Criteria Relative to Disturbance and Reclamation (2004) divides criteria into three regions: Plains Region, Northern Forest region and Eastern Slopes region. A rating system from good to unsuitable is used where pH, EC, SAR, percent saturation, texture, etc. are taken into consideration (Macyk et al. 2004). Saline and sodic soils assessment include soluble cations although not showing any specific threshold. Pre-disturbance values if available, or background values of soil should be provided for salt affected soils in the Alberta criteria for different regions and criteria could be based on it. Criteria are also divided between topsoil and subsoil.

5.2. EC And SAR As Reclamation Criteria

EC is a measure of conductivity resulting from the amounts of soluble salts present in the soil. However, it does not indicate which ions are found in highest concentrations. Since ions have different properties and interactions in the soil, EC might not always reflect detrimental effects for vegetation. Therefore, EC may be used to determine whether soluble salts are present in the soil, but may not be used to accurately assess a site at the level of detail needed to determine if a reclamation certificate may be given. For example, EC may be under acceptable criteria, however, one salt might be present in higher concentrations than another and have detrimental effects on soil and vegetation. In our study an EC of 1.74 dS m^{-1} met reclamation criteria although it had higher concentrations of sodium (380 mg kg^{-1}), chloride (152 mg kg^{-1}), and sulfate (293 mg kg^{-1}) than the same value of EC (1.74 dS m^{-1}) that had considerably lower concentrations of sodium (94 mg kg^{-1}), chloride (28.2 mg kg^{-1}), and sulfate (224 mg kg^{-1}). An EC of 2.5 dS m^{-1} did not meet reclamation criteria, but had a small concentration of sodium (17.9 mg kg^{-1}) and high sulfate (1070 mg kg^{-1}). Research has shown that sodium becomes toxic for most plants after 230 mg L^{-1} of soil and chloride at 4 to 7 mg g^{-1} (Tavakkoli et al. 2010, Meehan et al. 2017). Many papers discuss the negative effects of chloride and sulfate on vegetation, however, no specific threshold has been given (Eaton 1942, Reich et al. 2017), mainly since plant species will respond differently.

SAR is the ratio of sodium, calcium, and magnesium concentrations which shows high sodium values when SAR is elevated. High sodium concentrations indicate potential detrimental impacts on the soil including dispersion which causes swelling and surface crusting (Qadir and Oster 2004). Swelling results in decreased large pores, reducing water infiltration and air movement. Reduced infiltration leads to decreased water available for plants, and increased runoff and erosion (Qadir and Oster 2004). Sodium was well represented by SAR in that is shows when sodium is high or low relative to calcium and magnesium. However, if calcium and magnesium were also high, SAR would not represent sodium impacts on soil and plants. For example, SAR could be low but ion concentrations could still be high enough to have detrimental impacts on soil and vegetation. The opposite may also hold true, where the ratio could be high, but the sodium concentration would not be high enough to have adverse impacts on soil and vegetation. For example, our data showed an SAR of 3.49 with higher sodium (507 mg kg^{-1}), calcium (1460 mg kg^{-1}), and magnesium (925 mg kg^{-1}) than an SAR of 7 with low sodium (1.3 mg kg^{-1}), calcium (34.8 mg kg^{-1}), and magnesium (10.1 mg kg^{-1}). Therefore, SAR alone may not be an adequate measure to assess sodicity in determining reclamation success.

From a regulatory perspective, EC and SAR should not be used interchangeably since both measures are not related. Those measures should also not be the only ones taken into consideration when determining reclamation success.

5.3. Ions As Reclamation Criteria

Calcium and magnesium are major exchangeable cations in soils. Even though they have been grouped together in classifications, magnesium can be more detrimental than calcium (USDA 1954, Rahman and Rowell 1979). Their ratio can dictate how soils will react (Rahman and Rowell 1979). For example, in most magnesium systems, magnesium adsorbs more sodium than in calcium systems, resulting in adverse impacts on soil structure (Rahman and Rowell 1979, Andreeva 2020). Thus, it might be useful to include these ions in reclamation criteria. Other salts could also be included. For example, when soil cations with monovalent and divalent cations charges are in the same space, both dispersion and flocculation of clay particles induce soil pore stability and enhance air and water movement (Litalien and Zeeb 2020). When soils are mainly charged with monovalent cations such as sodium and potassium, dispersion leading to the reduction of pore size, slaking, macro pore reduction, and reduced water infiltration can occur. When a soil is mainly charged with divalent cations such as calcium and magnesium, flocculation may result. Therefore, a soil containing high sodium and potassium would have a greater impact on soil and water relationships and potential negative impacts on vegetation (Litalien and Zeeb 2020). For this reason, knowing which cations are present in the soil results in a better prediction of outcomes and may affect how reclamation success is assessed.

6. CONCLUSIONS

Reclamation criteria focusing only on soil EC and SAR may not be sufficient to determine salt impacts in the reclaimed plant community, particularly to assess salt affected soils. Reclamation criteria could be strengthened by including individual ions to specifically assess salts that have adverse effects on soil properties and vegetation when criteria are met but vegetation is not acceptable. Individual concentrations of salts including sodium, chloride, sulfate, calcium, magnesium, and potassium could be good indicators of soil health. The more potentially toxic ions including sodium, chloride, and sulfate would be even more important to include in the reclamation criteria.

Reclamation criteria should be modified or interpreted differently for specific ecoregions and soil depths. Although this is done to some extent already, it can be amplified to smaller areas, particularly those associated with salt affected soils.

Table 1. Pairwise comparison of depths for soil variables in Dry Mixed Grass and Central Parkland.

Depth Comparisons	F value	R^2 value	P value
Measurements and depth	13.07	0.083	0.001
Depth 0.00 to 0.15 m with			
0.15 to 0.30	5.08	0.0170	0.0069
0.30 to 0.45	16.42	0.0550	0.0021
0.45 to 0.60	27.66	0.0902	0.0021
0.60 to 0.75	39.27	0.1245	0.0021
0.75 to 0.90	49.09	0.1533	0.0021
0.90 to 1.05	58.41	0.1784	0.0021
1.05 to 1.20	53.08	0.1717	0.0021
1.20 to 1.35	53.15	0.1719	0.0021
1.35 to 1.50	53.62	0.1777	0.0021
Depth 0.15 to 0.30 m with			
0.30 to 0.45	3.10	0.0109	0.0370
0.45 to 0.60	8.87	0.0309	0.0021
0.60 to 0.75	15.79	0.0540	0.0021
0.75 to 0.90	22.02	0.0754	0.0021
0.90 to 1.05	27.93	0.0944	0.0021
1.05 to 1.20	24.82	0.0887	0.0021
1.20 to 1.35	25.07	0.0895	0.0021
1.35 to 1.50	25.63	0.0940	0.0021
Depth 0.30 to 0.45 m with			
0.45 to 0.60	1.60	0.0057	0.2359
0.60 to 0.75	5.31	0.0189	0.0037
0.75 to 0.90	9.27	0.0331	0.0021
0.90 to 1.05	13.09	0.0464	0.0021
1.05 to 1.20	11.58	0.0433	0.0021
1.20 to 1.35	12.22	0.0455	0.0021
1.35 to 1.50	12.69	0.0486	0.0021
Depth 0.45 to 0.60 m with			
0.60 to 0.75	1.14	0.0042	0.4116
0.75 to 0.90	3.40	0.0125	0.0370
0.90 to 1.05	5.78	0.0213	0.0037
1.05 to 1.20	5.11	0.0198	0.0069
1.20 to 1.35	5.70	0.0220	0.0037
1.35 to 1.50	5.98	0.0239	0.0021
Depth 0.60 to 0.75 m with			
0.75 to 0.90	0.65	0.0025	0.6935
0.90 to 1.05	1.87	0.0071	0.1713
1.05 to 1.20	1.77	0.0071	0.1884
1.20 to 1.35	2.34	0.0092	0.1020
1.35 to 1.50	2.43	0.0100	0.0884
Depth 0.75 to 0.90 m with			
0.90 to 1.05	0.37	0.0014	0.8775
1.05 to 1.20	0.54	0.0022	0.7853
1.20 to 1.35	1.01	0.0041	0.4461
1.35 to 1.50	1.00	0.0042	0.4600
Depth 0.90 to 1.05 m with			
1.05 to 1.20	0.40	0.0017	0.8775
1.20 to 1.35	0.91	0.0038	0.5072
1.35 to 1.50	0.69	0.0029	0.6549
Depth 1.05 to 1.20 m with			
1.20 to 1.35	0.15	0.0007	0.9750
1.35 to 1.50	0.22	0.0010	0.9750
Depth 1.20 to 1.35 m with			
1.35 to 1.50	0.15	0.0007	0.9750

Table 2. Mean and standard error of soil parameters in Dry Mixed Grass Prairie and Central Parkland.

Ecoregion	Depth (m)	Electrical Conductivity (dS m^{-1})	Sodium Adsorption Ratio	PH	Sodium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Calcium (mg kg^{-1})	Magnesium (mg kg^{-1})	Potassium (mg kg^{-1})
Dry Mixed Grass	0.0 to 0.15	3.5 ± 1.9	3.4 ± 0.8	7.5 ± 0.05	94.2 ± 24.9	90.0 ± 28.7	294.4 ± 73.8	84 ± 14.9	22.5 ± 3.9	45.0 ± 11.8)
	0.15 to 0.30	3.6 ± 0.5	5.7 ± 1.0	7.8 ± 0.06	258.3 ± 64.1	243.7 ± 67.6	828.6 ± 205.9	138.1 ± 19.0	74.7 ± 15.6	67.5 ± 17.9
	0.30 to 0.45	5.7 ± 0.7	7.3 ± 1.0	8.0 ± 0.08	403.8 ± 74.8	444.2 ± 108.3	1273.1 ± 232	206.3 ± 30.0	132.7 ± 21.4	85.8 ± 21.3
	0.45 to 0.60	7.4 ± 0.8	8.5 ± 1.0	8.0 ± 0.04	505.8 ± 83.8	654.4 ± 137.1	1516.3 ± 277.5	250.9 ± 37.0	176.7 ± 29.5	105.7 ±28.2
	0.60 to 1.50	8.4 ± 0.6	9.1 ± 1.1	8.1 ± 0.02	590.7 ± 85.4	739.8 ± 130.0	1804.3 ± 287.9	261.3 ± 22.1	208.5 ± 17.3	147.0 ± 50.4
Central Parkland	0.0 to 0.15	1.0 ± 0.2	0.7 ± 0.2	7.0 ± 0.20	14.2 ± 5.3	23.1 ± 7.5	133.8 ± 71.0	74.1 ± 17.0	23.3 ± 6.8	12.5 ± 2.5
	0.15 to 0.30	0.9 ± 0.2	0.7 ± 0.1	7.3 ± 0.09	16.3 ± 5.3	26.1 ± 11.0	106.1 ± 60.1	54.8 ± 14.4	19.4 ± 5.9	6.7 ± 1.4
	0.30 to 0.45	0.8 ± 0.2	1.2 ± 0.3	7.5 ± 0.04	20.6 ± 4.7	34.1 ± 14.2	58.0 ± 27.0	36.6 ± 7.7	14.8 ± 3.6	6.8 ± 2.7
	0.45 to 0.60	1.0 ± 0.2	2.1 ± 0.7	8.1 ± 0.04	31.2 ± 8.0	58.9 ± 16.9	44.4 ± 147.0	35.7 ± 5.6	14.6 ± 2.5	6.9 ± 3.1
	0.60 to 1.50	2.3 ± 0.5	1.1 ± 2.1	8.1 ± 0.03	95.2 ± 40.4	343.4 ± 125.7	95.8 ± 33.7	120.7 ± 45.1	43.2 ± 12.0	9.8 ± 2.7

Table 3. Correlation between soil variables across Dry Mixed Grass and Central Parkland (R).

Depth (m)		SAR	PH	Sodium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Calcium (mg kg^{-1})	Magnesium (mg kg^{-1})	Potassium (mg kg^{-1})
0 to 0.15	EC	0.62 ***	0.61 ***	0.73***	0.63 ***	0.78 ***	0.65 ***	0.72***	0.38**
	SAR		0.36***	0.77***	0.47***	0.53***		0.28*	
	PH			0.44***	0.26*	0.46***	0.44**	0.42**	0.34*
	Sodium				0.66***	0.78***		0.51***	
	Chloride					0.47***	0.27*	0.45***	0.32*
	Sulfate						0.54***	0.69***	
	Calcium							0.80***	0.34*
	Magnesium								0.24*
0.15 to 0.30	EC	0.72***	0.67***	0.86***	0.82***	0.89***	0.77***	0.84***	0.67***
	SAR		0.63***	0.94***	0.69***	0.71***		0.39**	0.24*
	PH			0.68***	0.51***	0.69***	0.44***	0.57***	0.41**
	Sodium				0.77***	0.84***	0.47***	0.63***	0.35*
	Chloride					0.64***	0.49***	0.60***	0.62***
	Sulfate						0.69***	0.81***	0.46***
	Calcium							0.88***	0.63***
	Magnesium								0.57***
0.30 to 0.45	EC	0.78***	0.70***	0.91***	0.80***	0.89***	0.85***	0.87***	0.79***
	SAR		0.68***	0.93***	0.55***	0.75***	0.47***	0.54***	0.41**
	PH			0.73***	0.49***	0.77***	0.54***	0.64***	0.50***
	Sodium				0.62***	0.91***	0.74***	0.80***	0.55***
	Chloride					0.57***	0.65***	0.64***	0.80***
	Sulfate						0.83***	0.88***	0.63***
	Calcium							0.94***	0.72***
	Magnesium								0.67***
0.45 to 0.60	EC	0.65***	0.65***	0.87***	0.80***	0.86***	0.87***	0.89***	0.81***
	SAR		0.76***	0.88***	0.38**	0.71***	0.37**	0.42**	0.35*
	PH			0.75***	0.46***	0.71***	0.40**	0.52***	0.41**
	Sodium				0.50***	0.93***	0.73***	0.78***	0.59***
	Chloride					0.46**	0.62***	0.64***	0.74***
	Sulfate						0.82***	0.86***	0.63***
	Calcium							0.93***	0.76***
	Magnesium								0.74***
0.60 to 1.50	EC	0.54***	0.55***	0.83***	0.68***	0.70***	0.84***	0.92***	0.70***
	SAR		0.65***	0.88***		0.71***	0.20*	0.36***	0.18*
	PH			0.66***	0.27**	0.53***	0.18*	0.48***	0.29***
	Sodium				0.36***	0.84***	0.60***	0.71***	0.45***
	Chloride						0.66***	0.61***	0.68***
	Sulfate						0.53***	0.69***	0.44***
	Calcium							0.86***	0.68***
	Magnesium								0.68***

EC = electrical conductivity, SAR = sodium adsorption ratio, * = 0.05, ** = 0.01, *** = 0.001.

Table 4. Correlations (R) between soil variables in Dry Mixed Grass.

Depth (m)		SAR	PH	Sodium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Calcium (mg kg^{-1})	Magnesium (mg kg^{-1})	Potassium (mg kg^{-1})
0 to 0.15	EC	0.68***	0.44*	0.75***	0.58***	0.83***	0.66***	0.78***	0.32*
	SAR			0.88***	0.59***	0.52**		0.43*	
	PH					0.33*	0.51**	0.46**	
	Sodium				0.66***	0.76***		0.59***	
	Chloride					0.37*		0.47**	0.41*
	Sulfate						0.65***	0.77***	
	Calcium							0.80***	0.44*
	Magnesium								
0.15 to 0.30	EC	0.56***	0.39*	0.78***	0.70***	0.79***	0.78***	0.85***	0.47**
	SAR		0.44*	0.90***	0.53**	0.52**			
	PH			0.50**		0.49**	0.30*	0.48**	
	Sodium				0.60***	0.72***	0.39*	0.60***	
	Chloride					0.29*	0.35*	0.46**	0.56***
	Sulfate						0.68***	0.81***	
	Calcium							0.88***	0.47**
	Magnesium								0.35*
0.30 to 0.45	EC	0.52**	0.40*	0.78***	0.64***	0.71***	0.76***	0.85***	0.54**
	SAR		0.51**	0.84***		0.52**			
	PH			0.59***		0.63***		0.45**	
	Sodium					0.85***	0.53**	0.67***	
	Chloride						0.46**	0.46**	0.67***
	Sulfate						0.67***	0.79***	
	Calcium							0.90***	0.50**
	Magnesium								0.43*
0.45 to 0.60	EC	0.36*		0.70***	0.69***	0.62***	0.74***	0.86***	0.68***
	SAR		0.65***	0.76***		0.53**			
	PH			0.46**		0.39*			
	Sodium					0.88***	0.55**	0.66***	
	Chloride						0.42*	0.50**	0.74***
	Sulfate						0.63***	0.72***	
	Calcium							0.83***	0.58***
	Magnesium								0.56**
0.60 to 1.50	EC			0.38*	0.61***		0.75***	0.78***	0.53**
	SAR		0.56***	0.88***	-0.33*	0.70***			-0.45**
	PH			0.42*			-0.38*		
	Sodium					0.88***			
	Chloride						0.50**	0.54**	0.73***
	Sulfate								
	Calcium							0.73***	0.61***
	Magnesium								0.44*

EC = electrical conductivity, SAR = sodium adsorption ratio, p = 0.05, ** p = 0.01, *** p = 0.001.

Table 5. Correlations (R) between soil variables in Central Parkland.

Depth (m)		SAR	PH	Sodium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Calcium (mg kg^{-1})	Magnesium (mg kg^{-1})	Potassium (mg kg^{-1})
0 to 0.15	EC		0.64**		0.45*		0.94***	0.77***	
	SAR		0.49*						
	PH			0.52*		0.45*	0.50*		
	Sodium				0.47*	0.59*			
	Chloride						0.59*	0.47*	
	Sulfate							0.54*	
	Calcium							0.82***	
	Magnesium								0.47*
0.15 to 0.30	EC	0.44*	0.59*	0.70**	0.54*	0.77***	0.67**	0.72**	0.75***
	SAR		0.65**	0.85***	0.45*	0.57*			
	PH			0.68**		0.60*			0.50*
	Sodium				0.71**	0.76**		0.51*	
	Chloride					0.58*	0.56*	0.56*	
	Sulfate							0.71**	0.48*
	Calcium							0.69**	0.63**
	Magnesium								0.70**
0.30 to 0.45	EC	0.66**		0.84***	0.60*	0.82***		0.53*	0.68**
	SAR			0.86***					
	PH								
	Sodium					0.64**			0.57*
	Chloride					0.48*			
	Sulfate						0.54*	0.79***	0.55*
	Calcium							0.85***	0.46*
	Magnesium								0.60*
0.45 to 0.60	EC				0.90***		0.69**	0.62*	0.47*
	SAR			0.89***			-0.53*	-0.49*	
	PH								
	Sodium								
	Chloride						0.67**	0.56*	
	Sulfate						0.54*	0.63*	0.60*
	Calcium							0.95***	
	Magnesium								0.45*
0.60 to 1.50	EC			0.71**	0.94***		0.80***	0.77***	0.77***
	SAR			0.44*					
	PH								
	Sodium				0.54*		0.54*	0.46*	0.51*
	Chloride						0.70**	0.69**	0.67**
	Sulfate								
	Calcium							0.88***	0.68**
	Magnesium								0.59*

EC = electrical conductivity; SAR = sodium adsorption ratio, p = 0.05, ** p = 0.01, *** p = 0.001.

Table 6a. Hierarchical partitioning showing percent contribution of soil parameters in Dy Mixed Grass.

Depth (m)	Variables	EC	SAR	PH	Sodium	Chloride	Sulfate
0 to 0.15	EC		16.4*	7.2	22.4*	19.0*	35.0*
	SAR	26.1*		2.3	44.6*	12.2	14.7
	PH	55.5*	10.8		7.6	8.0	18.1
	Sodium	27.4*	34.9*	2.2		13.4	22.1*
	Chloride	43.8*	13.8	3.6	21.5*		17.3*
	Sulfate	50.6*	12.4*	5.1	24.3*	7.7	
0.15 to 0.30	EC		15.4*	5.2	31.3*	25.0*	23.1*
	SAR	16.4*		2.8	59.0*	10.2	11.5*
	PH	19.4	13.9		28.2	5.2	33.4
	Sodium	30.0*	27.7*	8.4		9.2	24.7*
	Chloride	52.2*	8.6	1.6	17.6*		20
	Sulfate	31.1*	15.1	9.5	33.7*	10.5	
0.30 to 0.45	EC		12.7*	3.9	30.3*	34.6*	18.4*
	SAR	13.5*		2.9	65.9*	3.6	14.1*
	PH	15.2	11.1		24.5	3.3	45.9*
	Sodium	22.5*	31.6*	17.4*		3.4	24.5*
	Chloride	56.4*	9.5	1.6	16.4*		16.1*
	Sulfate	23.2*	14.5*	20.9*	32.2*	9.2	
0.45 to 0.60	EC		10.3	1.2	32.8*	35.4*	20.2*
	SAR	8.0		18.3*	55.1*	2.0	16.7*
	PH	10.0	47.8*		23.8*	5.0	13.5
	Sodium	22.8*	30.1*	10.3		4.0	32.6*
	Chloride	49.0*	14.8*	4.2	16.2*		15.7*
	Sulfate	22.1*	15.2*	8.8	40.5*	13.5*	
0.60 to 1.50	EC		11.8	2.4	28.5*	47.9*	9.4
	SAR	6.4		22.4*	50.4*	4.0	16.8*
	PH	4.1	57.2*		24.7*	4.5	9.5
	Sodium	12.5	43.8*	4.6		4.1	35.0*
	Chloride	47.6*	16.6*	3.5	13.6		18.8*
	Sulfate	11.4	27.0*	2.5	41.5*	17.5*	

EC = electrical conductivity, SAR = sodium adsorption ratio, * = significant contribution from randomization.

Table 6b Hierarchical partitioning showing percent contribution of soil parameters in Central Parkland.

Depth (m)	Variables	EC	SAR	PH	Sodium	Chloride	Sulfate
0 to 0.15	EC		4.4	7.1	21.3	25.4*	41.8*
	SAR	12.4		21.0	18.9	21.6	26
	PH	37.9*	13.6		14.3	19.7	14.3
	Sodium	31.7*	5.9	6.1		19.9	36.4*
	Chloride	34.2*	2.5	3.9	21.6		37.9*
	Sulfate	42.7*	5.5	5.9	23.5*	22.2*	
0.15 to 0.30	EC		12.9	4.5	26.4	25.6	30.6*
	SAR	10.3		15.6	53.0*	9.0	12.0
	PH	14.4	35.6*		25.7	10.8	13.4
	Sodium	30.9*	20.5*	7.0		18.8	22.8
	Chloride	34.7*	9.6	4.8	21.0*		29.9*
	Sulfate	36.4*	11.0	4.6	24.1	24.0	
0.30 to 0.45	EC		7.4	1.3	21.5	35.6*	34.1*
	SAR	9.3		7.7	64.5*	4.0	14.5
	PH	9.7	36.1		23.1	23.5	7.6
	Sodium	25.2	47.5*	2.2		13.9	11.2
	Chloride	49.0*	5.5	1.1	16.1		28.8*
	Sulfate	45.1*	7.8	1.5	19.2	26.4*	
0.45 to 0.60	EC		5.2	7.9	9.6	51.0*	26.4*
	SAR	3.9		5.3	80.2*	2.6	8.0
	PH	14.8	20.4		22.7	30.3*	11.7
	Sodium	8.0	82.4*	0.9		7.1	1.7
	Chloride	64.9*	4.4	14.2	7.2		9.3
	Sulfate	45.8*	10.3	4.8	18.8	20.3	
0.60 to 1.50	EC		11.7	1.9	32.8*	47.2*	6.3
	SAR	7.6		4.1	74.6*	5.1	8.5
	PH	11.6	30.1		14.8	20.9	22.7
	Sodium	13.1	71.8*	3.0		9.3	2.9
	Chloride	51.0*	8.2	2.6	25.5*		12.7
	Sulfate	15.0	22.2	2.7	44.7*	15.3	

EC = electrical conductivity, SAR = sodium adsorption ratio, * = significant contribution from randomization.

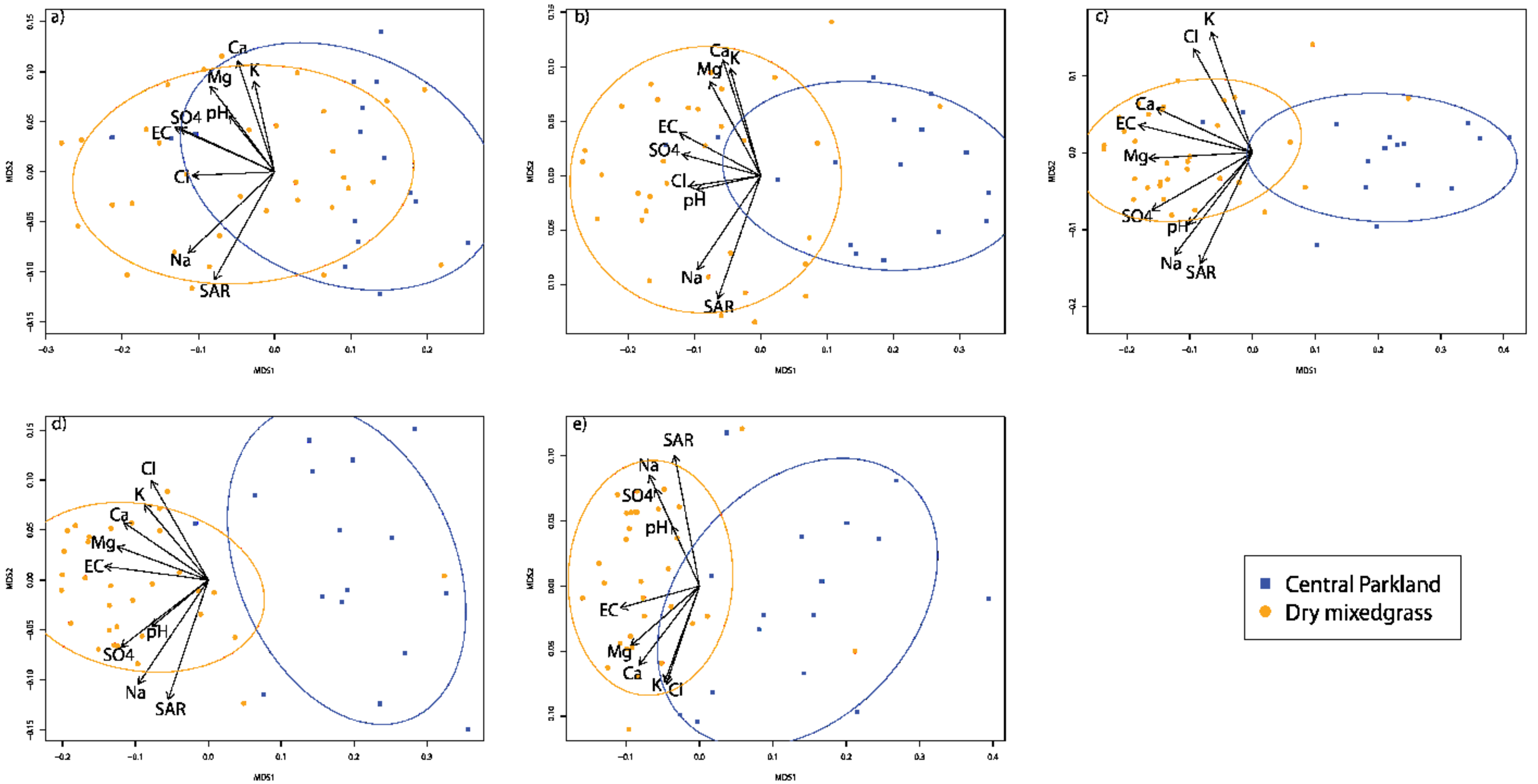

Figure 1. NMDS at five depths (m): 0 to 0.15 (a), 0.15 to 0.30 (b), 0.30 to 0.45 (c), 0.45 to 0.60 (d), 0.60 to 1.50 (e) showing two ecoregions with ellipses of 75 % confidence intervals. Dry Mixed Grass (n=16), Central Parkland (n=6). Stress values were 0.111 (a), 0.072 (b), 0.058 (c), 0.068 (d), and 0.084 (e).

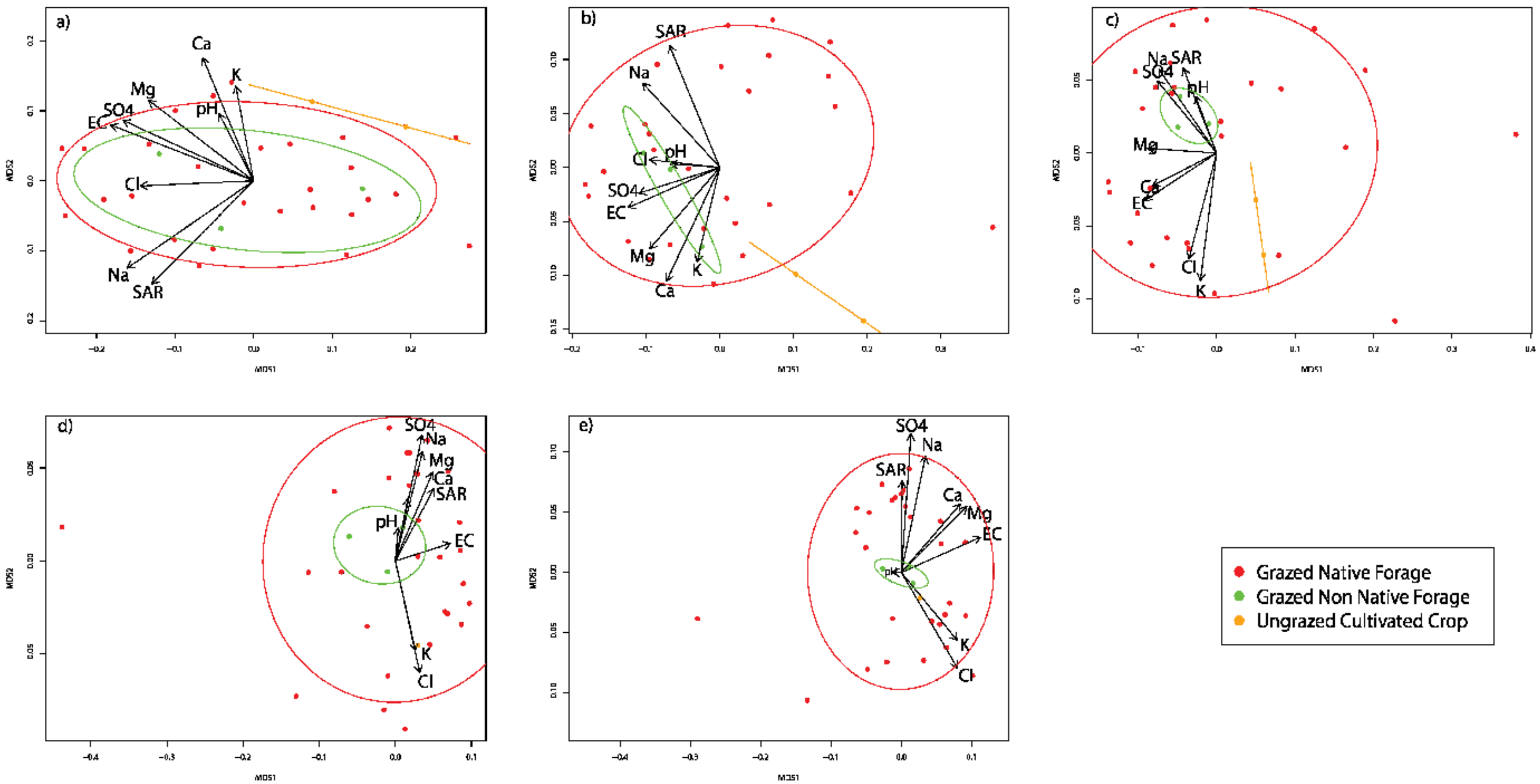

Figure 2. NMDS at five depths (m): 0 to 0.15 (a), 0.15 to 0.30 (b), 0.30 to 0.45 (c), 0.45 to 0.60 (d), 0.60 to 1.50 (e) in Dry Mixed Grass with ellipses of 75 % confidence intervals. Stress values were 0.105 (a), 0.114 (b), 0.058 (c), 0.071 (d), and 0.082 (e).

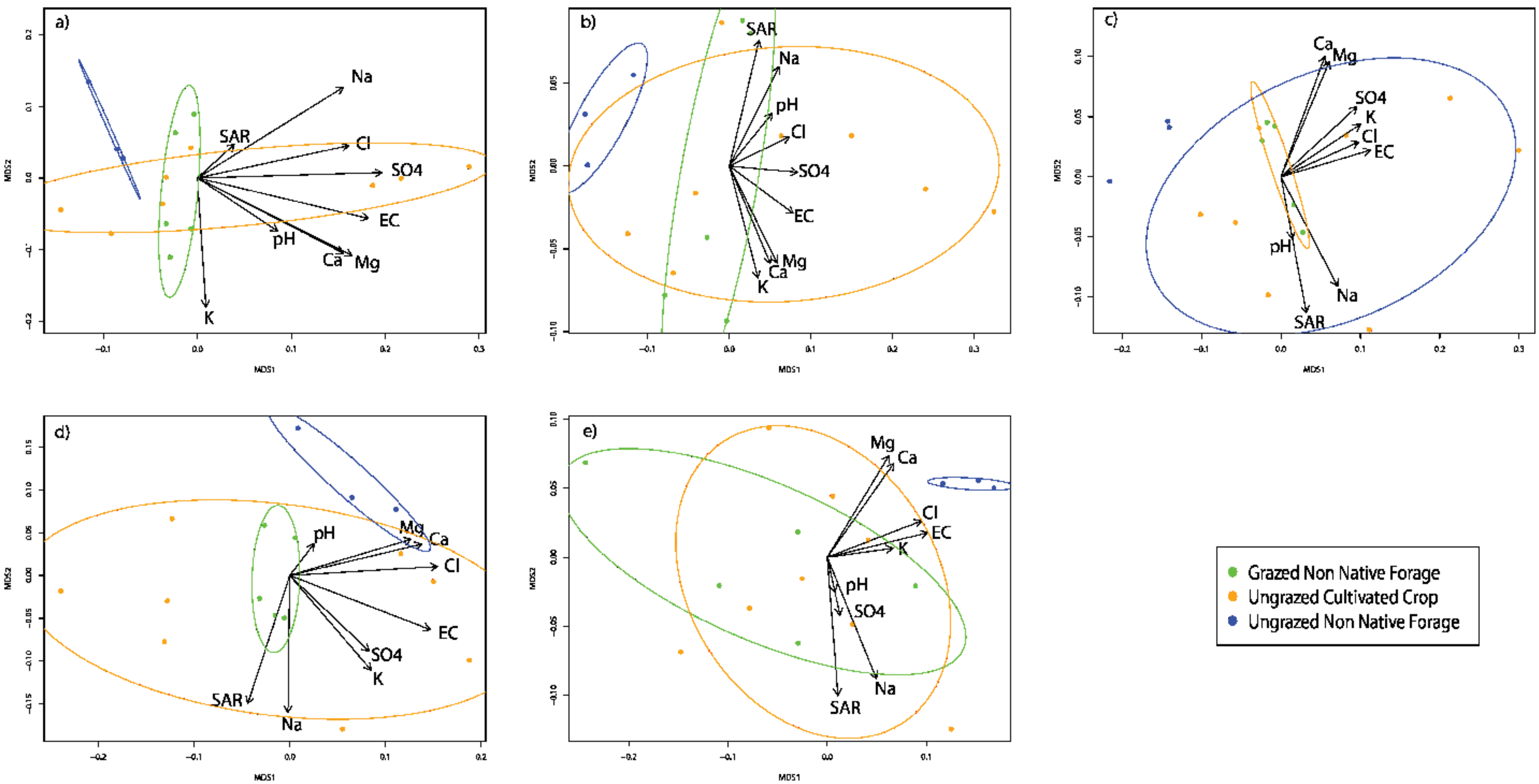

Figure 3. NMDS at five depths (m): 0 to 0.15 (a), 0.15 to 0.30 (b), 0.30 to 0.45 (c), 0.45 to 0.60 (d), 0.60 to 1.50 (e) in Central Parkland with ellipses of 75 % confidence intervals. Stress values were 0.105 (a), 0.049 (b), 0.065 (c), 0.080 (d), and 0.098 (e).

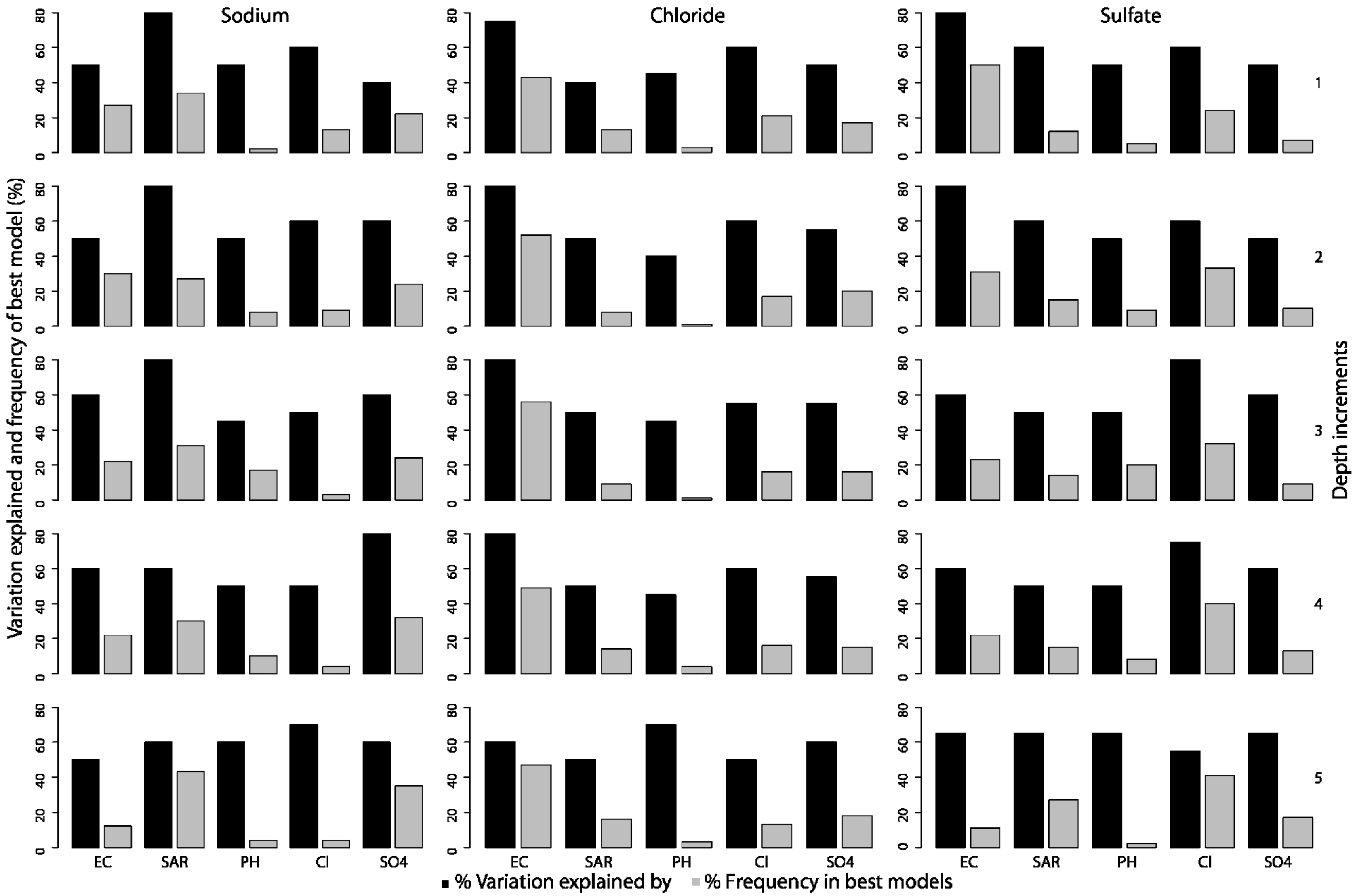

Figure 4. Generalized linear model and hierarchal partitioning regressions in Dry Mixed Grass for sodium, chloride, and sulfate at depth increments 0 to 0.15 m (1), 0.15 to 0.3 m (2), 0.3 to 0.45 m (3), 0.45 to 0.6 m (4), and 0.6 to 1.5 m (5).

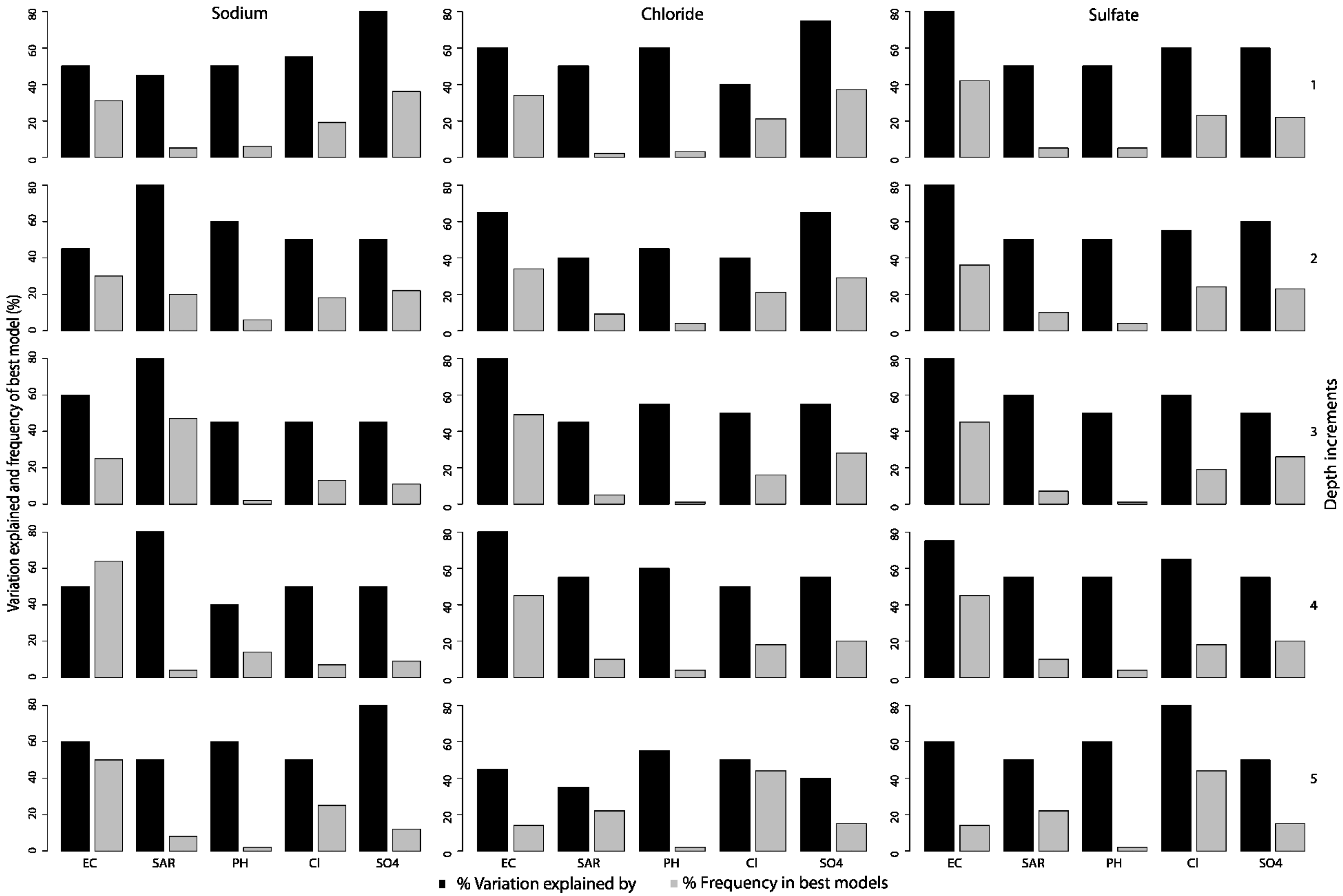

Figure 5. Generalized linear model and hierarchal partitioning regressions in Central Parkland for sodium, chloride, and sulfate at depth increments 0 to 0.15 m (1), 0.15 to 0.3 m (2), 0.3 to 0.45 m (3), 0.45 to 0.6 m (4), and 0.6 to 1.5 m (5).

CHAPTER III: SOIL PARAMETERS AND VEGETATION RELATIONSHIPS

1. INTRODUCTION

Salt affected soils originate through both natural and anthropogenic events. Worldwide, most important land degradation processes in agricultural areas come from soil salinization and alkalization (Wang et al. 2020). Over 900 million hectares of land are estimated to be contaminated with salts (Shin et al. 2016), with salinity and sodicity varying greatly across locations due to parent material, landscape position, climatic conditions, and human activities (Aldabaa et al. 2015).

Western Canada is known to hold a large quantity of oil and natural gas. In Alberta, there are over 336,000 wells sites and over 433,000 km of pipelines which contain oil and gas reserves (Alberta Energy Regulator 2020). Several production sites are located in natural salt affected soils, and further soil contamination with saline waste water is frequent during oil and gas production. These waste waters usually contain chloride salts such as sodium chloride (NaCl), calcium chloride (CaCl), and/or potassium chloride (KCl). Changes in salt composition are affected by geomorphology. The most prevalent salt for saline waste water in western Canada is sodium chloride (Alberta Environment 2001). As chloride molecules do not bind to soil particles, they easily leach in soils and are more likely to reach ground water. Sodium ions attach to soil particles leading to clay dispersion and soil structure breakdown. Excess sodium can result in high soil pH and poor soil structure due to aggregate slaking and swelling and clay dispersion, which further impede root penetration leading to poor conditions for plant growth (Essington 2005). Salinity promotes soil flocculation, while sodicity promotes soil dispersion.

In most cases, soluble salts move downwards; however, when moved through leaching, capillary actions can move the soluble salts in any direction (Klopp and Daigh 2020). This means capillary action moves salts through pore water upward from a high water table to the root zone (Landsburg 1981). Therefore, capillary rise in soil impacts salinization of the root zone for plants.

Salts have inhibitory effects on plant growth since they accumulate outside roots and inside cells, causing osmotic and ionic stress (Orozco-Mosqueda et al. 2020). Salt effects on plants and soils are generally linked to toxicity level, which is based on bioavailability and solubility; plant physiological processes, such as photosynthesis, might be inhibited by salts (Orozco-Mosqueda et al. 2020). Macro and micro nutrients, such as salts, influence interactions with the environment, can be found in the plant root zone, and are regularly transported into roots when in aqueous solution (Warrance et al. 2016). Salts such as sodium are easily transported, others such as chloride are not; concentrations fluctuate with water source, drainage, evapotranspiration, solute availability, and hydrostatic pressure (Volkmar et al. 1998). Soil with high pH, poor soil structure from swelling, and dispersion due an excessive amount of salts interferes with root penetration resulting in poor conditions for plant growth (Essington 2005). Ion composition and concentration in the plant results in salt stresses from salinity. Salts impact osmosis since higher quantities of salts in the soil result in difficulties for water and nutrients to move in and out of root membranes into the plant (Shin et al. 2016). This might slow the rate at which plants uptake water and solute, but will not terminate the process (Munns and Termaat 1986).

Plant salt tolerance is influenced by salt ion transport rate which affects plant growth (Munns and Termaat 1986). For instance, halophytes use salts at a rate that prevents cell death (Munns and Termaat 1986). The main halophyte families are Poaceae, Asteraceae, and Chenopodaceae (Vavrek et al. 2004). Salt tolerance mechanisms are not well known and mainly plant dependent. For example, barley is capable of making osmotic adjustments to preserve cell turgor and volume, and some plants can exude salts (Munns and Termaat 1986, Blumwald et al. 2000, Franklin and Zwiazek 2004). Salt gets into the plant and travels to the leaves, crosses the plasma membrane, and accumulates in the cell vacuole (Munns and Termaat 1986). Therefore, salt accumulation in the mature leaves causes them to die first, due to salt ion toxicity (Munns 1993).

Revegetation problems can leave large areas of bare ground, contributing to soil loss from wind and water erosion. Industries are required by government regulation to remediate salt affected soils as part of land reclamation (Alberta Government 2019a). For successful reclamation, soil must satisfy provincial guidelines for salinity and sodicity. In Alberta, salinity is mainly measured by electrical conductivity (EC), and sodicity by sodium adsorption ratio (SAR). Since plant community reestablishment during reclamation can be influenced by soil salinity and sodicity, EC and SAR have been accepted as measurements that are critical to facilitate reestablishment of functioning soil and plant communities during reclamation. Regulatory requirements include the Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guideline.

There is some concern among industry, scientists, and regulators that SAR and EC may not be the most appropriate metrics for assessing salt contaminated soils. Upper limit specific ions, soil structural properties, and/or plant community composition may be more effective indicators of detrimental salt conditions or of the ability of the ecosystem to recover from oil and gas extraction and production activities. These more extensive indicators would be potentially important if vegetation was in good condition, but regulatory criteria for EC and SAR were not met.

2. RESEARCH OBJECTIVES

The overall objective of this research project was to address whether EC and SAR are the most scientifically appropriate indicators of salt affected sites and their potential negative impacts on soil and plants from a remediation criteria perspective. Specific research objectives were to assess the relationships of EC and SAR to plant community composition, health, and diversity across a range of salt affected sites; and to assess plant response in relation to alternative or complementary measures of salinity and sodicity, namely total salts and ion concentrations.

3. MATERIALS AND METHODS

3.1. Research Sites

A list of potential oil and gas well sites in Alberta with saline issues was obtained from oil and gas companies and municipalities (Canadian Natural Resources Limited, Perpetual Energy, City of Medicine Hat, Orphan Well Association). Phase I and II reports for each site were used to locate saline areas; to provide detailed site diagrams with historic work areas such as well head, above ground storage tank, flare pit and drilling waste disposal area, that could be sources of salinity; and to provide information on whether any spill occurred, what contaminants were released on site and any contaminant remediation techniques and timelines. Well sites selected for study required a saline issue that had been addressed in some way; revegetation at least a year old; a reclamation certificate applied for, received, or not yet been applied for; and accessibility by four wheel drive truck or by walking a short distance.

Twenty-two sites were selected for study, 16 located in the Dry Mixed Grass and 6 in Central Parkland ecoregions (Appendix). Sites had four different land uses: grazed native forage (13 sites), grazed non-native forage (4 sites), ungrazed cultivated (4 sites), and ungrazed non-native forage (1 site). Sites were drilled between the years 1951 and 2003, most were drilled in the 1970s. Wells produced for 1 to 36 years, with a median of 23 years, and one well never produced at all. Wells were abandoned between the years 1970 and 2014. Documented spills were infrequent, with most salt affected soil resulting from regular production activities near the well centre, flare pits, drilling waste disposal areas, and/or storage tanks. There was little documentation on what reclamation had occurred, although most sites had some soil remediation, mainly contaminated soil removal and replacement with clean topsoil in highly contaminated areas. Cultivated and non-native forage sites were seeded. Soil was fine textured in 17 sites, coarse textured in four and a mix in one.

3.2. Soil Sampling And Vegetation Assessment

The four corners of each site were marked with pegs every 10 m. An EM38-MK2 ground conductivity meter (Geonics Canada) was used to survey the sites. The readings were taken in areas previously identified as having high EC or SAR, usually in production areas (well centre, drilling waste disposal area, above ground storage tank, flare pit), and in areas with evidence of poor revegetation such as high amounts of bare ground and visibly stressed vegetation. Areas where EC was >2 or between 1.5 and 2 with poor vegetation were marked on the site diagram. One to three of these poorly reclaimed areas were randomly selected for soil sampling.

At each of the selected research areas, a hole was augered; then two subsequent holes were augered approximately 1 to 2 m from the first. Each auger hole was marked with a pin flag and GPS location recorded. Sampling was conducted with a hand auger when possible. A percussion auger (Cobra PRO, TT, TT-AWD, 2010) was used to sample depths that could not be hand augered. At cultivated sites, all augering was done by hand to avoid damaging the crops. After each hole the auger was cleaned by removing excess soil with a knife and wiping with isopropanol. Augering was done to 1.5 m by 15 cm increments. When 1.5 m could not be reached due to compaction, the sample was taken as deep as possible. Ziploc bags were labeled with site, auger hole ID, and sample depth. If sufficient soil could not be obtained from one hole, another hole was augered next to the first one. Samples were stored in buckets during the field trips at ambient temperatures.

After every field trip, soil samples were sent to a commercial laboratory in Edmonton Alberta for analyses. Analyses were conducted according to Carter (2007) unless otherwise noted. Soil pH was determined using a pH meter in a 1:2 extraction with 0.01M $CaCl_2$ solution (CSSS 16.3). Conductivity saturation paste was used to determine EC by meter (CSSS 15.2.1, 15.3.1), and SAR was calculated (CSSS 15.4.4). Saturation paste analysis with Inductively coupled plasma optical emission spectrometry was used to determine concentrations of sodium (CSSS CH15, EPA 6010B), calcium (CSSS CH15, EPA 6010B), magnesium (CSSS CH15, EPA 6010B), potassium (CSSS CH15, EPA 6010B), chloride (colourimetry CSSS 15.2.1, ALPHA 45000-Cl E), and sulfur (CSSS CH15, EPA 6010B and converted to sulfate).

Adjacent to each of these auger hole locations, in an area of similar vegetation, a 20 x 50 cm quadrat was placed. Total vegetation canopy cover, canopy cover and mean height of each species, and ground cover by categories (bare ground, litter, live vegetation, rock, lichen, moss, rocks, feces, and other) were visually assessed. One location on one side of the well site was randomly selected to collect background soil and vegetation data. The auger hole and placement of vegetation quadrat was about 5 to 10 m from the well site edge. Location was representative of conditions off the well site.

3.3. Data Analyses

Statistical analyses were conducted in R version 1.1.456 (RStudio 2020) All data were tested for normality and homogeneity using density and residual plots. Data were non-normal and non-homogeneous. Spearman correlation analysis, which does not assume normality of data, was used to determine if variables were correlated using PerformanceAnalytics package (Peterson 2020) and R and p-values <0.05 were obtained. Values of R above 0.7 were considered strongly correlated. Permutational analysis of variance using adonis was used from the ecodist package (Goslee and Urban 2007) followed by pairwise comparison using RVAideMemoire package (Hervé 2020) to determine how to combine multiple soil sampling depths and to assess significant differences between ecoregions, land uses, soil textures, and years the wells were drilled.

Redundancy Analysis (RDA) was performed to determine which soil variables (explanatory variables) most accurately explained the response of vegetation. Data were log transformed and standardized. The forward stepwise model selection permutational tests with 1000 permutations and Akaike Information Criterion (AIC) was used to select explanatory variables and determine the best model and significant explanatory variables (Peres-Neto et al. 2006). RDA model significance was determined by 1000 permutations and adjusted $R^{2 \text{ values}}$ were used for variation partitioning in all RDAs to explain the variance proportion of each of the explanatory variables (Jassey et al. 2011, Heffernan 2020). Hierarchal partitioning predictor significance was calculated for selected explanatory variables with randomization testing using negative log-likelihood (n=1000) (Emilson et al. 2017) using hier.part package (Walsh et al. 2003).

4. RESULTS

4.1. Vegetation Communities

Dry Mixed Grass and Central Parkland had similar ground covers of bare ground, live vegetation, and litter; and diversity and species richness (Table 1). Central Parkland had more total vegetation canopy cover than Dry Mixed Grass did, as land use was mainly ungrazed cultivated crops in that area, which were healthy and advanced in growth stage, with canopy cover greater than 50 %.

Dominant plant species were *Avena sativa* L. (common oats) and *Hordeum vulgare* L. (common barley). Dry Mixed Grass had more native species than Central Parkland (Table 1) due to cultivated crops being of non native species. Dominant plant species in Dry Mixed Grass were the common grasses *Agropyron pectiniforme* L. (crested wheat grass), *Agropyron* smithii (Rydb.) Á. Löve (western wheat grass), *Bouteloua gracilis* (Willd. ex Kunth) (blue grama grass), and *Stipa comata* (Trin. & Rupr.) (needle and thread grass).

In Dry Mixed Grass and Central Parkland, redundancy analysis showed that overall, 12 to 25.8 % and 29 to 31.6 % of vegetation parameters were explained by soil variables from 0 to 0.45 m in the respective ecoregions (Figures 1, 2). At depths greater than 0.45 m, vegetation was not influenced much by soil properties with only 8 and 18 % of vegetation parameters explained by them in Dry Mixed Grass and Central Parkland, respectively (Figures 1, 2). Redundancy analysis showed higher numbers for unconstrained than constrained axes, meaning that although approximately 12 to 30 % of the soil variables explained the vegetation responses, there was still more environmental variability that explained vegetation parameters.

4.2. EC And Vegetation Relationships

In Dry Mixed Grass, EC was positively correlated with bare ground cover and ground cover of live vegetation and litter, and canopy cover of total vegetation; non native species were negatively correlated with EC in the upper 0.15 m depth (Table 2). From 0.15 to 0.30 m depths, EC was negatively correlated with live vegetation ground cover, total vegetation canopy cover, and non native vegetation canopy cover, and from 0.30 to 0.45 m depths with only non native vegetation canopy cover (Table 2). In Central Parkland, EC was not correlated with vegetation in the upper 0.15 m depth (Table 3). However, EC was positively correlated with bare ground cover from 0.15 to 0.45 m depths, and negatively correlated with litter ground cover at those depths (Table 3). From 0.6 to 1.5 m depths, EC was negatively correlated with bare ground and native species canopy cover (Table 3).

In Dry Mixed Grass, when all parameters were assessed in the RDA, EC was positively correlated with bare ground cover in the upper 0.15 m (Figure 1). EC independently explained 8.6 % of vegetation parameter variations ($P<0.05$) in the upper 0.15 m. At other depths in Dry Mixed Grass and all depths in Central Parkland, EC was not a significant explanatory variable for vegetation (Figures 1, 2). Hierarchical partitioning showed EC significantly contributed to variation in non native vegetation canopy cover (34.3 %) and live vegetation ground cover (19 %) (Table 4).

4.3. SAR And Vegetation Relationships

In Dry Mixed Grass, SAR was negatively correlated with non native species canopy cover in the upper 0.15 m (Table 2). Below 0.15 m, SAR was negatively correlated with litter and non native vegetation canopy cover. Below 0.45 m, SAR was positively correlated with native vegetation canopy cover (Table 2). In Central Parkland in the upper 0.15 m, SAR was strongly positively correlated with bare ground cover and negatively correlated with ground covers of live vegetation and litter (Table 3). From 0.15 to 0.30 m, SAR was positively correlated with bare ground cover and native vegetation canopy cover, and negatively correlated with litter ground cover (Table 3). From 0.30 to 0.45 m, SAR was positively correlated with species richness and diversity (Table 3).

In Dry Mixed Grass, when all parameters were assessed together in the RDA, SAR was a significant explanatory variable from 0.15 to 0.45 m and below 0.6 m (Figure 2). SAR was negatively associated with non native vegetation canopy cover. Overall, the RDA showed that SAR significantly influenced vegetation parameters, although more in Dry Mixed Grass where SAR independently had a significant impact on vegetation parameters ($P<0.05$) from 0 to 0.45 m explaining 3, 5, and 5 % of the variation, at respective depth intervals (Figure 1). Hierarchical partitioning showed that SAR significantly influenced non native vegetation canopy cover (45.6, 48.8, 58.9 %) and litter ground cover (27.2, 17, 20.3 %) from 0 to 0.45 m depths (Table 4).

In Central Parkland, RDA indicated total vegetation canopy cover was negatively associated with SAR, and bare ground was positively associated with SAR in the upper 0.15 m (Figure 2). SAR independently explained 18.4 % ($P<0.04$) of the variation in vegetation parameters in the upper 0.15 m. Hierarchical partitioning showed that SAR had a significant impact on bare ground cover (26.3 %) and litter ground cover (30 %) (Table 4).

4.4. Vegetation And PH Relationships

In Dry Mixed Grass, pH was negatively correlated with total vegetation canopy cover, species richness, and diversity in the upper 0.15 m (Table 2). From 0.15 to 0.30 m, pH was negatively correlated with non native vegetation canopy cover. Below 0.3 m, pH was positively correlated with native vegetation canopy cover and negatively correlated with non native vegetation canopy cover (Table 2). In Central Parkland, pH was negatively correlated with litter ground cover, and positively correlated with bare ground cover in the upper 0.30 m and species richness between 0.30 to 0.45 m (Table 3). From 0.30 to 0.45 m depths, pH was positively correlated with bare ground cover and negatively correlated with live vegetation ground cover, total vegetation canopy cover, and non native vegetation canopy cover (Table 3).

In Dry Mixed Grass and Central Parkland, when all parameters were assessed together in the RDA, pH was significantly associated with vegetation from 0.30 to 0.45 m only. In Dry Mixed Grass, pH was a significant soil variable ($P < 0.02$) independently explaining 3.3 % of vegetation variation (Figure 1c). Hierarchical partitioning (Table 4) showed that pH had no significant impact on vegetation parameters. In Central Parkland, pH was a significant soil variable ($P < 0.06$) independently explaining 15.8 % of vegetation variation (Figure 2c). Hierarchical partitioning (Table 4) showed pH had a significant impact on live vegetation ground cover (39.1 %) and bare ground cover (25.5 %).

4.5. Vegetation And Ions Relationships

In Dry Mixed Grass, sodium was negatively correlated with non native vegetation canopy cover at every depth (Table 2). Chloride had no significant correlations with vegetation above 0.45 m but was negatively correlated with live vegetation ground cover and total vegetation canopy cover below 0.45 m (Table 2). Sulfate was positively correlated with bare ground cover and negatively correlated with live vegetation ground cover in the upper 0.15 m and non native vegetation canopy cover at all depths (Table 2). Calcium was negatively correlated with live vegetation ground cover in the upper 0.15 m and total vegetation canopy cover between 0.15 to 0.30 m (Table 2). Magnesium was positively correlated with bare ground cover and negatively correlated with non native vegetation canopy cover in the upper 0.15 m. Potassium was positively correlated with species richness in the upper 0.15 m and negatively correlated with it from 0.15 to 0.45 m. Potassium was negatively correlated with live vegetation ground cover, total canopy cover, and native vegetation canopy cover from 0 to 0.45 cm, and just ground cover of live vegetation and total canopy cover below 0.6 m (Table 2).

In Central Parkland, sodium was positively correlated with bare ground cover in the upper 0.15 m and negatively correlated with litter ground cover from 0 to 0.45 m (Table 3). Below 0.6 m, sodium was negatively associated with bare ground cover and positively associated with ground covers of live vegetation and litter. Chloride was negatively correlated with native vegetation canopy cover in the upper 0.15 m and litter ground cover between 0.15 and 0.45 m (Table 3). Sulfate was positively correlated with bare ground cover from 0.15 to 0.45 m, negatively with it from 0.60 to 1.50 m; and negatively correlated with litter ground cover between 0 to 0.45 m (Table 3). Calcium was negatively correlated with native vegetation canopy cover in the upper 0.30 m. Below 0.6 m, calcium, magnesium, and potassium were negatively associated with native vegetation canopy cover; calcium and magnesium negatively with bare ground cover and positively with live vegetation ground cover; and calcium positively with litter ground cover.

In Dry Mixed Grass, when all parameters were assessed together in the RDA, magnesium had a small significant impact on vegetation (0.5 %) ($P< 0.05$) in the upper 0.15 m (Figure 1a); however, in conjunction with EC explained 20 % of the variation in vegetation. Magnesium was negatively associated with non native vegetation canopy cover and closely correlated with SAR (Figure 1a). From 0.15 to 0.6 m, potassium was a significant explanatory variable (Figure 1b, c, d). Potassium was a significant soil variable ($P < 0.02$) independently explaining 8.7, 7.2, and 8.1 %, at respective depths, of the variation in vegetation parameters (Figure 1b, c, d). In conjunction with SAR, potassium explained approximately 14 % of the vegetation variation from 0.15 to 0.45 m. Hierarchical partitioning showed that magnesium significantly influenced non native vegetation canopy cover (45.6 %) and potassium had a significant impact on live vegetation ground cover (20.7 %) from 0.15 to 0.3 m and had no significant impact from 0.3 to 0.45 m (Table 4).

In Central Parkland, when all parameters were assessed together in the RDA, chloride was a significant explanatory variable from 0 to 0.15 m and independently explained 18.4 % ($P<0.004$) of vegetation variation (Figure 2a). At 0.15 to 0.30 m, sulfate (15.2 %) and magnesium (6 %) were significant soil variables ($P < 0.004$) influencing vegetation (Figure 2b). Both were negatively associated with species richness and diversity. At 0.30 to 0.45 m magnesium (5.8 %) was a significant soil variable ($P < 0.04$) influencing vegetation (Figure 2c). Below 0.6 m, sodium was the only significant explanatory variable, explaining 18.4 % of vegetation variation and negatively associated with native vegetation canopy cover. Hierarchical partitioning showed chloride had a significant impact on diversity (37.9 %), sulfate had a significant impact on diversity (38.3 %) and litter ground cover (29.1 %), and magnesium had a significant impact on diversity (35.4 %) from 0.15 to 0.3 m and a significant impact on diversity (42.7 %) from 0.3 to 0.45 m (Table 4).

5. DISCUSSION

5.1. Ecoregion And Vegetation Type Variation And Root Depth

Since the upper 0.45 m of soil was the depth that soil properties explained vegetation responses the most, it may most likely be explained by rooting depths. While, some plants have very deep roots, they can vary considerably due to environmental conditions.

Dry Mixed Grass plant communities were mainly composed of low growing and drought tolerant mixed grasses including *Agropyron smithii*, *Bouteloua gracilis*, *Koeleria macrantha* (Ledeb) Schult (June grass), and *Stipa comata* (Natural Regions Committee 2006). Rooting depth for these plant species can be as deep as 2 m (Natural Regions Committee 2006). However, some species have their roots concentrated in the upper depths. For instance, *Agropyron pectiniforme* can root to 2.4 m; however, the majority of its roots go only 1 m deep (Dzyubenko 2009). *Bouteloua gracilis* has

80 % of its root system in the upper 0.5 m (Lee and Lauenroth 1994) and *Koeleria macrantha* have roots at 0.3 to 0.75 m, although root density decreases considerably under 0.3 m (Simonin K. 2000). Similarly, *Stipa comata* can root as deep as 1.5 m but has half the total root biomass in the first 0.2 m (Zlatnik E.1999).

Most of Central Parkland is cultivated in the areas that the research sites were located. Our sites consisted of *Avena sativa* and *Hordeum vulgare*, with rooting as deep as 0.95 m, depending on growing conditions (Dwyer et al. 1988). It was shown that even if a crop is considered salt tolerant and will growth in saline and sodic conditions, yield reduction will is most likely occur further impacting farmers (Xiong 2007).

The upper 0.45 m of soil impacting vegetation responses could be explained and/or associated with the first growing stages such as germination, emergence, and early vegetative development, which under environmental stress would limit later plant growth (Hilal et al. 1998). The apparition of salt crust can inhibit germination and leave bare ground (Bernstein 1975). In soils with saline parent material, water uptake becomes difficult for plants and halophytic species and plant toxicity can further impede growth (Reich et al. 2017, Natural Regions Committee 2006).

5.2. EC, SAR, And PH As Reclamation Criteria

Detrimental effects of EC on soil properties including reduction of infiltration rate and drainage can add to plant stress, resulting in plant growth reductions (Warrence et al. 2002, Lupardus et al. 2020). Many plants tolerate salts throughout the germination phase of growth even though it may increase the time for germination; and plants become more sensitive to salts during emergence and early vegetative development (Xiong 2007). Repercussions of salinity are often observed in reduced shoot growth rather than root growth (Xiong 2007). Although in both Dry Mixed Grass and Central Parkland, EC contributed to bare ground and reduced vegetation ground cover and in Dry Mixed Grass EC was a significant indicator of vegetation response at the upper 0.15 m, EC contributed only 8.6 % to vegetation response. Thus, it cannot be considered a satisfactory measure alone to assess how vegetation will respond in saline soils although significantly impacting ground cover of live vegetation in Dry Mixed Grass. It has been shown that crop sensitivity based on yield reduction may range from 0.6 to 7.5 dS m^{-1} (Grieve et al. 2012,) showing that even the smallest amount of salts may be detrimental for vegetation. Hence, EC is not a sufficient measure to predict vegetation responses.

SAR is important relative to sodium concentration and its toxicity for plants. Sodium toxicity usually disrupts potassium homeostasis which can impede enzyme activities (Reich et al. 2017).

High sodium concentrations can result in osmotic stress due to its accumulation in the root zone (Cruz et al. 2018). Since SAR was a significant contributor at most depths in Dry Mixed Grass, it could be considered a good indicator of sodicity for plant communities. In Central Parkland, the higher SAR was, the higher diversity was. Greater diversity with higher sodium concentrations could be explained by the crop having more competition with other plants in a saline environment since it cannot develop as easily, although both oat and barley are salt tolerant cultivars (Maas and Grattan 1999, Kumar et al. 2010). Low diversity is wanted for cultivated crops. While SAR explained 18.4 % of variability in vegetation, it only had a significant impact in the upper 0.15 m, although significantly increasing bare ground cover. Consequently in Central Parkland, SAR is not a sufficient indicator alone for the whole soil profile and to ensure reclamation success.

Plant growth is influenced by soil pH. Saline and sodic soils are known to have high soil pH (Allison et al. 1954, Sharpley 1991). Even though it only significantly contributed to vegetation parameters between 0.3 to 0.45 m depth, pH plays an important role in plant growth and soil fertility (Chen et al. 2020). In Central Parkland, a higher pH was shown to increase bare ground cover. It regulates nutrient availability which directly affect plants. It has been shown that pH under 3 and over 9 is detrimental for most plant species and high pH decreases phosphorus availability, for example (Sharpley 1991). Our sites did not have pH of high values, therefore pH was not an issue for vegetation parameters. Consequently, since pH was not a problem at our sites, the individual ions were most likely those impacting and driving vegetation responses.

5.3. Ions As Reclamation Criteria

In Dry Mixed Grass, important ions influencing vegetation in the upper 0.45 m included magnesium and potassium. Magnesium is a crucial nutrient contributing to plant growth. However, when present in high quantities can become toxic (Andreeva 2020). It was shown to be more toxic to plants when found in high concentrations than other salt isosmotic concentrations although it may be mitigated when adding calcium (Allison et al. 1954). Potassium is known to be an important nutrient for plant growth. In sodic soils, plants may develop potassium deficiency when sodium is present due to competitive processes (Pitman 1965 Xiong 2007, Grieve et al. 2012). Plants affected by salinity have nutrient imbalances which are expressed differently between species (Maas and Grattan 1999). Nutrient uptake and distribution in plants result in physiological damage due to competitive processes between nutrients and major salts.

In Central Parkland, important ions influencing vegetation in the upper 0.45 m depth included sulfate, chloride, and magnesium. Sulfate had detrimental impacts on plant communities likely from toxic effects on specific plant metabolisms due to inhibition of photophosphorylation (Reich et al. 2017). Sulfate can limit calcium uptake by plants disturbing cationic balance due to calcium reduction that increases sodium and potassium absorption in plants (Allison et al. 1954). Chloride ions in high concentration are toxic to many plant species. It can compete with other anions (Renault 2012). For example, chloride may compete with nitrate plant uptake which reduces plant nitrogen. It may increase membrane permeability in some plants resulting in reduction of tissue ability to compartmentalize ions (Franklin and Zwiazek 2004). Other research has shown that for certain plants, chloride that accumulates in leaves is more toxic than sodium (Xiong 2007) and has detrimental effects on vegetation from osmotic stress (Grieve et al. 2012).

Sodium, sulfate, and chloride are the most toxic ions in saline and sodic soils. Sodium chloride is usually the salt that damages plant growth, and depending on the plant species, chloride might be more toxic than sodium (Reich et al. 2017). Magnesium and potassium were a significant contributor to and had detrimental effects on vegetation responses. Thus, those five ions having an important contributions to vegetation responses across ecoregions should be considered when making reclamation criteria to ensure revegetation and reducing bare ground cover.

6. CONCLUSIONS

Reclamation criteria focusing only on soil EC and SAR may not be sufficient to assess the potential negative impacts of soil parameters on plant communities. Although SAR may be a good indicator for sodium toxicity in Dry Mixed Grass, it is not sufficient to predict vegetation success. Reclamation criteria may benefit from having specific indicators for depths of 0 to 0.45 m since they were the depths that soil variables were impacting vegetation parameters the most across ecoregions, and are key rooting depths for most plant species.

Reclamation criteria could be strengthened by including individual ions to specifically assess salts that have adverse effects on vegetation. Individual concentrations of salts including sodium, chloride, sulfate, magnesium, and potassium could be good indicators of vegetation success. The more potentially toxic ions including sodium, chloride, and sulfate would be even more important to include in the reclamation criteria. Individual ions could be assessed when EC and SAR do not meet criteria but vegetation is normal in growth and health.

Reclamation criteria should be modified or interpreted differently for specific ecoregions and soil depths. Although this is done to some extent already, it can be amplified to smaller areas, particularly those associated with salt affected soils.

Table 1. Mean and standard error of vegetation parameters.

Ecoregion	Bare Ground Cover	Live Vegetation Cover	Litter	Total Vegetation Cover	Diversity	Species Richness	Native Vegetation Cover	Non Native Vegetation Cover
Dry Mixed Grass	46.6 ± 4.6	28.5 ± 3.5	20.4 ± 3.5	31.7 ± 3.7	0.39 ± 0.04	2.24 ± 0.2	20.6 ± 3.4	9.3 ± 2.6
Central Parkland	39.3 ± 6.0	28.1 ± 2.3	29.3 ± 5.2	52.5 ± 4.5	0.33 ± 0.06	2.3 ± 0.4	3.9 ± 2.9	48.4 ± 4.1

Table 2. Correlation (R) matrix in Dry Mixed Grass between soil parameters and vegetation variables.

Depth (m)		Bare Ground	Live Vegetation Ground Cover	Litter Ground Cover	Total Vegetation Canopy Cover	Species Richness	Diversity	Native Vegetation Canopy Cover	Non Native Vegetation Canopy Cover
0-0.15	EC	0.46**	-0.43*	-0.40*	-0.37*				-0.47*
	SAR								-0.49**
	PH		-0.30*			-0.37*	-0.35*		
	Sodium								-0.59***
	Chloride								
	Sulfate	0.41*	-0.36*						-0.52**
	Calcium		-0.33*						
	Magnesium	0.44*							-0.36*
	Potassium		-0.40*		-0.36*	0.42*	-0.33*	-0.36*	
0.15-0.30	EC		-0.31*		-0.37*				-0.38*
	SAR			-0.31*					-0.61***
	PH								-0.37*
	Sodium								-0.58***
	Chloride								
	Sulfate								-0.47**
	Calcium				-0.31*				
	Magnesium								
	Potassium	0.33*	-0.46*		-0.44*	-0.34*		-0.35*	
0.30-0.45	EC								-0.35*
	SAR			-0.45**					-0.64***
	PH							0.34*	-0.30*
	Sodium			-0.33*					-0.59***
	Chloride								
	Sulfate								-0.40*
	Calcium								
	Magnesium								
	Potassium		-0.37*		-0.38*	-0.31*		-0.34*	
0.45-0.60	EC								
	SAR			-0.52**				0.35*	-0.59***
	PH						0.45*	0.42*	-0.43*
	Sodium			-0.41*			0.33*		-0.48**
	Chloride		-0.41*		-0.35*				
	Sulfate						0.34*		-0.32*
	Calcium								
	Magnesium								
	Potassium								
0.60-1.50	EC						0.34*		
	SAR			-0.38*				0.46**	-0.66***
	PH						0.35*	0.34*	-0.34*
	Sodium							0.43*	-0.58***
	Chloride		-0.31*		-0.30*				
	Sulfate						0.36*	0.32*	-0.42*
	Calcium								
	Magnesium								
	Potassium		-0.31*		-0.33*				

Table 3. Correlation (R) matrix in Central Parkland between soil parameters and vegetation variables.

Depth (m)		Bare Ground	Live Vegetation Ground Cover	Litter Ground Cover	Total Vegetation Canopy Cover	Species Richness	Diversity	Native Vegetation Canopy Cover	Non Native Vegetation Canopy Cover
0.0-0.15	EC								
	SAR	0.90***	-0.55*	-0.79***					
	PH	0.52*		-0.53*		0.68*			
	Sodium	0.46*		-0.60*					
	Chloride							-0.43*	
	Sulfate			-0.49*					
	Calcium								
	Magnesium								
	Potassium								
0.15-0.30	EC	0.47*		-0.53*					
	SAR	0.54*		-0.59				0.46*	
	PH	0.53*		-0.51		0.67*			-0.51*
	Sodium			-0.56*					
	Chloride			-0.50*					
	Sulfate	0.48*		-0.56*					
	Calcium							-0.49*	
	Magnesium								
	Potassium								
0.30-0.45	EC	0.43*		-0.53*					
	SAR					0.65*	0.76*		
	PH	0.44*	-0.70*		-0.52*				-0.53*
	Sodium					0.68*	0.77*		
	Chloride			-0.52*					
	Sulfate	0.45*		-0.50*					
	Calcium								
	Magnesium								
	Potassium								
0.45-0.60	EC								
	SAR								
	PH								
	Sodium								
	Chloride								
	Sulfate								
	Calcium								
	Magnesium								
	Potassium								
0.60-1.50	EC	-0.43*						-0.53*	
	SAR								
	PH								
	Sodium	-0.72**	0.44*	0.64**				-0.44*	0.58*
	Chloride								
	Sulfate	-0.46*	0.46*		0.46*				
	Calcium	-0.58*	0.54*	0.44*				-0.44*	
	Magnesium	-0.62*	0.49*					-0.47*	
	Potassium							-0.58*	

Table 4. Hierarchical partitioning in Dry Mixed Grass and Central Parkland showing independent contributions of soil variables to vegetation variables in percentage.

Ecoregion	Depth (m)	Variables	Bare Ground	Total Vegetation Canopy Cover	Litter Ground Cover	Total Vegetation Canopy Cover	Species Richness	Diversity	Native Vegetation Canopy Cover	Non Native Vegetation Canopy Cover
			Independent Contributor (%)							
Dry Mixed Grass	0 to 0.15	EC	7.8	19.0*	11.2	12.8	5.8	4.3	4.6	34.3*
		Magnesium	5.3	6.4	20.9	4.9	3.6	3.1	10.2	45.6*
		SAR	1.7	2.7	27.2*	3.1	7.4	2.8	5.5	49.7*
	0.15 to 0.30	Potassium	19.4	20.7*	5.0	14.1	10.7	1.4	8.2	20.5
		SAR	0.8	4.4	17.0*	8.1	7.0	2.3	11.6	48.8*
	0.30 to 0.45	Potassium	17.7	14.4	3.1	14.2	14.2	1.5	14.7	20.1
		SAR	1.2	1.9	20.3*	2.5	4.5	3.3	7.5	58.9*
		PH	22.6	15.9	15.5	9.6	9.6	2.7	4.7	19.3
	0.45 to 0.60	Potassium	20.3	9.1	2.9	9	6.9	1.8	11.9	38.1*
	0.60 to 1.50	SAR	0.7	1.7	4.8	2.5	1.1	0.87	17.7*	70.7*
Central Parkland	0 to 0.15	SAR	26.3*	16.7	30.0*	5.3	5.3	5.5	5.9	5.4
		Chloride	2.2	9.5	11	10.2	14.7	37.9*	9.3	5.2
	0.15 to 0.30	Sulfate	4.9	3.4	29.1*	3.1	11.9	38.3*	4.6	4.5
		Magnesium	13.7	3.5	18.0	3.5	16.3	35.4*	5.2	4.6
	0.30 to 0.45	PH	25.5*	39.1*	5.8	7.7	4.3	3.6	4.0	9.9
		Magnesium	9.9	3.7	20.2	3	13.5	42.7*	3.9	3.2
	0.60 to 1.50	Sodium	5.4	6.5	18.9	10.3	5.3	7.6	15	31*

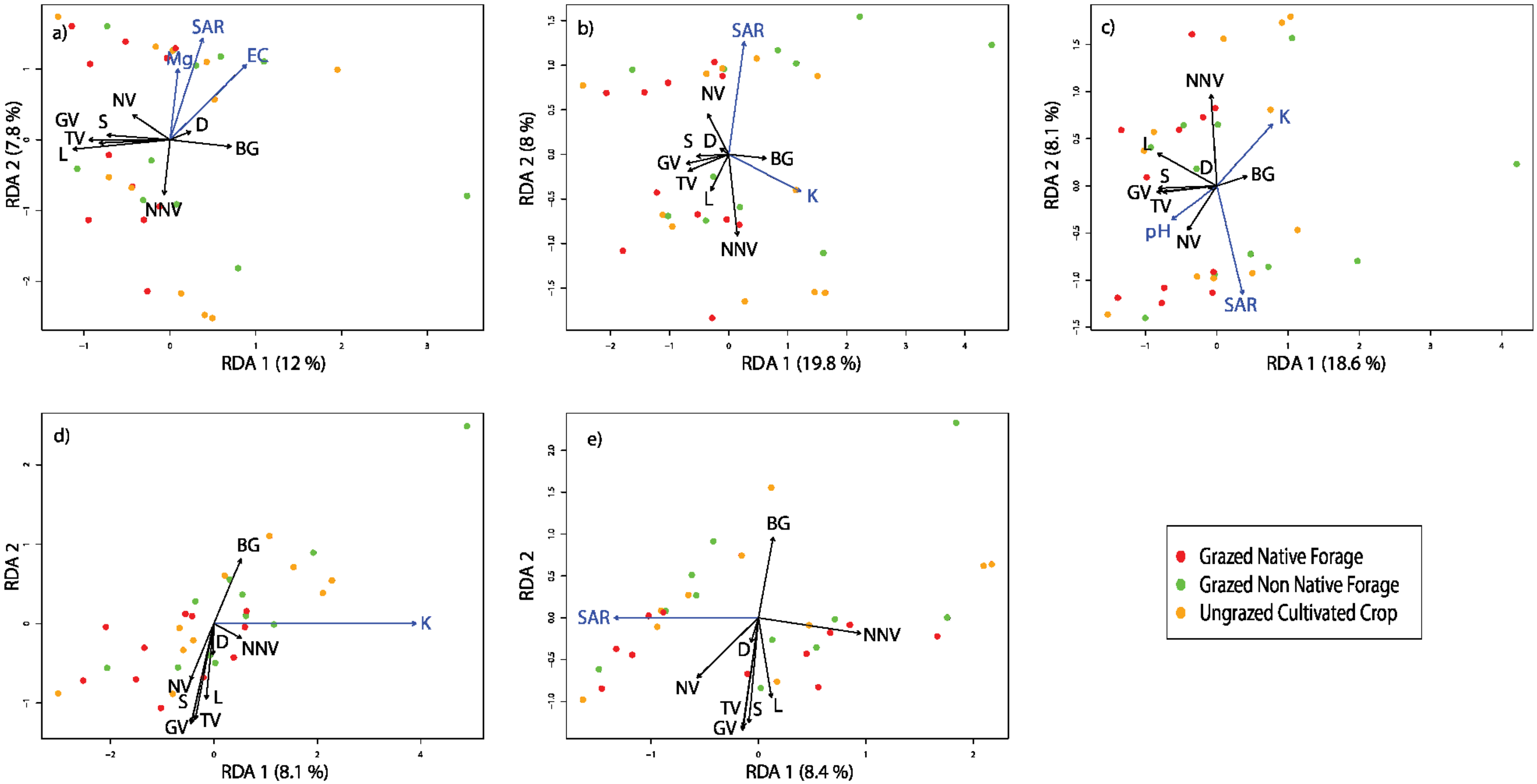

Figure 1. Redundancy analysis (RDA) biplot of log transformed and standardized soil and vegetation parameters in Dry Mixed Grass. Vegetation parameters: bare ground cover (BG), live vegetation ground cover (GV), litter ground cover (L), total vegetation canopy cover (TV), Simpson diversity index (D), species richness (S), native vegetation canopy cover (NV), non native vegetation canopy cover (NNV). Soil parameters are represented by blue vectors and only those with a significant impact ($P < 0.05$) on vegetation are used: electrical conductivity (EC), sodium adsorption ratio (SAR), pH, sodium (Na), chloride (Cl), sulfate (S), calcium (Ca), magnesium (Mg), potassium (P). Land uses are: grazed native forage (red), grazed non native forage (green), ungrazed cultivated crop (orange). Letters represent different depths (m): 0 to 0.15 (a), 0.15 to 0.30 (b), 0.30 to 0.45 (c), 0.45 to 0.60 (d), 0.60 to 1.50 (e).

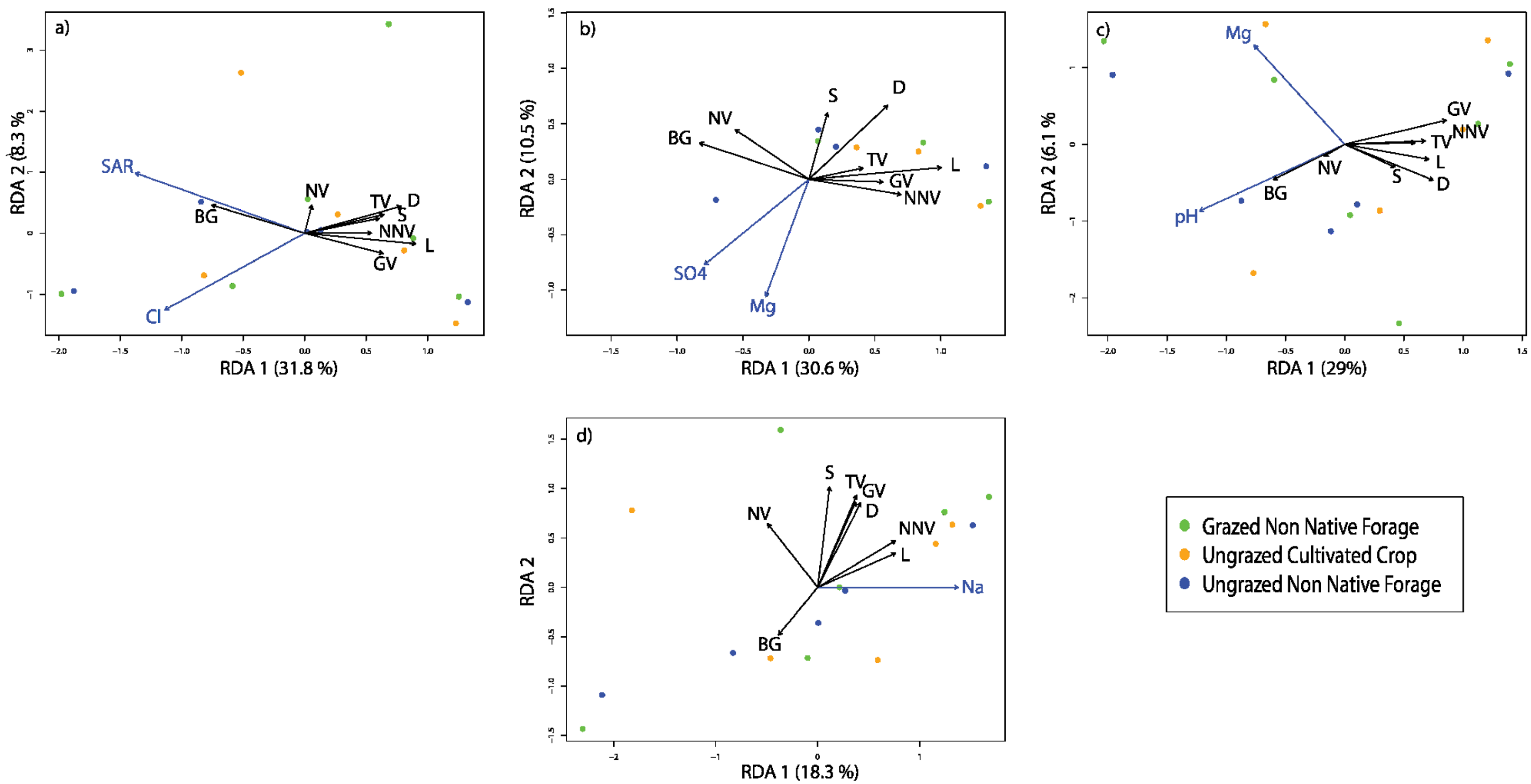

Figure 2. Redundancy analysis (RDA) biplot of log transformed and standardized soil and vegetation parameters in Central Parkland. Vegetation parameters: bare ground cover (BG), live vegetation ground cover (GV), litter ground cover (L), total vegetation canopy cover (TV), Simpson diversity index (D), species richness (S), native vegetation canopy cover (NV), non native vegetation canopy cover (NNV). Soil parameters are represented by blue vectors and only those with a significant impact ($P < 0.05$) on vegetation are used: electrical conductivity (EC), sodium adsorption ratio (SAR), pH, sodium (Na), chloride (Cl), sulfate (S), calcium (Ca), magnesium (Mg), potassium (P). Land uses are: grazed non native forage (green), ungrazed cultivated crop (orange), ungrazed non native forage (blue). Letters represent different depths (m): 0 to 0.15 (a), 0.15 to 0.30 (b), 0.30 to 0.45 (c), 0.60 to 1.50 (d).

CHAPTER IV. SYNTHESIS

1. RESEARCH SUMMARY

This research assessed the relationships between salt affected soil parameters (electrical conductivity (EC), sodium adsorption ratio (SAR), pH, individual ions), and between soil parameters and vegetation responses (bare ground cover, live vegetation ground cover, total vegetation canopy cover, native vegetation canopy cover, non native vegetation canopy cover, diversity, species richness) to determine whether reclamation criteria focused on EC and SAR in Alberta are the most scientifically appropriate indicators for reclamation success in salt affected soils. Study sites were in two ecoregions in Alberta, Dry Mixed Grass and Central Parkland, with 16 and 6 well sites, respectively. There were four land uses of grazed native forage, grazed non native forage, ungrazed cultivated crops, and ungrazed non native forage.

1.1. Salt Affected Soils And Their Saline Ion Relationships.

The relationships between soil parameters were assessed in saline and sodic soils in Alberta. Soil parameters were EC, SAR, pH, and the individual ions sodium, chloride, sulfate, calcium, magnesium, and potassium. The data were assessed and interpreted to determine whether EC and SAR were the most appropriate indicators for salt affected soils and if there were other relationships between soil variables that had an effect on EC and SAR. There were no determined relationships between EC and SAR. Although EC represented well the amount of soluble salts in the soil, it does not indicate what the individual salts and/or ions are. Therefore, damages to plants cannot be adequately predicted using only EC. SAR represented well sodium concentrations when it was in high quantity. However, since SAR represents a ratio of sodium, calcium, and magnesium, a low ratio does not mean that ions are present in concentrations small enough to not impede plant growth. In conclusion, reclamation criteria focusing only on soil EC and SAR may be inappropriate to determine specific salt impacts in the reclaimed plant community, particularly to assess salt affected soils.

1.2. Soil Parameters And Vegetation Relationships

The relationships between soil parameters and vegetation responses were assessed. Vegetation parameters were bare ground cover, live vegetation ground cover, litter ground cover, total vegetation canopy cover, species richness, species diversity, native vegetation canopy cover, and non native vegetation canopy cover. The response of vegetation parameters to soil variables were used to address whether EC and SAR are appropriate for reclamation for Dry Mixed Grass and Central Parkland. Soil parameters explained vegetation responses mostly from 0 to 0.45 m for both ecoregions. In Dry Mixed Grass, EC was a good measure of salts in the upper 0.15 m, and SAR explained vegetation responses well regarding sodium. However, other ions were also explaining vegetation responses including potassium and magnesium. PH was also a good indicator at 0.30 to 0.45 m depths. In conclusion, reclamation criteria focusing on soil EC and SAR may not be sufficient to assess the potential negative impact of soil parameters on plant communities and ions may need to be used. This may be particularly important when EC and SAR do not meet criteria but vegetation is healthy and productive. Although SAR may be a good indicator for sodium toxicity in Dry Mixed Grass, it is not sufficient to predict vegetation success. Reclamation criteria should have specific indicators for depths of 0 to 0.45 m since they were the depths that soil variables were impacting vegetation parameters the most across ecoregions.

2. RESEARCH LIMITATIONS

The research was limited by the amount and type of sites that were available to assess. Only two ecoregions in Alberta were assessed, which does not cover the Albertan province since there are six natural regions and 21 ecoregions. There were a larger number of sites in Dry Mixed Grass than Central Parkland. Sites with different land uses, soil textures, and year drilled were not equally represented and hence they may not be entirely representative of sites with those properties. Most of the research sites had soils that were fine grained and drilled after 1983. This design imbalances in our categories brings us to be critical with our results, knowing that we cannot draw strict conclusions if one category is better represented than another.

Since the study focused on salinity and sodicity, there was no accounting for carbonates or other nutrients or soil properties that could have explained better vegetation responses. Other parameters that could have had an impact on vegetation could also include soil physical properties such as compactions and soil water content. Not having those other soil parameters and even other site data will restrict understanding that other environmental variables that could explain vegetation responses.

Research sites and sampling locations were selected with an EM38 and past industry reports, and there was only time and budget to sample up to three areas and one background at each site. Therefore, only part of the sites were assessed and some potential saline and sodic area might have been missed or they might be a bit different than the ones selected. Vegetation assessment was limited by grazing. Plant height was not always representative of all the research sites since some sites were grazed and some were not grazed, or grazed at different times of the year, resulting in outcomes or interpretations that could not be totally comparable for that specific vegetation parameter.

Different weather conditions were not studied in this research. Dry Mixed Grass and Central Parkland wet or dry conditions would influence salt movements and could change salt concentrations. Precipitation and evapotranspiration would also affect salt movements. Sites that had precipitation before sampling would be expected to have more salt leached therefore salts at greater depth than if there were drier weather conditions.

3. RESEARCH APPLICATIONS

This research has shown potential to improve or modify reclamation criteria and guidelines in Alberta for salt affected soils by giving a better understanding of what happens in the soil at different depths and how it links to vegetation parameters. Exploring these relationships put in perspective the use of EC and SAR in reclamation criteria. This research showed that EC and SAR were not sufficient measures alone to ensure reclamation success for both soil and vegetation. Research showed that applying the same criteria for all ecoregions of Alberta may not be appropriate since our data showed that there were differences between our two ecoregions. Reclamation could be focused on the 0.45 m to ensure good revegetation.

Having appropriate criteria and reclamation targets for consulting companies can save time and money when reclaiming a site by targeting the salts of importance and preventing further environmental damage. Reclamation criteria could be strengthened by including individual ions to specifically assess salts that have adverse effects on soil properties and vegetation. Individual concentrations of salts including sodium, chloride, sulfate, calcium, magnesium, and potassium could be good indicators of soil health and could be added to reclamation guidelines. The more potentially toxic ions including sodium, chloride, and sulfate would be most important to include in the reclamation criteria. Plant communities were more susceptible to sodium, chloride, sulfate, magnesium, and potassium. Individual concentrations of salts could be good indicators of vegetation success. Including specific salt ions would be particularly important when EC and SAR do not meet reclamation criteria but the vegetation is healthy and productive.

4. FUTURE RESEARCH

Much future research could be done to modify remediation criteria in Alberta. As EC and SAR are not always sufficient measures alone to determine reclamation success, more research should focus on individual salt concentrations. Research focused on ions concentrations threshold for different soils and plants should be done in different ecoregions. Important species in main regions and/or ecoregions could be targeted and tested in a greenhouse experiment to see at which threshold they are impeded. Other ecoregions should also be investigated. Other research could include salt threshold for plant germination in to determine at which concentration plants are not growing.

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APPENDIX: SITE SPECIFIC DETAILS

List of sites and their specific history and location information.

Site	Ecoregion	Land Use	Drilling Date	Texture
GNF1	Dry Mixed Grass	Grazed native forage	1978	Fine grained
GNF2	Dry Mixed Grass	Grazed native forage	1978	Fine grained
GNF3	Dry Mixed Grass	Grazed native forage	1978	Fine grained
GNF4	Dry Mixed Grass	Grazed native forage	1975	Fine grained
GNF5	Dry Mixed Grass	Grazed native forage	1979	Coarse grained
GNF6	Dry Mixed Grass	Grazed native forage	1983	Fine grained
GNF7	Dry Mixed Grass	Grazed native forage	1975	Fine grained
GNF8	Dry Mixed Grass	Grazed native forage	1978	Fine grained
GNF9	Dry Mixed Grass	Grazed native forage	2003	Fine grained
GNF10	Dry Mixed Grass	Grazed native forage	2002	Coarse grained
GNF11	Dry Mixed Grass	Grazed native forage	1973	Fine grained
GNF12	Dry Mixed Grass	Grazed native forage	2002	Fine grained
GNF13	Dry Mixed Grass	Grazed native forage	1978	Fine grained
GNNF1	Dry Mixed Grass	Grazed non native forage	1977	Fine grained
GNNF2	Dry Mixed Grass	Grazed non native forage	1970	Fine grained
GNNF3	Central Parkland	Grazed non native forage	1980	Fine grained
GNNF4	Central Parkland	Grazed non native forage	1975	Fine grained
UC1	Dry Mixed Grass	Ungrazed cultivated crop	1980	Fine grained
UC2	Central Parkland	Ungrazed cultivated crop	1969	Fine grained
UC3	Central Parkland	Ungrazed cultivated crop	1976	Coarse grained
UC4	Central Parkland	Ungrazed cultivated crop	1993	Mixed
UNNF1	Central Parkland	Ungrazed non native forage	1951	Coarse grained

SITE GNF1 (14-12)

Site access by Canadian Natural Resources Limited. Site 61 km from Medicine Hat in Dry Mixed Grass. Site grazed native forage. Soil series Halliday, Brown Solod, Solonetzic at B horizon; Ronalaine, Solonetzic Brown Chernozem; Hemaruka, Gleyed Brown Solodized Solonetz, Solonetzic at B horizon formed on medium textured till. Soil silty clay to silty clay loam texture, fine grained. Site drilled in 1978, produced 1978 to 2006, abandoned 2007. Historical infrastructure on site was well head, access road, pipeline. No spills reported.

Phase II (2010) two areas of concern, well head and sump; KCL drilling fluid, hydrocarbon. Head EC 8.52 to 10.7 at 0.85 to 3 m, SAR 17.6 to 21.7 at 0.85 to 3 m exceeded Alberta Tier 1; sodium 1800 to 1920 mg kg^{-1} at 0.85 to 3 m, chloride 381 to 1020 mg kg^{-1} at 0.85 to 3 m exceeded BC guidelines; sulfate 4800 to 5580 mg kg^{-1} at 0.85 to 3 m. Sump EC 5.2 to 15.2 dS m^{-1} at 0 to 2 m, SAR 10.9 to 27.1 at 0 to 2 m above Alberta Tier 1; sodium 961 to 4330 mg kg^{-1} at 0 to 4 m, chloride 253 to 2520 mg kg^{-1} at 0 to 3.5 above BC guidelines; sulfate 2130 to 13900 mg kg^{-1} at 0 to 4 m elevated. Potassium high in one borehole 883, 1090 mg kg^{-1} at 0.45 to 1 m. Background EC 2.3 to 10.6 mg kg^{-1}, SAR 9.3 to 18.4, sodium 856 to 2290 mg kg^{-1} 0.45 to 4 m, chloride 233 to 266 mg kg^{-1} at 0.85 to 3 m above guidelines; sulfate 1080 to 7100 mg kg^{-1} at 0 to 4 m.

Five yards topsoil placed 2016, aerated, broadcast seeded, harrowed few weeks later. 2018, site drill seeded Eastern Irrigation District reclamation mix 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15% *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*. In 2019 native hay spread, crimped on well.

Reference area 70 % live vegetation, 30 % litter, 50 % vegetation canopy cover. Dominant plant species *Muhlenbergia richardsonis*, *Selaginella densa*. Well site mean 44.1 % bare ground, 27.7

% live vegetation, 22.3 % litter, 34.4 % vegetation canopy cover. Dominant plant species *Muhlenbergia richardsonis*, *Selaginella densa*. At 0 to 1.5 m, EC 2.6 to 19.1 dS m^{-1}, SAR 5.2 to 26.9 exceeds Alberta Tier 1; sodium 293 to 2640 mg kg^{-1}), chloride 220 to 2420 mg kg^{-1}) exceeds BC guidelines; sulfate 14.2 to 9040 mg kg^{-1} elevated relative to other samples. Potassium elevated relative to other samples in one borehole 2.5 to 383 mg kg^{-1}. Reference EC above 3.5 dS m^{-1} at 0.6 to 1.5 m, SAR above 9.5 at 0.45 to 1.5 m, pH under 5.54 at 0 to 0.45 m, sodium above 320 mg kg^{-1} at 0.6 to 1 m, sulfate 41.7 to 1670 mg kg^{-1}.

Reference lower sodium, sulfate than Phase II, similar EC, SAR. On well EC, SAR, sodium, chloride above guidelines; sulfate elevated relative to others at most depths. Similar to Phase II and increase with depth. Three of nine boreholes close to sump, which has historic exceedances. Potassium elevated relative to other samples in area due to use of KCL drilling fluid. Greater bare ground, less litter at well head, drill sump. Vegetation dominated by different species in three sampling areas; drill sump and well head *Poa sandbergii*, *Atriplex nuttallii*, *Artemisia frigida*; north *Agropyron* sp., *Artemisia frigida*, *Agropyron tridentata*, *Heterotheca villosa*; west *Muhlenbergia richardsonis*, *Agropyron smithii*, *Selaginella densa*, similar to reference.

Mean percent ground and vegetation cover on well site GNF1 (14-12)

Category	Well Site	Reference
Bare Ground	44.1	0.0
Ground Vegetation	27.7	70.0
Lichen	1.8	0.0
Litter	22.3	30.0
Total Canopy Cover	34.4	50.0
Salt Tolerant Species	17.6	28.0
Agropyron smithii	2.8	8.0
Agropyron species	1.8	0.0
Agropyron trachycaulum	2.0	0.0
Muhlenbergia richardsonis	8.2	20.0
Poa sandbergii	2.8	0.0
Artemisia frigida	3.6	5.0
Artemisia tridentata	1.7	0.0
Atriplex nuttallii	2.2	0.0
Heterotheca villosa	2.8	0.0
Selaginella densa	4.7	10.0
Sphaeralcea coccinea	1.6	0.0

SITE GNF2 (16-02)

Site access by Canadian Natural Resources Limited. Site approximately 60 km from Medicine Hat in Dry Mixed Grass. site grazed native forage. Soil series Halliday, Brown Solod and Solonetzic at B horizon; Ronalaine, Solonetzic Brown Chernozem, usually over 4 dS m^{-1}; Hemaruka, Gleyed Brown Solodized Solonetz, Solonetzic at B horizon. Soil silty loam to silty clay till texture and fine grained. Site drilled 1978, produced 1978 to 2009, abandoned 2009. Historical infrastructure on site was well head, pipeline riser, pipeline, access road. No spills reported.

Phase II (2012) reports two areas of concern, well head, drilling waste disposal area due to KCl drilling fluid. Well head area EC 11.3 to 13.6 dS m^{-1} at 0.85 to 3.15 m exceeded Alberta Tier 1; sodium 645 to 1370 mg kg^{-1} at 0.45 to 3.15 m, chloride 380 to 1080 mg kg^{-1} at 0.45 to 4 m exceeded BC guidelines; sulfate 1830 to 3790 mg kg^{-1} at 0.45 to 4 m elevated relative to other samples. Drill sump area EC 11.2 to 22.1 dS m^{-1} at 0 to 2.0 m, SAR 21.3 to 24.4 0.45 to 1 m, pH 8.7 to 11.5 at 0.45 to 1 m, boron 2.8 to 7.5 mg kg^{-1} 0.45 to 1 m exceeded Alberta Tier 1. Sodium 627 to 2170 mg kg^{-1} at 0.45 to 2 m, chloride (421 to 10700 mg kg^{-1} at 0.45 to 2 m exceeded BC guidelines; sulfate 1640 to 5200 mg kg^{-1} at 0.45 to 2 m, calcium 309 to 3030 mg kg^{-1} at 0.45 at 2 m elevated relative to other samples. From sampling 2017, drilling waste disposal area EC 11.2 to 22.1 dS m^{-1}, SAR 21.3 to 26.2, boron 2.8, 7.4 mg kg^{-1} at 0.45 to 1 m exceeded Alberta Tier 1; chloride 240 to 1800 mg kg^{-1} at 0.2 to 3.1 m exceeded BC guidelines. Background soil exceeded for EC, SAR, sodium, high sulfate. 2017 background values similar to well site except chloride.

Site partially reclaimed by 2012. In 2018 aerated, broadcast seeded and harrowed. Eastern Irrigation District reclamation mix contained 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15 % *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*.

Reference area has 5 % bare ground, 45 % live vegetation cover, 49 % litter, 50 % total vegetation canopy cover. Dominant plant species *Stipa comata*. Our well site mean 46.1 % bare ground, 33.1 % live vegetation cover, 15.4 % litter, 36.7 % vegetation canopy cover. Dominant plant species *Poa sandbergii*, *Selaginella densa*. At 0 to 1.5 m, EC 2.04 to 16.4 dS m^{-1}, SAR 7.85 to 25 exceeds Alberta Tier 1 guidelines; sodium 159 to 2040 mg kg^{-1}, chloride 200 to 2570 mg kg^{-1} exceeds BC guidelines; sulfate 17.6 to 6510 mg kg^{-1}, magnesium 6.3 and 460 mg kg^{-1}, calcium 18.7 to 587 mg kg^{-1} elevated relative to other samples. Reference EC 3.37 to 9.06 dS m^{-1}, SAR 5.1 to 11.6, sodium 203 to 813 mg kg^{-1} exceeds guidelines; sulfate 41.9 to 3310 mg kg^{-1}.

Reference naturally high EC, sodium, sulfate at depth characteristic of Solenetzic soils. On well site EC, SAR, sodium well above guidelines, reference values in all but one borehole and at most depths; chloride above guideline in 7 of 9 boreholes. Samples from former drill sump area, higher values than in other areas. EC, SAR, sodium, sulfate elevated in south east corner of well site away from production areas but downgradient. Compared to reference, well site vegetation different composition, poorer health, less height, more bare ground in work areas.

Mean percent ground and vegetation cover on well site GNF2 (16-02)

Category	Well Site	Reference
Bare Ground	46.1	5.0
Ground Vegetation	33.1	45.0
Lichen	3.4	0.0
Litter	15.4	49.0
Total Canopy Cover	36.7	50.0
Salt Tolerant Species	18.9	5.0
Agropyron smithii	6.7	0.0
Bouteloua gracilis	1.4	5.0
Muhlenbergia richardsonii	3.9	0.0
Poa sandbergii	6.9	0.0
Stipa comata	1.1	45.0
Carex pensylvanica	1.7	0.0
Artemisia frigida	0.2	0.0
Fabaceae species	0.6	0.0
Heterotheca villosa	0.9	0.0
Selaginella densa	13.33	0.0

SITE GNF3 (16-10)

Site access by Canadian Natural Resources Limited. Site approximately 60 km from Medicine Hat in Dry Mixed Grass. Site grazed native forage. Soil series Karlsbad, Brown Solod, may have EC over 4 dS m^{-1}; Tilley, Solonetzic Brown Chernozem; Chinz, Solonetzic Brown Chernozem; Walsh, Rego Gleysol. Karlsbad series is most applicable to the research site. Soil silty clay to silty clay loam texture and fine grained. Site drilled in 1978, produced 1978 to 2009, abandoned 2009. Historical infrastructure well head, access road, pipeline. No spills reported.

Phase II (2012) three areas of concern, well head, sump, historic disturbed area south of well head. Well head EC 9.44 dS m^{-1}, SAR 17.4 above Alberta Tier 1; sodium 1630 mg kg^{-1}, chloride 200 mg kg^{-1} above BC guidelines; sulfate 5420 mg kg^{-1} high at 1.85 to 2 m. Sump EC 2.96 to 18.8 dS m^{-1} at 0 to 2 m, SAR 8.2 to 22.2 from 0.45 to 2 m exceeded Alberta Tier 1; sodium 679 to 2290 mg kg^{-1} at 0.45 to 2 m, chloride 263 to 3450 mg kg^{-1} at 0 to 2 m exceeded BC guidelines; sulfate 1890 to 5530 mg kg^{-1} at 0 to 2 m, potassium 166 to 1430 mg kg^{-1} at 0 to 1 m elevated. Background EC 6.8 to 10.5 dS m^{-1}, SAR 10.7 to 19.0 exceeded Alberta Tier 1; sodium 222 to 1830 mg kg^{-1}, chloride 370 mg kg^{-1} exceed BC guidelines; sulfate 3110 to 5820 mg kg^{-1} elevated at 0 to 3.15 m.

Site partially reclaimed 2012. 2016 aerated, broadcast seeded, harrowed. 2018, drill seeded with Eastern Irrigation District reclamation mix 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15 % *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*.

Reference area 80 % vegetation cover, 10 % litter, 80 % vegetation canopy cover. Dominant species *Agropyron dasystachyum*, *Selaginella densa*. Well area 41.3 % bare ground, 47.8 % vegetation ground cover, 3.3 % litter, 57 % vegetation canopy cover. Dominant species *Agropyron trachycaulum*, *Selaginella densa*. At 0 to 1.5 m, EC 2.2 to 9.8 dS m^{-1}, SAR 4.5 to 16.6 exceeds Alberta Tier 1, sodium 172 to 2030 mg kg^{-1} exceeds BC guideline. Sulfate 59.7 to 6620 mg kg^{-1} at some boreholes over reference. Reference exceeds EC 4.9 to 7.4 dS m^{-1} at 0.45 to 1.5 m, SAR 6.7 to 12.4 at 0 to 1.5 m, sodium 172 to 930 mg kg^{-1}, sulfate 118 to 3320 mg kg^{-1}.

Reference had natural high sodium and sulfate. Well site EC, SAR, sodium above guidelines, similar to reference. Boreholes in 2019 outside of historic work areas including drill sump area which had highest values in Phase II. Bare ground cover high on well site relative to reference.

Mean percent ground and vegetation cover on well site GNF3 (16-10)

Category	Well Site	Reference
Bare Ground	41.3	0.0
Ground Vegetation	47.8	80.0
Lichen	6.2	10.0
Litter	3.3	10.0
Total Canopy Cover	57.0	80.0
Salt Tolerant Species	2.3	35.0
Agropyron dasystachyum	0.0	30.0
Agropyron trachycaulum	7.5	0.0
Bouteloua gracilis	0.8	0.0
Muhlenbergia cuspidata	3.3	0.0
Poa sandbergii	0.8	0.0
Stipa comata	3.3	0.0
Achillea millefolium	0.2	0.0
Artemisia frigida	3.3	5.0
Selaginella densa	25.8	40.0
Sphaeralcea coccinea	0.50	5.0

SITE GNF4 (06-24)

Site access by Canadian Natural Resources Limited. Site 35 km from Brooks in Dry Mixed Grass. Site grazed native forage. Soil series Tilley, Solonetzic Brown Chernozem on medium textured; Wardlow, Brown Solodized Solonetz on moderately fine textured. Silty clay to sandy clay till texture, fine grained. Site drilled 1975, produced 1975 to 1991, abandoned 1991. No spills.

Phase II (2011) reported six areas of concern, well head, drilling waste disposal area with KCL drilling fluid with diesel, EM anomaly area, four bare areas. Drilling waste disposal area 0 to 2 m

EC 5.24 to 23.6 dS m^{-1}, SAR 5.2 to 14.7 exceeded Alberta Tier 1; sodium 249 to 1620 mg kg^{-1}, chloride 269 to 9140 mg kg^{-1} exceeded BC guidelines; potassium 16 to 4640 mg kg^{-1} elevated relative to others. Background subsoil EC 2.04 to 8.83 dS m^{-1}, SAR 6.4 to 15.2, sodium 402 to 1340 mg kg^{-1} elevated relative to guidelines but in natural range for area. From additional sampling 2016, EC 18 to 20 dS m^{-1}, SAR 6.5 to 10, chloride 2300 to 2700 mg kg^{-1}, potassium 1800 to 2900 mg kg^{-1} elevated in 3 boreholes at 0 to 0.75 m in drilling waste disposal area. Sodium 340 to 1200 mg kg^{-1}, sulfate 720 to 5500 mg kg^{-1} high but similar to background concentrations.

Little reclamation information provided. In 2016 site aerated, broadcast seeded, harrowed. Eastern Irrigation District reclamation mix contained 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15 % *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*.

Reference has 40 % vegetation ground cover, 54 % litter, 50 % vegetation canopy cover; no bare ground. Dominant plant species are *Stipa comata*, *Selaginella densa*. Well site has mean 41.8 % bare ground, 32.7 % vegetation ground cover, 16.8 % litter, 30.8 % vegetation canopy cover. Dominant species *Agropyron smithii*, *Muhlenbergia cuspidata*. At 0 to 1.5 m EC 2.2 to 11.5 dS m^{-1}, SAR 4.63 to 21.5 exceeds Alberta Tier 1; sodium 194 to 1180 mg kg^{-1} exceeds BC guideline; sulfate 39.8 to 4650 mg kg^{-1}. Reference SAR 5.63 to 15.7 exceeds guideline 0.45 to 0.9 m.

Reference values for all parameters much lower than well site, past background values. Well site EC, SAR, sodium above guidelines and within Phase II ranges. Chloride, potassium not elevated as reported in past. Boreholes advanced in 2019 south of drilling waste disposal area and north west of well head. Bare ground high, vegetation health low on well site relative to reference.

Mean percent ground and vegetation cover on well site GNF4 (06-24)

Category	Well Site	Reference
Bare Ground	41.8	0.0
Ground Vegetation	32.7	40.0
Lichen	2.0	5.0
Litter	16.8	54.0
Total Canopy Cover	30.8	50.0
Salt Tolerant Species	18.5	11.0
Agropyron smithii	13.3	4.0
Bouteloua gracilis	1.2	7.0
Muhlenbergia cuspidata	7.7	0.0
Stipa comata	0.8	20.0
Selaginella densa	0.0	19.0
Sphaeralcea coccinea	3.2	0.0

SITE GNF5 (16-34)

Site access by Canadian Natural Resources Limited. Site approximately 46 km from Empress in Dry Mixed Grass. Site is grazed native forage. Soil series Foremost, Orthic Brown Chernozem on medium textured. Soil has a sandy loam textured A horizon, sandy loam textured B horizon and sand and sandy clay loam textured C horizon and coarse grained. Site drilled in 1979, produced 1979 to 2014, abandoned 2014. No spills reported. Historical infrastructure on site was well head, pipelines, pipeline riser, access road.

Phase II (2017) reports one area of concern, drilling waste disposal area. Exceedances in this area for EC 3 to 12 dS m^{-1} at 0.3 to 3 m, SAR 9.7 to 19.0 at 0.3 to 1.5 m, pH 8.7 to 11.3 at 0.3 to 1.5 m for Alberta Tier 1; sodium 190 to 700 mg kg^{-1} at 0.3 to 1.5 m), chloride (200.0 to 1300.0 mg kg-1) for BC guidelines; sulfate (9.2 to 1700.0 mg kg^{-1} at 0.3 to 1.5 m elevated relative to other samples. Well head 0.6 to 1.5 m EC 3.6 and 5.4 dS m^{-1}, SAR 36.2 and 41.0, pH 8.6 exceeded

Alberta Tier 1; sodium 401 and 441 mg kg^{-1}, chloride 357 and 414 mg kg^{-1} exceeded BC guidelines. Background values below guidelines except in one borehole below 2 m, EC 5.7 to 6 dS m^{-1}, sodium 160 to 220 mg kg^{-1}, sulfate 1000 to 1400 mg kg^{-1}.

Reclamation commenced September 2014, well head area backfilled, seed with native grasses. Topsoil likely from blow dirt ridges in adjacent hay field. Considered partially reclaimed in 2018.

Reference area has 42 % vegetation ground cover, 50 % litter, 50 % vegetation canopy cover; no bare ground. Dominant plant species *Stipa comata*, *Heterotheca villosa*. Well area has mean 90.7 % bare ground, 1 % vegetation ground cover, 1.7 % vegetation canopy cover; no litter. Only plant species is *Salsola kali*. At 0 to 1.5 m, EC 2.4 to 12.4 dS m^{-1}, SAR 4.3 to 32.3 exceeds Alberta Tier 1; sodium 153 to 533 mg kg^{-1}, chloride 240 to 1120 mg kg^{-1} exceeds BC guidelines.

Well site EC, SAR, chloride exceeds guidelines at all depths. EC, chloride increases, SAR decreases with depth. Our values within ranges in Phase II except sulfate. High bare ground, low vegetation cover in drilling waste disposal area and adjacent area where 2019 boreholes advanced compared to reference. Vegetation negatively affected by high EC, chloride, SAR in topsoil and at depth.

Mean percent ground and vegetation cover on well site GNF5 (16-34)

Category, Plant Species	Well Site	Reference
Bare Ground	90.7	0.0
Ground Vegetation	1.0	42.0
Litter	0.0	50.0
Total Canopy Cover	1.7	50.0
Salt Tolerant Species	1.7	5.0
Agropyron smithii	0.0	5.0
Stipa comata	0.0	20.0
Heterotheca villosa	0.0	15.0
Salsola kali	1.7	0.0

GNF6 (08-31)

Site access by City of Medicine Hat. Site approximately 58 km from Empress in Dry Mixed Grass. Site grazed native forage. Soil series Ramillies, Orthic Brown Chernozem on medium textured; Maleb-St, Orthic Brown Chernozem stony variant on medium textured; Bunton, Orthic Brown Chernozem on medium textured; miscellaneous undifferentiated mineral soils. Soil loam to clay loam texture and fine grained. Site drilled 1983, produced 1983 to 2013, abandoned 2013. No spills reported. Historical infrastructure on site was well head, pipeline, riser, access road.

Phase II (2015) reports three areas of concern, well head with surrounding EM anomaly in north west corner, drilling waste disposal area. Well head EC 2.2 to 15 dS m^{-1} at 0 to 1.5 m exceeded Alberta Tier 1. Drilling waste disposal area EC 2.3 to 20 dS m^{-1} at 0 to 2 m exceeded Alberta Tier 1; chloride 210 to 3100 mg kg^{-1} at 0 to 3 m, sodium 150 to 480 mg kg^{-1} at 0 to 3 m exceeded BC guidelines. In two boreholes potassium 2.1 to 1800 mg kg^{-1} at 0 to 3 m elevated; boron 3 to 3.4 mg kg-1 at 1.35 to 1.50 m, lead 72 to 92 mg kg-^{1} at 1.35 to 1.50 m exceeded Alberta Tier 1.

Reclamation commenced September 2013 and is ongoing. Approximately 600 m^3 of soil excavated and replaced.

Reference area 10 % bare ground, 65 % vegetation ground cover, 25 % litter, 75 % vegetation canopy cover. Dominant plant species *Bouteloua gracilis*, *Stipa comata*. Well area mean 28.3 % bare ground, 46.3 % vegetation ground cover, 20 % litter, 50.8 % vegetation canopy cover. Dominant plant species *Agropyron smithii*, *Carex* species. At 0 to 1.5 m, EC 2.1 to 57.8 dS m^{-1}, SAR 5.0 to 8.1 exceeds Alberta Tier 1; sodium 158 to 619 mg kg^{-1}, chloride 238 to 9400 mg kg^{-1}

exceeds BC guidelines; sulfate 13.2 to 2650 mg kg^{-1}, calcium 7.7 to 1080. mg kg^{-1}, potassium 2.8 to 8770 mg kg^{-1} elevated compared to other samples.

Boreholes advanced in 2019 in two areas east of well head and identified drilling waste disposal area, in area of Phase II boreholes. Well site EC exceeds Alberta Tier 1 below 0.3 m in all boreholes; SAR slightly above guideline at 5 to 8 at depth in some holes. In two holes chloride exceeds BC guideline; potassium elevated relative to others; sulfate highly elevated in one. EC highest recorded 57.4 dS m^{-1} on any site, likely due to disposed drilling waste. Vegetation variable among sample locations, many similar to reference in abundance, height, not composition.

Mean percent ground and vegetation cover on well site GNF6 (08-31)

Category	Well Site	Reference
Bare Ground	28.3	10.0
Ground Vegetation	46.3	65.0
Litter	20.0	25.0
Total Canopy Cover	50.8	75.0
Salt Tolerant Species	24.2	50.0
Agropyron smithii	15.8	0.0
Bouteloua gracilis	3.3	50.0
Muhlenbergia cuspidata	4.5	0.0
Stipa comata	0.8	15.0
Carex species	9.2	0.0
Artemisia frigida	6.7	5.0
Chenopodiastrum species	2.5	0.0
Fabaceae species	0.8	0.0
Lepidium virginicum	5.0	0.0
Selaginella densa	0.0	5.0
Taraxacum officinale	0.8	0.0
Unknown forb	1.7	0.0

GNF7 (06-19)

Site access by City of Medicine Hat. Site approximately 64 km from Empress in Dry Mixed Grass. Site grazed native forage. Soil series Maleb, Orthic Brown Chernozem on medium textured; Cranford, Orthic Brown Chernozem on medium textured; Maleb-St, Orthic Brown Chernozem stony variant on medium textured. Soil silty loam to loam over clay to clay loam textured horizons and fine grained. Site drilled 1975, produced 1976 to 2006, abandoned 2013. No spills reported. Historical infrastructure on site was well head, pipelines, riser, access road.

Phase II (2015) reports five areas of concern, well head, drilling waste disposal area, EM anomaly area, two disturbed areas. KCL drilling mud used. Well head disturbed area EC 2.4 to 5.6 dS m^{-1} at 0 to 6 m, SAR 5.5 to 7.6 at 0 to 2 m exceeded Alberta Tier 1; sodium 150 to 180 mg kg^{-1} at 0.85 to 8 m, chloride 200 to 470 mg kg^{-1} at 0 to 8 m exceeded BC guidelines; sulfate 6.7 to 1300 mg kg^{-1} at 0 to 6 m elevated relative to others. EM anomaly area 0.5 to 2 m EC 2.1 to 12 dS m^{-1}, SAR 5.2 to 32 exceeded Alberta Tier 1; sodium 160 to 500 mg kg^{-1}, chloride 410 to 1400 mg kg^{-1} exceeded BC guidelines; sulfate 15 to 1800 mg kg^{-1} at 0.5 to 9 m elevated relative to others. At disturbed area 1 EC 2.2 to 17.0 dS m^{-1} at 0.5 to 6 m above Alberta Tier 1; sodium 190 to 310 mg kg^{-1} at 0.5 to 2 m, chloride 330 to 2200 mg kg^{-1} at 0.5 to 3 m exceeded BC guidelines.

Reclamation commenced in September 2013 and is ongoing. Approximately 870 m^3 of soil excavated and replaced.

Reference area has 45 % bare ground, 20 % vegetation ground cover, 35 % litter, 20 % vegetation canopy cover. Dominant plant species *Agropyron smithii*, *Muhlenbergia cuspidata*. Well site 50.4

% bare ground, 33.3 % vegetation ground cover, 10.3 % litter, 29.0 % vegetation canopy cover. Dominant plant species *Bouteloua gracilis*, *Agropyron smithii.* At 0 to 1.5 m, EC 2.0 to 22.5 dS m^{-1}, SAR 5.2 to 30.1 exceeds Alberta Tier 1; sodium 161 to 507 mg kg^{-1}, chloride 211 to 3900 mg kg^{-1} exceeds BC guidelines; sulfate 9.7 to 960 mg kg^{-1}, calcium 10.9 to 1460 mg kg^{-1}, magnesium 4.4 to 925 mg kg^{-1} elevated compared to others. Reference EC 2 to 4.3 dS m^{-1} at 0.3 to 0.6 m, SAR 6.4 to 9.6 at 0.15 to 0.75 m above Alberta Tier 1; sodium 261 to 489 mg kg^{-1} at 0.3 to 0.6 m above BC guidelines; sulfate 10 to 1460 mg kg^{-1} elevated compared to others.

Reference EC, SAR above Alberta Tier 1 at 0.3 to 0.6 m only. On well site in all boreholes EC, SAR, sodium, chloride exceed guidelines. Sulfate, calcium, magnesium elevated relative to others in 3 of 7 boreholes. 2019 boreholes advanced south of well head close to past boreholes with elevated EC, SAR, sodium, chloride; near access road. Patches of bare ground throughout site and at reference. Vegetation composition variable across site and reference; weeds common.

Mean percent ground and vegetation cover on well site GNF7 (06-19)

Category	Well Site	Reference
Bare Ground	50.4	45.0
Ground Vegetation	33.3	20.0
Litter	10.3	35.0
Total Canopy Cover	29.0	20.0
Salt Tolerant Species	22.4	10.0
Agropyron smithii	9.3	10.0
Bouteloua gracilis	11.4	0.0
Hordeum jubatum	1.4	0.0
Muhlenbergia cuspidata	0.0	10.0
Chenopodiastrum species	5.3	0.0
Lepidium virginicum	0.3	0.0
Taraxacum officinale	0.0	3.0
Unknown forb	1.29	0.0

SITE GNF8 (08-08)

Site access by Canadian Natural Resources Limited. Site located in Alderson approximately 69 km from Medicine Hat in Dry Mixed Grass. Site is grazed native forage. Soil series Halliday, Brown Solod and Solonetzic at B horizon; Ronalaine, Solonetzic Brown Chernozem, usually over 4 dS m^{-1}; Hemaruka, Gleyed Brown Solodized Solonetz, Solonetzic at B horizon. Soil silty clay to silty clay loam texture and fine grained. Site drilled 1978, produced 1978 to 2003, abandoned 2003. No spills recorded. Historical infrastructure well head, pipelines, flowlines, pipeline risers, road.

Phase II (2014) reports three areas of concern, well head, sump, EM anomaly area. Well head 0.45 to 0.6 m EC 3.5 dS m^{-1}, SAR 7.4 exceeded Alberta Tier 1; sodium 499 mg kg^{-1} exceeded BC guideline; sulfate 1900 mg kg^{-1}. Sump EC 2.9 to 16.2 dS m^{-1} at 0.45 to 4 m, SAR 6 to 17.3 at 0.45 to 4 m exceeded Alberta Tier 1; sodium 215 to 2040 mg kg^{-1} 0.45 to 2 m, chloride 276 to 7940 mg kg^{-1} at 0.45 to 2 m exceeded BC guidelines; sulfate 41 to 3830 mg kg^{-1} at 0 to 4 m, calcium 56 to 928 mg kg^{-1} at 0 to 4 m, magnesium 11 to 599 mg kg^{-1} at 0 to 4 m elevated relative to others. EM anomaly area at 0.45 to 1.15 m EC 9.2 and 9.8 dS m^{-1}, SAR 15.7 and 16.3 above Alberta Tier 1; sodium 1600 and 1680 mg kg^{-1} above BC guideline; sulfate 5270 and 5430 mg kg^{-1}. Background 0 to 4 m EC 3.6 to 8.9 dS m^{-1}, SAR 6.2 to 14.6 exceeded Alberta Tier 1; sodium 184 to 1320 mg kg^{-1} above BC guideline; sulfate 26 to 4410 mg kg^{-1}.

Phase II (2014) site partially reclaimed. 2016 10 yards topsoil. aerated, broadcast seeded, harrowed a few weeks later. In 2018 site drill seeded with Eastern Irrigation District reclamation mix 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15 % *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*.

Reference 50 % bare ground, 15 % vegetation ground cover, 30 % litter, 20 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Selaginella densa*. Well 72.3 % bare ground, 11.1 % vegetation ground cover, 14.8 % litter, 18 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Agropyron trachycaulum*. At 0 to 1.5 m, EC 2.4 to 20.9 dS m^{-1}, SAR 4.2 to 17.3 exceeds Alberta Tier 1; sodium 174 to 1730 mg kg^{-1}, chloride 410 to 3050 mg kg^{-1} exceeds BC guidelines; magnesium 5.9 to 472 mg kg^{-1}, potassium 2 to 1660 mg kg^{-1} elevated compared to others; sulfate 28.8 to 4190 mg kg^{-1}. Reference EC 2.2 to 7.9 dS m^{-1}, SAR 7.5 to 14.1 exceeds Alberta Tier 1; sodium 230 to 1000 mg kg^{-1} exceeds BC guideline; sulfate 510 to 3500 mg kg^{-1}.

Well site EC, SAR sodium, chloride exceeds guidelines. Reference soil has naturally high EC, SAR, sodium, sulfate. Well site sodium, sulfate within these ranges but EC, SAR higher. Magnesium, potassium elevated compared to others including reference. Three of 9 boreholes advanced close to drill sump where patches of bare ground; potassium, chloride greatest in this area. Another 3 boreholes advanced in a historic EM anomaly area. Vegetation cover low in both these areas compared to reference and other well site sample locations.

Mean percent ground and vegetation cover on well site GNF8 (08-08)

Category	Well Site	Reference
Bare Ground	72.3	50.0
Ground Vegetation	11.1	15.0
Lichen	0.6	5.0
Litter	14.8	30.0
Total Canopy Cover	18.0	20.0
Agropyron pectiniforme	9.1	15.0
Agropyron trachycaulum	4.0	0.0
Fabaceae species	0.3	0.0
Selaginella densa	0.0	5.0

SITE GNF9 (06-25)

Site access by Canadian Natural Resources Ltd. Site 68 km from Medicine Hat in Dry Mixed Grass. Site grazed native forage. Series Halliday, Brown Solod, Hemaruka, Brown Solodized Solonetz, medium texture. Silty clay loam to clay loam, fine grained. Drilled 2003, produced 2003 to 2011, abandoned 2011. No spills. Overlap 100/06-25-014-12 with reclamation certificate 1994.

Phase I, II reports and site diagrams not available. From Risk Based Closure Report (2016) areas of potential concern were current well head, drilling waste disposal area of old well site. Drilling waste on current well site disposed off site. Current well head area EC 11.4 to 14 dS m^{-1} at 0.45 to 1.75 m, SAR 18.6 to 26.0 at 0.45 to 3.0 m, pH 9.6 at 1.0 m exceeded Alberta Tier 1; sodium 645 to 2320 mg kg^{-1}, chloride 278 to 1070 mg kg^{-1} at 0.45 to 1.75 m exceeded BC guidelines; sulfate 1360 to 5600 mg kg^{-1} at 0.45 to 1.75 m high but similar to background. Old waste disposal area EC 11.9 dS m^{-1} at 1 m above Alberta Tier 1. Background chloride 3 to 83 mg kg^{-1}.

Phase II (2014) reports site partially reclaimed. In 2016, site aerated, broadcast seeded, harrowed. Eastern Irrigation District reclamation mix contained 20 % *Stipa comata*, 20 % *Koeleria macrantha*, 15 % *Agropyron dasystachyum*, 15 % *Agropyron smithii*, 10 % *Poa sandbergii*, 10 % *Agropyron trachycaulum*, 10 % *Bouteloua gracilis*.

Reference 45 % vegetation ground cover, 55 % litter, 55 % vegetation canopy cover. Dominant species *Stipa comate*, *Muhlenbergia cuspidata*. Well 20 % bare ground, 43 % vegetation ground cover, 33.3 % litter, 50.6 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Poa sandbergii.* 0 to 1.5 m EC 2.7 to 16.4 dS m^{-1}; SAR 5.5 to 20.8 exceeds Alberta Tier 1; sodium 392 to 2380 mg kg^{-1}, chloride 230 to 560 mg kg^{-1} exceeds BC guideline; sulfate 1.6 to 8050 mg kg^{-1}, magnesium 4.4 to 747 mg kg^{-1}, calcium 11.8 to 426 mg kg^{-1} elevated relative to reference.

Well site EC, SAR, sodium, chloride above guidelines in 4 of 9 boreholes. Values increase with depth to 1 m; decrease to 1.5 m. Boreholes 2019 south west and east of well. Three south west of well had elevated values. Location of historic drilling waste disposal area or other production areas not known; could coincide with these boreholes. Patches of bare ground, vegetation canopy cover abundant. Well site dominated by non native grass, reference native grasses.

Mean percent ground and vegetation cover on well site GNF9 (06-25)

Category	Well Site	Reference
Bare Ground	19.9	0.0
Ground Vegetation	43.8	45.0
Lichen	1.8	0.0
Litter	33.3	55.0
Total Canopy Cover	50.6	55.0
Salt Tolerant Species	12.8	0.0
Agropyron pectiniforme	28.3	0.0
Agropyron smithii	0.8	0.0
Agropyron trachycaulum	0.8	0.0
Bouteloua gracilis	0.6	0.0
Muhlenbergia cuspidata	4.0	10.0
Muhlenbergia richardsonis	0.2	0.0
Poa sandbergii	5.9	0.0
Stipa comata	0.0	45.0
Achillea millefolium	2.0	0.0
Artemisia frigida	2.2	0.0
Atriplex nuttallii	1.1	0.0
Heterotheca villosa	0.6	0.0
Oxytropis species	0.6	0.0
Selaginella densa	3.3	0.0
Sphaeralcea coccinea	2.2	0.0

SITE GNF10 (06-09)

Site access by Canadian Natural Resources Limited. Site approximately 44 km from Empress in Dry Mixed Grass. Site grazed native forage. Soil series Cavendish, Orthic Brown Chernozem on, and Verdisant, Rego Brown Chernozem, on very coarse textured. Soil sandy loam A and B horizons and sandy clay to sandy clay loam textured C horizon and coarse grained. Drilled in 2002, produced 2002 to 2014, abandoned 2014. No spill reported. Historical infrastructure on site was well head, pipelines, pipeline riser, tech fence, access roads.

Phase II (2017) reported two areas of potential concern, well head, drilling waste disposal area. Well head EC 5.8 to 6.0 dS m^{-1} at 0 to 0.6 m, SAR 7.2 to 40 at 0 to 2 m, pH 8.17 to 8.7 at 0 to 0.3 m exceeded Alberta Tier 1; sodium 150 to 600 mg kg^{-1} at 0 to 1 m, chloride 220 to 730 mg kg^{-1} at 0 to 3 m exceeded BC guidelines. Drilling waste disposal area EC 4.9 to 19 dS m^{-1} at 0 to 3.3 m, SAR 8.8 at 0.4 to 1 m, F2 hydrocarbons 180 mg kg^{-1} at 1 to 1.3 m exceeded Alberta Tier 1; sodium 150 to 780 at 0.4 to 1.3 m, chloride 830 to 3200 mg kg^{-1} at 0.4 to 3.3 m exceeded BC guidelines; sulfate 14 to 1400 mg kg^{-1} at 0.4 to 3.3 m, potassium 8.6 to 1200 mg kg^{-1}, calcium 110 to 930 mg kg^{-1}, magnesium 110 to 590 mg kg^{-1} elevated relative to background.

Reclamation commenced September 2014, well head area backfilled, seeded to native grasses. Topsoil likely from blow dirt ridges in adjacent hay field. At Phase II reclamation not completed.

Reference 60 % vegetation ground cover, 40 % litter, 65 % vegetation canopy cover; Dominant species *Agropyron smithii*, *Stipa comata*. Well 51.7 % bare ground, 20 % vegetation ground cover, 24 % litter, 28.3 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Agropyron smithii*. 0 to 1.5 m, EC 2.0 to 13.4 dS m^{-1}, SAR 4.3 to 12.2 exceeds Alberta Tier 1; sodium 163 to 679 mg kg^{-1}, chloride 470 to 2900 mg kg^{-1} exceeds BC guidelines; sulfate 7.2 to 2020 mg kg^{-1}, magnesium 2 to 430 mg kg^{-1}, potassium 5 to 823 mg kg^{-1} elevated from reference.

Boreholes 2019 north of well head; drilling waste disposal area south of well head. On well site at 0.6 to 0.75 m, mean EC 11.4 dS m^{-1}, SAR 6.95, sodium 548 mg kg^{-1}, chloride 1936.7 mg kg^{-1}, sulfate 1416.7 mg kg^{-1}, magnesium 440 mg kg^{-1}, potassium 545 mg kg^{-1} more elevated than at other depths. Phase II report (2017) results were similar. No bare ground, good vegetation cover.

Mean percent ground and vegetation cover on well site GNF10 (06-09)

Category	Well Site	Reference
Bare Ground	51.7	0.0
Ground Vegetation	20.0	60.0
Litter	24.0	40.0
Total Canopy Cover	28.3	65.0
Salt Tolerant Species	10.0	60.0
Agropyron pectiniforme	20.0	0.0
Agropyron smithii	10.0	60.0
Stipa comata	0.0	20.0

SITE GNF11 (16-24)

Site access by City of Medicine Hat. Site approximately 80 km from Empress in Dry Mixed Grass. Site is grazed native forage. Soil series Maleb-ST, Orthic Brown Chernozemic; Maleb, Orthic Brown Chernozemic with acid properties; Helmsdale, Rego Brown Chernozem; Miscellaneous Gleysol series. Soil clayey silty sand underlain by silt, clayey silt and clay textured horizons and fine grained. Site drilled 2002, produced 1981 to 1992 and 2002 to 2010, abandoned 2013. Well site in same location as historic one that received reclamation certificate 1997. No spills reported.

Phase II (2014) reported five areas of concern, well head, potential drilling waste disposal area, potential flare pit, aerial photo anomalies. Supplemental Phase II (2015) delineated extent of drilling waste disposal area. Well head EC 4.8 dS m^{-1} exceeded Alberta Tier 1; sodium 290 mg kg^{-1}, chloride 329 mg kg^{-1} at 1 m exceeded BC guidelines; sulfate 1950 mg kg^{-1} elevated relative to background. Anomaly area guideline exceedances EC 2.8 dS m^{-1}, SAR 6.1, sodium 328 mg kg^{-1}, chloride 222 mg kg^{-1}; sulfate 975 mg kg^{-1} elevated relative to background. Drilling waste disposal area EC 2.8 to 13.1 dS m^{-1} at 0.3 to 3.75 m, SAR 4.1 to 10.7 at 0.3 to 3.75 m, boron (2.3 mg kg^{-1} at 1 m exceeded Alberta Tier 1; sodium 189 to 550 mg kg^{-1} at 0.3 to 2.75 m, chloride 329 to 2660 mg kg^{-1} at 0.3 to 3.75 m exceeded BC guidelines; sulfate 170 to 4450 mg kg^{-1} elevated relative to background. Delineation around drilling waste disposal area guideline exceedances EC 2.0 to 12.1 dS m^{-1}, SAR 4 to 8.5, sodium 177 to 543 mg kg^{-1}, chloride 232 to 299 mg kg^{-1}; sulfate 34 to 3610 mg kg^{-1} elevated relative to background. Background EC 2.2 to 6.75 dS m^{-1} at 0 and 6 m, SAR 4.3 to 5.7 at 1.0 to 1.2 m, pH 5.8 at 0 to 0.15 m above Alberta Tier 1; sodium 3 to 581 mg kg^{-1} above BC guideline; sulfate 23 to 4890 mg kg^{-1} 0 to 3 m. Supplement Phase II included anomaly area boreholes as background, had highest values.

Reclamation activities commenced February 2014 and are ongoing. Based on Alberta Tier 1 approximately 6250 m^3 of salt affected soil identified for remediation.

Reference 20 % vegetation ground cover, 80 % litter, 20 % vegetation canopy cover; no bare ground. Dominant species *Agropyron smithii*, *Bouteloua gracilis*. Well area 40.7 % bare ground, 21.8 % vegetation ground cover, 37 % litter, 21.7 % vegetation canopy cover. Dominant species *Agropyron pectiniforme.* 0 to 1.5 m, EC 2.4 to 17.5 dS m^{-1}, SAR 4.02 to 7.75, pH 8.01 to 8.16 exceeds Alberta Tier 1; sodium 158 to 709 mg kg^{-1}, chloride 340 to 3370 mg kg^{-1} exceeds BC guideline; sulfate 15.4 to 1650 mg kg^{-1}, magnesium 7.3 to 696 mg kg^{-1}, calcium 21.9 to 881 mg kg^{-1}, potassium 11.3 to 1580 mg kg^{-1} elevated relative to reference. Reference SAR 4.9 to 12.8, pH 5.69 to 8.91 does not meet Alberta Tier 1, pH at most depths; sodium 158 to 195 mg kg^{-1} slightly above BC guideline below 0.9 m.

Well site EC, SAR, sodium, chloride exceeds guidelines. Sodium exceeds guidelines below 0.3 m, chloride, EC below 0.15 m in all boreholes. Sulfate, calcium, magnesium, potassium 0.6 to 1.05 m elevated relative to reference. 2019 boreholes south and east of well head in drilling waste disposal areas. Similar results to past reports. High bare ground, vegetation dominated by *Agropyron pectiniforme* on well site; no bare ground, diverse native vegetation cover at reference.

Mean percent ground and vegetation cover on well site GNF11 (16-24)

Category	Well Site	Reference
Bare Ground	40.7	0.0
Ground Vegetation	21.8	20.0
Litter	37.0	80.0
Total Canopy Cover	21.7	20.0
Salt Tolerant Species	1.3	20.0
Agropyron pectiniforme	12.4	0.0
Agropyron smithii	0.0	10.0
Agropyron trachycaulum	0.7	0.0
Bouteloua gracilis	1.3	10.0
Carex species	0.0	5.0
Artemisia frigida	5.7	0.0

SITE GNF11 (10-01)

Site access by Canadian Natural Resources Ltd. Site 39 km from Empress in Dry Mixed Grass. Site grazed native forage. Soil series Chin, Orthic Brown Chernozem, medium textured; Cavendish, Orthic Brown Chernozem, very coarse textured; Vendisant, Rego Brown Chernozem on very coarse textured; Antelope, Orthic Regosol on very coarse textured. Silty loam, clay and silty clay textured and fine grained. Site drilled 1973, produced 1975 to 1995 and in 2002, abandoned 2009. No spills reported.

Phase II (2013) reports one area of concern, well head. Well head EC 2.1 to 13 dS m^{-1} at 0.5 to 2 m, SAR 4 to 9.9 at 0.5 to 3 m exceeded Alberta Tier 1; sodium 150 to 750 mg kg^{-1} at 0.5 to 4 m, chloride 320 to 1400 mg kg^{-1} at 0.5 to 1.65 m exceeded BC guidelines; sulfate 21 to 1500 mg kg^{-1} at 0 to 4 m elevated relative to other. One background borehole exceeded guidelines at 1.85 to 5 m for EC 2.7 to 5.9 dS m^{-1}, SAR 4.7 to 6.1, sodium 180 and 3810 mg kg^{-1}, chloride 190 mg kg^{-1} at 1.85 to 2 m; sulfate 3.1 to 1900 mg kg^{-1} at 0.5 to 5 m elevated relative to other samples.

CNRL obtained site in 2015, reclamation soon after abandonment in 2009. No record of soil brought onto site. Likely seeded with *Agropyron pectiniforme* shortly after drilling.

Reference 2 % bare ground, 30 % vegetation ground cover, 66 % litter, 45 % vegetation canopy cover. Dominant species *Muhlenbergia cuspidata*, *Stipa comata*. Eell site 69.7 % bare ground, 19.7 % vegetation ground cover, 8.3 % litter, 23.0 % vegetation canopy cover. Dominant species *Agropyron pectiniforme, Agropyron smithii*. At 0 to 1.5 m EC 2.3 to 11.2 dS m^{-1}, SAR 4 to 20.7, pH 8 to 8.7 exceeds Alberta Tier 1; sodium 154 to 914 mg kg^{-1}, chloride 217 to 1500 mg kg^{-1} exceeds BC guidelines; sulfate 7.8 to 1200 mg kg^{-1} elevated compared to the others.

Boreholes advanced in 2019 north of well head. Well EC, SAR, pH, sodium, chloride exceed guidelines, sulfate elevated relative to others. Phase II exceedances EC, SAR, sodium, chloride, sulfate in well head. High bare ground, low litter on well than reference. Well centre *Agropyron pectiniforme*, reference native.

Mean percent ground and vegetation cover on well site GNF11 (10-01)

Category	Well Site	Reference
Bare Ground	69.7	2.0
Ground Vegetation	19.7	30.0
Lichen	0.0	2.0
Litter	8.3	66.0
Total Canopy Cover	23.0	45.0
Salt Tolerant Species	2.3	15.0
Agropyron pectiniforme	13.3	0.0
Agropyron smithii	2.3	0.0
Bouteloua gracilis	0.0	5.0
Muhlenbergia cuspidata	0.0	20.0
Poa sandbergii	0.0	10.0
Stipa comata	0.0	15.0
Artemisia frigida	2.3	0.0
Descurainia sophia	1.3	0.0
Lappula squarrosa	1.0	0.0
Selaginella densa	0.0	1.0
Vicia americana	0.0	3.0

SITE GNF13 (2-06-24)

Site access by City of Medicine Hat. Site approximately 80 km from Empress in Dry Mixed Grass. Site grazed native forage. Soil series Cranford, Orthic Brown Bhernozem; Chin, Orthic Brown Chernozem with acid properties; Maled, Orthic Brown Chernozem. Soil has silt A horizon with some clay and sand, underlain by clayey silt, clay and silt textured B and C horizons and fine grained. Site drilled 1978 by Exxon Mobil, produced 1981 to 1990, surface abandoned 1992, reclamation certificate received 1999. Well re-entered by City of Medicine Hat in 2002, produced until 2007, abandoned in 2013. No spills reported.

Phase II (2014) reports four areas of concern, well head, potential drilling flare pit, suspected drilling waste disposal area, aerial photo anomalies. Supplemental Phase II (2015) delineated contaminated areas. Well head EC 2 to 6.9 dS m^{-1} at 1.2 to 3 m exceeded Alberta Tier 1; sodium 160 to 323 mg kg^{-1} at 1.2 to 3 m, chloride 277 and 367 at 1.2 to 1.5 m exceeded BC guidelines; sulfate 53 to 3230 mg kg^{-1} elevated relative to others. Drilling waste disposal area EC 2 to 7.3 dS m^{-1} at 0.3 to 4.5 m, SAR 4.1 to 5 at 0.3 to 2.25 m exceeded Alberta Tier 1; sodium 158 to 288 mg kg^{-1} at 0.3 to 3.75 m, chloride 259 to 1570 mg kg^{-1} at 0.3 to 4.5 m exceeded BC guidelines; sulfate 12 to 2960 mg kg^{-1} elevated compared to others. Background guideline exceedances EC 2.3 to 4.7 dS m^{-1} at 1.2 to 4.5 m, SAR 4.8 at 1.2 m, pH 5.9 at 0 to 0.15 m, sodium 182 to 193 mg kg^{-1} at 1.2 to 4.5 m; sulfate 5 to 1630 mg kg^{-1} variable.

Initial reclamation certificate (1999) indicated site dominated by *Agropyron pectiniforme* (seeded), *Agropyron trachycaulum* with encroaching native species. Reclamation activities on current disturbance commenced February 2014 and are ongoing.

Reference area 5 % bare ground, 45 % vegetation ground cover, 50 % litter, 50 % vegetation canopy cover. Dominant plant species *Agropyron smithii*, *Bouteloua gracilis*. Well site has 55 % bare ground, 6.7 % vegetation ground cover, 38.3 % litter, 13.3 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*. 0 to 1.5 m EC 2.3 to 12.3 dS m^{-1}, SAR 4.1 to 4.9 exceeds Alberta Tier 1; sodium 154 to 211 mg kg^{-1}, chloride 221 to 1670 mg kg^{-1} exceeds BC guidelines; sulfate 13.4 to 1400 mg kg^{-1} elevated compared to other samples.

Well site EC, chloride above guidelines below 0.3 m in 2 of 3 boreholes and all depths in one borehole. Sodium slightly above guideline at some depths and sulfate elevated compared to the other samples in one borehole. 2019 boreholes south east of the well head in flare pit. Results similar to past reports. High bare ground, dominated by *Agropyron pectiniforme* on well site; no bare ground, diverse native vegetation cover at reference.

Mean percent ground and vegetation cover on well site GNF12 (2-06-24)

Category	Well Site	Reference
Bare Ground	55.0	5.0
Ground Vegetation	6.7	45.0
Litter	38.3	50.0
Total Canopy Cover	13.3	50.0
Salt Tolerant Species	0.0	40.0
Agropyron pectiniforme	13.3	0.0
Agropyron smithii	0.0	15.0
Bouteloua gracilis	0.0	25.0
Stipa comata	0.0	10.0

SITE GNNF1 (16-16)

Site access by City of Medicine Hat. Site approximately 7.7 km from Medicine Hat in Dry Mixed Grass. Site is grazed non native forage. Soil series Cranford, Orthic Brown Chernozemic; sandy clay texture and fine grained. Site drilled 1977, produced 1977 to 2013, abandoned 2013. Natural gas spill (1000 m^3) reported in August 2005; none recovered. Historical infrastructure well head, access road, pipeline.

Phase II (2015) reports three areas of concern, well head, EM anomaly surrounding well head, area of salinity staining near and east of well head. Well head area exceedances at 0 to 3 m EC 3.4 to 9.04 dS m^{-1}, SAR 5.1 to 7.1 for Alberta Tier 1; sodium 155 to 451 mg kg^{-1}, chloride 260 to 1610 mg kg^{-1} for BC guidelines; sulfate 268 to 2470 mg kg^{-1}. Background EC 3 to 5.8 dS m^{-1} at 0.5 to 3 m, SAR 5 to 5.8 at 0.5 to 3 m exceeded Alberta Tier 1; sodium 200 to 421 mg kg^{-1} at 0.5 to 3 m exceeded BC guideline; sulfate 51.6 to 2480 mg kg^{-1}. Well site sodium, sulfate within background. For Supplemental Phase II (2015), additional boreholes advanced by well head and south east. EC 2.4 to 14.5 dS m^{-1} at 0 to 2.5 m, SAR 5.1 to 10.8 at 0 to 2.5 m exceeded Alberta Tier 1; sodium 176 to 1040 mg kg^{-1} at 0 to 2.5 m, chloride 205 to 2800 mg kg^{-1} at 0 to 2.5 m exceeded BC guidelines; sulfate 40.9 to 3380 mg kg^{-1}. Background similar to initial Phase II.

Reclamation commenced August 2014. Phase I (2014) reported site was tame pasture overseeded with *Agropyron pectiniforme*. Phase II (2015) reported approximately 1980 m^3 of salt affected soil and recommended remediation. Remediation proposal (2015) indicated soil would be excavated and backfilled with soil from local source. Reclamation is ongoing.

Reference 7 % bare ground, 40 % vegetation ground cover, 53 % litter 45 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*. Well site 56.7 % bare ground, 10 % vegetation ground cover, 30.7 % litter, 8.3 % vegetation canopy cover. Dominant species *Agropyron dasystachyum*. 0 to 1.5 m EC 2.2 to 12.7 dS m^{-1}, SAR 5.3 to 9.1 exceeds Alberta Tier 1; sodium 157 to 505 mg kg^{-1}, chloride 350 to 1730 mg kg^{-1} exceeds BC guidelines; sulfate 150 to 1980 mg kg^{-1}, calcium 52.1 to 431 mg kg^{-1}, magnesium 6.3 to 573 mg kg^{-1} elevated. Reference below 0.6 m exceeds guidelines for EC 2.75 dS m^{-1}, SAR 5.9 to 7.7, sodium 160 and 206 mg kg^{-1}.

Reference slight guideline exceedances for EC, SAR, sodium at depth. Sulfate considerably lower than Phase II background values. Well site EC, SAR, sodium above guidelines at most depths; chloride above at below 0.6 m. Sulfate, calcium, magnesium high at all depths compared to reference, and all increase with depth. 2019 boreholes advanced in well head area. Patches of bare ground throughout that area; vegetation not grazed. Well *Agropyron dasystachyum*, reference *Agropyron pectiniforme.*

Mean percent ground and vegetation cover on well site GNNF1 (16-16)

Category	Well Site	Reference
Bare Ground	56.7	7.0
Live Vegetation	10.0	40.0
Litter	30.7	53.0
Total Canopy Cover	8.3	45.0
Salt Tolerant Species	7.7	0.0
Agropyron dasystachyum	7.7	0.0
Agropyron pectiniforme	0.0	45.0

SITE GNNF2 (11-04)

Site access by Orphan Well Association. Site 3.4 km from Drumheller in Northern Fescue. Site grazed non native forage. Soil series Coronation, Orthic Dark Brown Chernozem, moderately fine textured; Provost, Orthic Dark Brown Chernozem, medium textured; Drumheller, Vertic Dark Brown Chernozem, fine textured. Soil silty clay loam texture with silty clay subsoil and fine grained. Site drilled 1970, never produced, abandoned1970. No spills reported.

Subsurface investigation (2016) identified two areas of concern, well head, EM anomaly south of well. Well head EC 3.6 to 4.7 dS m^{-1} at 0.6 to 3.0 m, SAR 4.3 at 0.6 m exceeding Alberta Tier 1; sodium 212 to 308 mg kg^{-1} at 0.6 to 3.0 m exceeding BC guideline; sulfate 92 to 2210 mg kg^{-1} at 0.15 to 3 m elevated compared to others. EM anomaly area guideline exceedances EC 2.2 to 7.0 dS m^{-1} at 0.6 to 3.0 m, SAR 4.1 to 7.4 at 0.6 to 1.2 m, sodium 170 to 676 mg kg^{-1} at 0.6 to 3 m, chloride 208 to 678 mg kg^{-1} at 0.6 to 1.2 m; sulfate 243 to 2690 mg kg^{-1} at 0.2 to 3 m. Background at 0.2 to 3.0 m sodium 212 to 308 mg kg^{-1} above guidelines; sulfate 92 to 2210 mg kg^{-1}. For supplemental subsurface investigations (2017), EC 2.2 to 6.9 dS m^{-1} at 1.2 to 6 m), SAR 4 to 6.2 at 0.6 to 2 m exceeding Alberta Tier 1; sodium 152 to 619 mg kg^{-1} at 0.6 to 6 m, chloride 250 and 373 mg kg^{-1} at 0.6 to 1.2 m exceeding BC guidelines; sulfate 25 to 4450 mg kg^{-1} at 0.15 to 6 m.

Site fully reclaimed 2016 when subsurface investigated. Detailed site assessment (2018) site meets 2010 reclamation criteria for cultivated land, ready for reclamation certification.

Reference 65 % bare ground, 20 % vegetation ground cover, 15 % litter, 20 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Medicago sativa*. Well 27.3 % bare ground, 45 % vegetation ground cover, 27.7 % litter, 43.3 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Medicago sativa*. 0 to 1.5 m EC 2.3 to 6.4 dS m^{-1}, SAR 4.1 to 7, pH 8 to 8.3 above Alberta Tier 1; sodium 162 to 323 mg kg^{-1}, chloride 210 to 300 mg kg^{-1} above BC guidelines; sulfate 17.6 to 2150 mg kg^{-1}, calcium 41 to 341 mg kg^{-1}, magnesium 11 to 326 mg kg^{-1} elevated compared to reference and top 0.15 m. Reference EC 2.1 to 2.3 dS m^{-1}, SAR 4.2 to 4.9, sodium 177 to 218 mg kg^{-1} above guidelines below 0.9 m.

Reference naturally high EC, sodium, sulfate below 0.3 m; SAR, pH below 0.45 m; chloride at some depths. Well EC, SAR, sodium and chloride above guidelines; sulfate high. 2019 boreholes close to well head. Similar to past values. Reference more bare ground, less vegetation than well.

Mean percent ground and vegetation cover on well site GNNF2 (11-04)

Category	Well Site	Reference
Bare Ground	27.3	65.0
Ground Vegetation	45.0	20.0
Litter	27.7	15.0
Total Canopy Cover	43.3	20.0
Salt Tolerant Species	11.7	5.0
Agropyron pectiniforme	31.7	15.0
Medicago sativa	11.7	5.0

SITE GNNF3 (11-10)

Site access by Canadian Natural Resources Limited. Site 24 km from Elk Point in Central Parkland. Site grazed non native forage. Series Angus Ridge, Eluviated Black Chernozem, medium textured; Uncas, Dark Gray Luvisol, medium textured. Sandy loam textured A horizon, clay loam textured B horizon, clay loam or sandy clay loam texture C horizon, fine grained. Drilled 1980, produced 1981 to 2004, abandoned 2014. Infrastructure well head, motor shack, propane tanks, above ground storage tank, pipeline riser, road. Spills reported at well head and tank area.

Phase II (2016) reports three areas of concern, well head and associated spill area, pop tank spill area and above ground storage tank area. Well head and spill area EC 2.1 to 3.6 dS m^{-1} at 0 to 2 m, SAR 4.2 to 10 at 0 to 3 m exceeded Alberta Tier 1; sodium 200 mg kg^{-1} at 0 to 0.3 m, chloride 220 and 350 mg kg^{-1} at 0 to 2 m above BC guideline. Above ground storage tank area EC 2 to 4.3 dS m^{-1} at 0.3 to 2 m above Alberta Tier 1; sodium 150 mg kg^{-1} at 0.3 to 0.6 m above BC guideline; sulfate 180 to 1700 mg kg^{-1} at 0 to 2 m elevated compared to other samples. No exceedances reported at historical pop tank spill.

Reclamation commenced 2018, no soil excavated. Seeded with *Bromus bierbersteinii*, *Phleum pratense*, *Elymus dahuricus*, *Dactylis glomerata*, *Alopecurus pratensis*, *Agropyron pectiniforme*, *Medicago sativa*, *Trifolium pratense*, *Trifolium hybridum*, *Astragalus cicer*, *Onobrychis arenaria.*

Reference 60 % bare ground, 35 % vegetation ground cover, 5 % litter, 100 % vegetation canopy cover. Dominant species *Elymus* species, *Agropyron pectiniforme*, *Agropyron trachycaulum*, *Medicago sativa*. Well area 64.2 % bare ground, 26.7 % vegetation ground cover, 6.8 % litter, 70 % vegetation canopy cover. Dominant species *Agropyron pectiniforme*, *Carex atherode*, *Elymus* species. In two boreholes at 1.35 to 1.5 m, SAR 4.9 and 5.1 exceeds Alberta Tier 1.

Well site does not appear to be salt affected. Boreholes in 2019 near and south west of well head; contaminated boreholes in Phase II were closer to well head Vegetation and ground cover on well site and reference similar; tallest plants of all sites and may not have been grazed recently.

Mean percent ground and vegetation cover on well site GNNF3 (11-10)

Category	Well Site	Reference
Bare Ground	64.2	60.0
Ground Vegetation	26.7	35.0
Litter	6.8	5.0
Total Canopy Cover	70.0	100.0
Salt Tolerant Species	21.7	25.0
Agropyron pectiniforme	21.7	15.0
Agropyron trachycaulum	10.8	15.0
Elymus species	15.8	20.0
Phleum pratense	3.2	5.0
Stipa viridula	0.0	2.0
Carex atherode	19.2	0.0
Anemone species	0.8	0.0
Descurainia sophia	0.8	5.0
Medicago sativa	2.5	15.0
Melilotus alba	0.0	10.0
Thlaspi arvense	0.3	0.0
Unknown forb	0.8	0.0

SITE GNNF4 (14-07)

Site access by Canadian Natural Resources Ltd. Site approximately 23 km from Lloydminster in Central Parkland. Site is grazed non native forage. Soil series Elnora, Orthic Black Chernozem developed on moderately fine till. Soil sandy clay texture and fine grained. Site drilled 1975, produced 1975 to 1995, abandoned 2002. Historical infrastructure on site was well head, pump jack, motor shack, risers, flowlines, above ground storage tank, access road. No spills reported.

Phase II (2015) reported four areas of concern, well head, shack, above ground storage tank, pump jack. Pump jack area EC 3.1 to 5.1 dS m^{-1} at 0.5 to 3 m, SAR 4.2 at 1.5 to 2 m exceeded Alberta Tier 1; sodium 285 and 334 mg kg^{-1} at 1.5 to 3 m exceeded BC guideline; sulfate 3.7 to 854 mg kg^{-1}, calcium 46.8 to 352 mg kg^{-1} elevated compared to others. Above storage tank EC 3.2 to 13.8 dS m^{-1} at 0.5 to 4 m, SAR 5 to 62.9 at 0.5 to 4 m, pH 8.3 to 8.5 at 0.5 to 1 m exceeded Alberta Tier 1; sodium 162 to 3000 mg kg^{-1} at 0.5 to 4 m, chloride 504 to 5800 mg kg^{-1} at 0.5 to 3 m exceeded BC guidelines; calcium 6.3 to 534 mg kg^{-1} elevated compared to others. Shack EC 2.04 dS m^{-1} at 0.5 to 1 m above guideline; pH 5.8 below guideline.

Reclamation commenced in 2003. Phase II reports site was reclaimed at time of assessment (September 2014).

Reference 30 % vegetation ground cover, 50 % litter, 40 % vegetation canopy cover; no bare ground. Dominant species *Bromus biebersteinii, Bromus inermis*. Well site 1.9 % bare ground, 38.3 % vegetation ground cover, 57.2 % litter, 61.7 % vegetation canopy cover. Dominant species *Bromus inermis*, *Elymus repens*. In 2 of 9 boreholes below 0.75 EC 2 to 6.5 dS m^{-1}, SAR 4 to 5.4 exceeds Alberta Tier 1; sodium 154 to 419 mg kg^{-1}, chloride 270 to 850 mg kg^{-1} exceeds BC guidelines; sulfate 10.4 to 1910 mg kg^{-1} elevated compared to others; pH 5.3 to 5.9 below guideline in two boreholes.

Well site guideline exceedances in two boreholes west of above ground storage tank area. Sulfate elevated compared to other samples. High values in Phase II from above ground storage tank area. Site located in wetter area than in south, salt might have leached, which could explain why did not get values like in past reports. Other boreholes in 2019 north of well area. Vegetation and ground cover similar between well site and reference. Vegetation healthy and tall.

Mean percent ground and vegetation cover on well site GNNF4 (14-07)

Category	Well Site	Reference
Bare Ground	1.9	0.0
Ground Vegetation	38.3	30.0
Litter	57.2	50.0
Total Canopy Cover	61.7	40.0
Salt Tolerant Species	6.7	0.0
Bromus biebersteinii	5.6	35.0
Bromus inermis	30.6	5.0
Elymus repens	14.4	0.0
Melilotus alba	5.0	0.0
Melilotus officinalis	1.7	0.0

SITE UC1 (14-30)

Site access by City of Medicine Hat. Site approximately 14 km from Medicine Hat in Dry Mixed Grass. Site ungrazed cultivated crop. Soil series Maleb,Orthic Brown Chernozemic; clay loam texture and fine grained. Site drilled 1980, produced 1981 to 1990. 2002 to 2007, abandoned 2013. Historical infrastructure well head, access road, pipeline. KCl water. No spills reported.

Phase II (2015) reports four areas of concern, well head, drilling waste disposal area, poor vegetation area, EM anomaly area. Drilling waste area EC 5.9 to 10 dS m^{-1} at 0.5 to 2 m, pH 9.4 at 0 to 0.5 m, boron 3.7 mg kg^{-1} at 0 to 2 m exceeded Alberta Tier 1; sodium 298 to 516 mg kg^{-1} at 0 to 2 m, chloride 329 to 976 mg kg^{-1} at 0 to 2 m exceeded BC guidelines; calcium 254 to 472 mg kg^{-1} at 0 to 2 m, magnesium 240 to 516 mg kg^{-1} at 0 to 2 m, sulfate 975 to 3430 mg kg^{-1} at 0 to 2 m elevated relative to others. Supplementary Phase II (2015) exceedance of guidelines for EC north east of well 7.68 to 8.3 dS m^{-1} at 1.5 to 2 m, background 6.31 dS m^{-1} at 1.5 to 2.0 m.

Reclamation commenced August 2014. 1632 m^3 of contaminated soil identified in Phase II. Reclamation proposal (2015) recommended excavation of contaminated soil and backfill with compatible soil from a local source. In 2019 half site seeded with *Hordeum vulgare*; half not seeded as at corner of property and not accessible to equipment. Reclamation ongoing.

Reference 28 % bare ground, 30 % vegetation ground cover, 40 % litter, 40 % vegetation canopy cover. Dominant species *Hordeum vulgare, Artemisia frigida*. Well site 59.6 % bare ground, 17 % vegetation ground cover, 14.5 % litter, 25 % vegetation canopy cover. Dominant species *Hordeum vulgare*. 0 to 1.5 m exceeds Alberta Tier 1 or BC guidelines for EC 0.32 to 10.5 dS m^{-1}, SAR 0.1 to 3.7, sodium 0.85 to 264.0 mg kg^{-1}, chloride 2.4 to 1240 mg kg^{-1}. Sulfate 3.8 to 1940 mg kg^{-1}, magnesium 4.9 to 400 mg kg^{-1}, calcium 0.8 to 439 mg kg^{-1} elevated relative to other samples.

From past reports, three of six boreholes at drilling waste disposal area. Drilling waste area EC above Alberta Tier 1; sodium, chloride above BC guidelines; sulfate, magnesium, calcium elevated relative to others. EC, sodium, chloride similar to past reports. Site dominated *Hordeum vulgare* in cultivated area, area not currently cultivated was dominated by *Agropyron pectiniforme* and *Bromus inermis*. Vegetation in non cultivated area doing poorly with patches of bare ground.

Mean percent ground and vegetation cover at well site UC1 (14-30)

Category	Well Site	Reference
Bare Ground	59.7	28.0
Ground Vegetation	17.0	30.0
Moss	0.0	1.0
Lichen	0.0	1.0
Litter	14.5	40.0
Total Canopy Cover	25.0	40.0
Salt Tolerant Species	22.0	20.0
Agropyron pectiniforme	1.5	0.0
Bromus inermis	1.7	0.0
Hordeum vulgare	17.0	20.0
Artemisia frigida	0.0	15.0
Aster species	0.0	5.0
Salsola kali	5.0	0.0
Taraxacum officinale	0.2	0.0

SITE UC2 (2-08-31)

Site access by Canadian Natural Resources Limited. Site approximately 18 km from Lloydminster in Central Parkland. Site is ungrazed cultivated crop. Soil series Beaverhills, Orthic Black Chernozem, on moderately fine till. Soils Chernozem with Solonetz and Gleysol soils. Soil sand to clay loam texture and fine grained. Site drilled 1969, produced 1969 to 1998, abandoned 2002. Historical infrastructure well head, pipeline, pipeline riser, pump jack, pad, above ground storage tank, electric motor and scrubber, electrical connections, access road. No spills recorded.

Phase II report (2013) reports Alberta Tier 1 guideline exceedances in SAR at well head 9.3 to 14.5 at 0 to 3.5 m, at above ground storage tank area 8.8 to 79 at 0 to 4 m, at EM anomaly area 10.5 at 3.0 to 3.2 m. EC exceeded Alberta guidelines at above ground storage tank area 5.28 to 9.4 at 0 to 4 m, EM anomaly area 11.8 at 3.0 to 3.2 m. In above ground storage tank area BC guidelines exceedances, sodium in two boreholes 224 to 924 mg kg^{-1} to 4 m with high values in surface soil 0 to 0.2 m; chloride in one borehole 267 to 1440 at 0 to 4 m with highest value in surface soil. Well head area ethylbenzene, F2, F3, and F4 hydrocarbons exceeded Alberta Tier 1 at 0.2 to 1 m; boron at 0.2 to 0.4 m. Above ground storage tank exceedances ethylbenzene, F2, F3, and F4 hydrocarbons at 0.5 to 1 m. Supplementary Phase II (2018) reports no guideline exceedances in SAR; hydrocarbons in historic locations including most contaminated 2013 boreholes. Most contaminated borehole in above ground storage tank area EC 5.64 at 0 to 0.2 m; sodium 246 to 316 mg kg^{-1}, chloride 1030 to 1120 mg kg^{-1} exceeded BC guidelines 0 to 2 m.

Flowlines, scrap metal, power poles removed 2013. Reclamation conducted in 2018. Total of 710 tonnes of soil landfilled during remediation and 30 loads of approximately 25 tonnes each of clean fill hauled onto site. Site seeded to *Avena sativa*.

Reference 30 % bare ground, 40 % vegetation ground cover, 30 % litter, 65 % vegetation canopy cover. Dominant species *Hordeum vulgare*. Well site 59.4 % bare ground, 21.4 % vegetation ground cover, 6.1 % litter, 35.6 % vegetation canopy cover. Dominant species *Hordeum vulgare*. 0 to 1.5 m EC 2.03 to 4.52 dS m^{-1}, pH 8 to 8.36 exceeds Alberta Tier 1; chloride 202 to 270 mg kg^{-1} exceeds BC guideline; sulfate 22.2 to 1220 mg kg^{-1} elevated relative to other samples. Reference exceedances at all depths EC 5.04 to 7.45 dS m^{-1}, SAR 4.68 to 5.71, sodium 157 to 391 mg kg^{-1}; sulfate 1680 to 2870 mg kg^{-1}.

Reference has naturally high sodium, sulfate at all depths, characteristic of Solonetzic soils. EC, SAR exceeds Alberta Tier 1 guidelines, but within ranges of Phase II background values. Sulfate considerably greater in 2019 than reported in 2013 and 2018; exception one 2018 borehole. On well site EC, chloride slightly above guidelines; sulfate elevated at some depth in boreholes south of above ground storage tank area. EC, sulfate higher in topsoil than at depth. Low values on well site and highest values in top 30 cm unexplained. Stunted vegetation near well centre, access road due to poor quality soil since historically not cultivated. Seeding 2018 so vegetation may not have yet established well.

Mean percent ground and vegetation cover on well site C2 (2-08-31)

Category	Well Site	Reference
Bare Ground	59.4	30.0
Ground Vegetation	21.4	40.0
Moss	12.2	0.0
Litter	6.1	30.0
Total Canopy Cover	35.6	65.0
Salt Tolerant Species	35.6	65.0
Hordeum vulgare	35.6	65.0

SITE UC3 (10-17)

Site access by Perpetual Energy. Site approximately 31 km from Vermillion in Central Parkland. Site ungrazed cultivated crop. Soil series Angus Ridge, Eluviated Black Chernozem; Beaverhills, Orthic Black Chernozem. These series have saline and sodic lower subsoils. Soil fine grained but due to layering of sand classified as coarse grained. Site drilled 1976, produced 1976 to 1998, abandoned 1998. Historical infrastructure was well head, riser, under ground storage tank, separator, production shack. No spills were reported.

Phase II (2006) investigated four areas of concern, well head, flare pit, drilling waste disposal area, EM anomaly area. Well head area EC 3.2 to 14.9 dS m^{-1} at 0.3 to 4.5 m, SAR 4.5 to 48.6 at 0.3 to 2.5 m exceeded guidelines; sodium 182.0 to 1650 mg kg^{-1} at 0.3 to 2.5 m, chloride 252 to 1210 mg kg^{-1} at 1.0 to 2.5 m exceeded BC guidelines. Benzene 0.08 mg kg^{-1}, toluene 0.41 mg kg^{-1} elevated at one hole near well head. Drilling waste disposal area EC 3.2 to 12.0 dS m^{-1} at 0.3 to 5.5 m, boron 2.7 mg kg^{-1} at 1.5 to 1.8 m above Alberta Tier 1. EM anomaly areas near well centre and production area explained by produced water moving down gradient. Sodium, chloride dominant ions likely due to introduction of produced water. Flare pit EC 3.2 to 9.7 dS m^{-1} at 0.3 to 3 m, SAR 5.3 and 29.2 mg kg^{-1} at 0.3 to 3 m exceeded Alberta Tier 1; sodium 178 and 1040 mg kg^{-1} at 0.3 to 3 m, chloride 270 mg kg^{-1} at 0.3 to 1 m exceeded BC guidelines. One background sample with elevated EC 3.97 dS m^{-1} at 2.5 to 3 m, SAR 4.8 at 0.3 to 1 m. Supplementary Phase II (2016) exceedances in EC 6.6 to 12 dS m^{-1}, SAR 11.2 to 37.4 at depth by well head, flare pit.

Infrastructure removed in 1998 to 1999, site reclaimed 1998 to 2000. At that time seeded to *Medicago sativa* and *Bromus* species mix. Currently seeded to *Avena sativa*.

Reference 75 % bare ground, 20 % vegetation ground cover, 5 % litter, 50 % vegetation canopy cover. Dominant species *Avena sativa*. Well site 54.4 % bare ground, 21.9 % vegetation ground cover, 23.7 % litter, 46.7 % vegetation canopy cover. Dominant species *Avena sativa*, *Thlaspi arvense*. Two of eight well holes EC 3.53 to 8.68 dS m^{-1} at 0.75 to 1.5 m, SAR 6.65 to 49.8 at 0.3 to 1.5 m exceeds Alberta Tier 1; sodium 310 to 1170 mg kg^{-1}, chloride 350 to 1800 mg kg^{-1} at 0.75 to 1.5 m exceeds BC guidelines. Reference soil pH 5.4 to 6.6 at 0 to 1.5 m below guideline.

Salinity and sodicity at depth common in soil series, though not found in reference. Reference pH lower than well site. On well site, 2019 boreholes close to well head, former production area, flare pit. EC, SAR, chloride, sodium above guidelines in three boreholes near well production area. All parameters increased with depth, opposite Phase II. SAR highest of all well sites for project. From historic data high sodium, chloride may be due to produced water. High bare ground, similar to surrounding cultivated fields. Vegetation stunted, sparsely distributed at well head.

Mean percent ground and vegetation cover on well site UC3 (10-17)

Category	Well Site	Reference
Bare Ground	54.4	75.0
Ground Vegetation	21.9	20.0
Litter	23.7	5.0
Total Canopy Cover	46.7	50.0
Salt Tolerant Species	35.6	47.0
Avena sativa	35.6	45.0
Fagopyrum esculentum	0.0	2.0
Taraxacum officinale	0.0	3.0
Thlaspi arvense	14.4	0.0

SITE UC4 (02-04)

Site access by Perpetual Energy. Site 42 km from Vermillion Central Parkland. Site ungrazed cultivated crop. Series Angus Ridge, Eluviated Black Chernozemic; Beaverhills, Orthic Black Chernozemic. Moderately sodic subsoils and non-Solonetzic B horizon. Soil clay till and sand texture and coarse and fine grained. Site drilled 1993, produced 1994 to 2003, abandoned 2003. Infrastructure well head, riser, methanol tank, separator, under ground water storage tank.

Phase II (2007) reports four areas of concern, well head, production area, drilling waste disposal area, under ground storage tank area. Under ground storage tank had a release of produced water which may have impacted well head and production areas; full extent of impact unknown. Under ground storage tank and area down gradient (north west) EC 3.2 to 8.9 dS m^{-1} at 1 to 6 m), SAR (4.2 to 4.3 at 2.0 to 6.0 m) exceeded Alberta Tier 1 guidelines; chloride (427 to 1380 mg kg^{-1} at 2 to 6 m, sodium 154 to 234 mg kg^{-1} at 2 to 6 m exceeded BC guidelines. Former separator area and one under ground storage tank area had high sulfate 412 and 531 mg kg^{-1}, respectively at depth relative to other samples. Drilling waste disposal area EC 3.77 dS m^{-1} at 0.15 to 1 m, SAR 7.1 to 20.3 at 0.15 to 2 m exceeded Alberta Tier 1; sodium 301 and 343 mg kg^{-1} at 0.15 to 2 m, chloride 207 and 396 mg kg^{-1} at 0.15 to 2 m exceeded BC guidelines.

Infrastructure removed in 2003, site reclaimed 2006 to 2007.

Reference 20 % bare ground, 20 %, vegetation ground cover, 60 % litter, 40 % vegetation canopy cover. Dominant species *Avena sativa*. Well site 36.7 % bare ground, 22 % vegetation ground cover, 41.3 % litter, 49.2 % vegetation canopy cover. Dominant species *Avena sativa*, *Taraxacum officinale*. Two of six boreholes on well EC 2 to 2.6 dS m^{-1}, SAR 4.3 to 6 exceeds Alberta Tier 1; chloride 270 to 480 mg kg^{-1} exceeds BC guideline. Reference pH 0 to 0.6 m 4.8 to 5.5 lowest.

2019 bore holes south east of well centre and south of drilling waste disposal area. No samples in under ground storage tank area or down gradient. On well site, EC, SAR slightly above Alberta Tier 1. Majority parameters increase with depth. Chloride exceedances in centre boreholes, not drilling waste disposal area. Well site greater bare ground, canopy cover than reference; vegetation tall, healthy at both.

Mean percent ground and vegetation cover at well site UC4 (02-04).

Category	Well Site	Reference
Bare Ground	36.7	20.0
Ground Vegetation	22.0	20.0
Litter	41.3	60.0
Total Canopy Cover	49.2	40.0
Salt Tolerant Species	43.3	35.0
Avena sativa	43.3	35.0
Cirsium arvense	0.8	0.0
Taraxacum officinale	5.0	5.0

SITE UNNF1 (05-29)

Site access by Esso. Site located in Devon approximately 26 km from Edmonton in Central Parkland. Site is ungrazed non native forage. Soil series Mundare, Orthic Black Chernozem on very coarse textured; Peacehills, Orthic Black Chernozem on moderately coarse textured. Soil silty clay, sandy silt to silty sand textured and coarse grained. Site has two wells, 100 and 102. Drilled 1951, produced 1951 to 1992 (100) and 1952 to 1967 (102), abandoned 1992. Historical infrastructure was well head, pump jack and turnaround, above ground storage tank, pipelines.

From Phase I (2011) release of an unknown volume of produced water in 1976 from satellite site south west of research site; contamination moving towards research site. Spill area remediated 1988 to 1993, drainage system installed and soil amended; stressed vegetation reported in 1994. Concerns raised by landowner about poor vegetation, potentially due to soil contamination. From Phase II (2016, 2019) multiple boreholes EC 2 to 7.9 dS m^{-1} at 0.3 to 5.3 m, SAR 4 to 5.3 at 0.45 to 5.9 m exceeded Alberta Tier 1; sodium 150 to 520 mg kg^{-1} at 0.1 to 1.9 m, chloride 260 to 1500 mg kg^{-1} at 0.1 to 2.4 m exceeded BC guidelines; sulfate 250 to 2500 mg kg^{-1} at 0.1 to 1.8 m elevated relative to other samples.

Partial reclamation certificate issued 1964 reduced size of site. Some remediation commenced 2005. Soil stockpile not recommended for use due to high EC, selenium, and boron. Soil excavated including former sump, garbage pit, and garbage pit fuel area. 1706 tonnes impacted soil removed, disposed, replaced. Reclamation started in 2015 and is still in progress.

Reference area 10 % bare ground, 65 % vegetation ground cover, 25 % litter, 44 % vegetation canopy cover. Dominant plant species are *Bromus inermis, Poa pratensis*. Well site 26.7 % bare ground, 36.1 % vegetation ground cover, 37.2 % litter, 32.7 % vegetation canopy cover. Dominant species *Medicago sativa*, *Taraxacum officinale*. At 0 to 1.5 m, EC 2.57 to 8.78 dS m^{-1}, pH 5.71 to 5.82 at 0 to 0.30 m exceeds Alberta Tier 1; chloride 200 to 2230 mg kg^{-1} exceeds BC guideline; calcium 8.9 to 970 mg kg^{-1} elevated compared to other samples.

Boreholes in 2019 accidentally advanced off well lease, adjacent on west side, south of access road, in potential area of historic produced water release. Reference borehole by main road, may not be representative of background conditions. EC exceeds Alberta Tier 1 guideline and chloride BC guideline below 0.60 m in all nine boreholes; calcium elevated under 0.6 m relative to other samples. A few patches of bare ground, vegetation growing but stunted with variable cover and height across site. High abundance of *Taraxacum officinale* for cultivated land.

Mean percent ground and vegetation cover on well site UNNF1 (05-29).

Category	Well Site	Reference
Bare Ground	26.7	10.0
Ground Vegetation	36.1	65.0
Litter	37.2	25.0
Total Canopy Cover	32.7	44.0
Salt Tolerant Species	35.3	0.0
Bromus biebersteinii	1.1	0.0
Bromus inermis	10.6	45.0
Poa pratensis	0.0	30.0
Medicago sativa	35.3	0.0
Taraxacum officinale	11.7	5.0