THE USE OF LAND MANAGEMENT PRACTICES TO RECLAIM BRINE-AFFECTED CROPLAND SOILS AND RESTORE SHRUB INVADED RANGELAND

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Dylan John Bartels

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Dylan John Bartels

The Supervisory Committee certifies that this *disquisition* complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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SUPERVISORY COMMITTEE:

Dr. Kevin Sedivec
Co-Chair

Dr. Michael Undi
Co-Chair

Dr. Ryan Limb

Dr. Thomas DeSutter

Approved:

10/21/2021
Date

Francis Casey
Department Chair

ABSTRACT

Land management techniques can enhance altered ecosystems on a variety of landscapes. In the Williston Basin of North Dakota, brine ponds created 50 years ago still cause problems today. We applied six treatments to reclaim the A-horizon of brine-affected soil on six legacy brine ponds and monitored soil nutrients until 23 months after treatment. We found that from 0-15 cm, all treatments were significantly better at reducing electrical conductivity than the control. In addition, sodium adsorption ratio was reduced at all depths over time. In Southcentral North Dakota, we monitored the effects of fire and grazing on colonies of western snowberry (*Symphoricarpos occidentalis*), an invasive woody shrub. Prescribed burning had a significant effect on western snowberry by reducing the number of mature plants and increasing the number of new shoots/m^2. By incorporating drone aerial imagery, we helped develop an increasingly useful tool in vegetation monitoring.

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DEDICATION

I dedicate this work to my great-grandmother Bernice Bartels

and my grandfather Dr. John H. Kok.

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1. LITERATURE REVIEW

Brine Contamination Associated with Energy Development in North Dakota

History of Williston Basin Brine

The Williston Basin is a geologic region that covers parts of Montana, North Dakota, and South Dakota in the United States, and Saskatchewan and Manitoba in Canada (Gleason et al. 2014). This is a major oil-producing region in North America. While production initially began early in the 20th century in Montana, it increased in the 1950's and is now one of the leading regions for oil and natural gas production in the United States (Gaswirth et al. 2015, Gleason et al. 2014). As of 2010, over 30,000 wells were located within the Williston Basin, with the majority (about 18,000) found in North Dakota (Gleason et al. 2014). North Dakota is ranked second to Texas in oil and natural gas production, with drilling and its associated activities contributing $1.6 billion to the state's annual tax revenue (USEIA 2020).

The region associated with the Williston Basin was created during the Ordovician period after a shear between the Brockton-Froid fault zone and the Transcontinental arch (Gerhard and Anderson, 1988). The resulting geographic action formed a depression where the Williston Basin lies today. Since the Ordovician period, the Williston Basin has comprised of multiple formations that produce oil, including the Three Forks and Bakken Formations (Anna et al. 2008, Gaswirth et al. 2013). These formations are rich in organic matter which attributes to the amount of oil they produce. An assessment of undiscovered oil and gas resources in the Williston Basin by Anna et al. (2008) found an estimated 3844 million barrels of oil, 3705 billion cubic feet of gas, and 202 million barrels of natural gas liquids. Clearly, oil and gas production will continue to be an important commodity of the region's economy.

Oil production in North Dakota has increased exponentially since the turn of the century (Gaswirth et al. 2013). One of the most notable challenges associated with oil drilling is brine. Brine is a solution of water and dissolved solids (predominantly salts) with a total dissolved solids (TDS) metric of at least 35,000 mg/L (Kalkhoff 1993, Veil and Clark 2011). On occasion, salinity levels in brine can reach five times greater than that of the ocean (Gregory et al. 2011). Brine is the primary bi-product of oil and gas production, and in some cases, 18 barrels of brine are produced for each barrel of oil (Murphy et al. 1988, Veil and Clark 2011, Gregory et al. 2011, Green et al. 2019).

Collecting and disposing of brine has always been a concern to drilling companies during the extraction process. Being largely unregulated during the beginning of oil production until 2010 in the Williston Basin, producers excavated unlined reserve pits (brine ponds) where the brine was deposited (Gleason et al. 2014). From early on, researchers noticed that these legacy brine ponds were beginning to have a detrimental effect on the surrounding ecosystem (Grandone and Schmidt 1943). While brine disposal is now more highly regulated, brine still creates problems on these legacy brine ponds as well as spills from pipelines (Green et al. 2020a). When brine contaminates an area or landscape, it often results in the immediate mortality of the vegetative community (Murphy et al. 1988). While this acute impact on the spill area is unfortunate, the chronic effect of brine spills on the soil is much more worrying (Murphy et al. 1988, Gleason et al. 2014).

Compounding all of the problems associated with brine are the specific characteristics of the brine found within the Williston Basin. The TDS metric of brine found in the Williston Basin can be greater than 450,000 mg/L, which is some of the most highly concentrated brine in the United States (Otton 2006, Klaustermeier et al. 2017). Over 90% of the dissolved solids within

Williston Basin brine is sodium chloride (NaCl) (Veil and Clark 2011), a salt which has a high solubility in water (Day et al. 2019, Haynes 2014). The impact of brine spills on the landscape makes for chemical and physical conditions similar to those soils classified as saline-sodic (He et al. 2015).

Brine ponds were typically constructed adjacent to well pads in the 1970s and 1980s. The semi-arid climate of the Williston Basin causes the water in the brine solution to evaporate, allowing the dissolved salts to migrate down into the soil profile. In a semi-arid climate, transpiration is often greater than evaporation. The high osmotic potential of the salts draws up water from deeper within the soil profile (Jambhekar et al. 2015), further exacerbating the salinity and even forming hard crusts on the soil surface (Qadir et al. 2007).

Salinity is one of the main abiotic factors that negatively affects crop yields worldwide (Isla et al. 1998, El Hasini et al. 2019). Plants vary in their response and tolerance to salinity. High salinity increases osmotic stress (Thapa et al. 2017) and high rates of sodicity can affect soil water holding capacity (He et al. 2015), reduce root penetration (Wamono et al 2016b), increase soil erosion (El Hasini et al. 2019) and negatively impact soil stability (Pils et al. 2007). These physical changes in the soil structure have a negative impact on the edaphic properties of soils. It is widely reported that salinity negatively affects seed germination (Munn and Stewart 1989, Neuman 1997, Askari et al. 2016, Dantas et al. 2019, Green et al. 2020a). High levels of salinity also reduce grain yield (Dang et al. 2006), limit plant available water (Bauder et al. 2008), and reduce photosynthesis in plant tissue (Neumann 1997).

Plants are unable to take up water through its roots when concentrations of Na are too high (Scagel et al. 2019). When a high presence of Na occurs in the soil, plants take up toxic levels of Na (Murphy et al. 1988). High Na content can result in Ca and Mg deficiencies (Scagel et al. 2019). In terms of soil properties, high levels of sodium can break up soil aggregates causing a decrease in aeration and conductivity (Chavez-Garcia and Siebe 2019). This is a process known as dispersion (Zhang and Norton 2002), where Na in the presence of high EC reduces swelling potential of clays (He et al. 2015). Sodium has a lower electrical charge and greater radius than other cations it replaces (e.g. Ca), causing bonds between clay particles to break down (Pils et al. 2007).

While plant production on saline-sodic soils is one concern, soil workability poses another constraint for farmers. Increased Na can contribute to the likelihood of hard-setting which leaves soils difficult to cultivate when dry (Wamono et al. 2016a). When soil is wet, its trafficability, or ability to support machinery becomes severely diminished making it even more difficult for use in farm production (Wamono et al. 2016b). While the chemical restraints described above make it hard for plants to thrive, physical soil conditions resulting from reduced trafficability and increased hard-setting can affect plant health (Green et al. 2020a).

Past reclamation techniques

Vertical movement of salts in brine affected soils occurs (Chen et al. 2016, Chen et al. 2019), but even more detrimental is the horizontal migration of brine leachate (Murphy et al. 1988). Horizontal migration of brine leachate can increase the amount of farmable soil that is susceptible to the negative effects of brine. Previous research has focused on reclamation efforts to improve soil properties such as bacterial and fungal communities (Feng et al. 2019, Cheng et al. 2019), soil workability and cultivation (Wamono et al. 2016a, Wamono et al. 2016b), and plant performance (El Hasini et al. 2019, Chavez-Garcia and Siebe 2019). Various amendments used to reduce soil salinity and sodicity have been used and studied. Manure, hay, biochar and compost are some of the most widely used biological amendments. Common chemical amendments include elemental sulfur, langbeinite, and gypsum (Wahid et al. 1998, Oster et al. 1999, El Hasini et al. 2019, Day et al. 2019, Cheng et al. 2019, Chavez-Garcia and Siebe 2019). As an amendment, the high concentration of Ca in gypsum allows for the displacement of Na and other soluble minerals to leach further in the soil profile (Qadir et al. 2001).

Shaygan et al. (2018) recognized the importance of vegetative cover in saline-sodic soil reclamation efforts. Response to salinity varies widely throughout the plant community depending on the growth stage of the plant (Ogle and St. John 2010). There are two main types of plants to consider when attempting revegetation of a brine-affected area: salt-tolerant halophytes and salt-intolerant glycophytes (Zhang et al. 2010). Some native grasses such as alkali sacaton (*Sporobolus airoides*) have a high tolerance to salinity and used in reclamation and revegetation efforts (Ogle and St. John 2010, Pessarakli et al. 2017). Barley and canola are glycophytic crops used on saline environments, with barley having the ability to grow in these conditions (Isla et al. 1998, Dang et al. 2006, Ogle and St. John 2010, Zhang et al. 2010). Alfalfa has low salinity tolerance (Ogle and St. John 2010), but there have been some genes showing salt tolerance in this forage crop (Sun et al. 2016, Kearl et al. 2019, Wang et al. 2019)

Increasing soil organic matter (SOM) through addition of amendments or establishment of plants can improve soil properties such as water holding capacity, cation exchange capacity (CEC) and trafficability (Wahid et al. 1998). Recent studies have proposed layering amendments within the soil profile (Zhang et al. 2008, Chavez-Garcia and Siebe 2019, Chen et al. 2019). Some studies found that the heterogeneous spread of salinity through the soil profile helped increase vegetative growth (Chen et al. 2019).

In previous research, methods of soil amendment application have varied, but there has been a focus on small-scale research due to limited space (Chavez-Garcia and Siebe 2019, Day et al. 2019). One study even proposed a new reclamation method that used a moisture wicking material to draw salts out of the soil (Green et al. 2019). Again, this study was a small-scale project, with foreseen problems associated with expanding on larger land areas. Green et al. (2020b) performed a comprehensive review of past reclamation methods both in-situ and ex-situ.

Western Snowberry (*Symphoricarpos occidentalis*) Response to Grazing and Fire

The temperate grassland landscape has been severely altered by human activity, leading to ecosystem conversion and diminishing biodiversity (Sher and Primack 2019). As the earth's atmosphere began to warm and precipitation in some areas diminished, graminoids dominated the landscape forming grasslands (Stromberg 2011). Animals soon followed as grazers of all shapes and sizes evolved to take advantage of this new dominant vegetation (Hillenbrand et al. 2019). Covering 27% of Earth's terrestrial land, temperate grasslands are an important contributor to agriculture and an area of economic interest (Henwood 1998, Geaumont et al. 2019). Historic grasslands are easily converted to anthropogenic systems such as crop land and pasture (Sher and Primack 2019). As a result, many grasslands have experienced a change in ecosystem function as areas have been transformed (Kaskie et al. 2019). Much of the converted grasslands provide food for a growing global population. Historically, evolution and upkeep of grassland systems was maintained through natural abiotic disturbances such as fire (Canadell et al. 1991, Gross and Romo 2010, Scasta et al. 2014) and grazing (Fuhlendorf and Engle 2001, Bai et al. 2009, Scasta et al. 2016). Research has pointed to the resulting implications of the removal of grazing and fire disturbances of which encroachment of woody species is a chief concern (Van Auken 2000, Knapp et al. 2008, Kaskie et al. 2019, Johnson et al. 2019).

Encroachment of woody species onto temperate grassland ecosystems has had significant ramifications in terms of reduced biodiversity and forage production (Bowes and Spurr 1995, Ratajczak et al. 2012, Teleki et al. 2020). Initially, warm-season (C_4) grasses dominated much of the Great Plains region, containing a high plant species diversity (Miles and Knops 2009). The region experienced significant loss of habitat and change in ecosystem function (Michel et al. 2020). Species composition homogenized and transitioned to being largely dominated by non-native cool-season (C_3) grasses and woody species, in turn impacting how carbon is stored in the ecosystem (Gehring and Bragg 1992, Briggs et al. 2002, Grant et al. 2020). The transition from graminoids to woody species results in unnatural levels of carbon and nitrogen which alters the soil health (McKinley and Blair 2008, Bai et al. 2009). Some woody species tend to colonize through rhizomatous reproduction and sprouting (Defelice 1991, Nesmith et al. 2006). Reduction of sunlight and decreased heat below canopies of woody species also plays a role in reducing graminoid presence in encroached areas (Gehring and Bragg 1992). The change in species composition associated with woody encroachment on rangelands has reduced productivity of grazable forage (Bowes and Spurr 1995). From a livestock production standpoint, woody species produce less forage than desirable herbaceous plants such as grasses (Defelice 1991, McCarty 1967, Van Auken 2000).

The Northern Great Plains (NGP) comprises areas from Nebraska in the United States to Alberta and Manitoba in Canada (Hendrickson et al. 2019). This region largely formed as the result of glaciation, most recently the Wisconsin Glaciation, which ended about 10,000 years ago (Coleman 1930, Hobbs 1945). Much of this region was converted to farmland, although a large portion is still characterized as native range and makes up a significant amount of North America’s rangeland (Barker and Whitman 1988). Samson and Knopf (1996) described the Great Plains as the continent’s most endangered ecosystem. Historically, these areas were grazed by large ungulates such as bison (*Bison bison*), elk (*Cervus canadensis*) and bighorn sheep (*Ovis* *canadensis*)(Matthiessen 1959). Today, most grazing is by domestic livestock (Augustine et al. 2019). Change in grazing disturbance and reduction in fire frequency has resulted in population increases of many native shrubs and woody plants, including western snowberry.

Western snowberry (*Symphoricarpos occidentalis*), also known as buckbrush or wolfberry, is a perennial shrub that has benefited from the alteration of grasslands in the NGP (McCarty 1967, Bai et al. 2009). It is a deciduous shrub measuring 30 to 100 cm in height with an extensive distribution ranging from the Canadian territories, south to Utah and east to Michigan (Pelton 1953). Western snowberry often reproduces through rhizomes, enabling the establishment of large colonies (Sbatella et al. 2011). Stems of western snowberry can form relatively close together, forming canopy covers up to 93% (Manske 2006). These dense colonies reduce underlying forage production while creating a physical deterrent to cattle, which may result in reduced stocking rates on rangeland with widespread western snowberry populations (Manske 2006, Sbatella et al. 2011). As grass vegetation reduces so does potential competition, meaning western snowberry colonies tend to spread under these conditions.

The yellowish-white fruits of western snowberry are a food source for many grassland birds, providing opportunity for seeds to establish new colonies (McCarty 1967). Although not commonly selected by cattle, Doucette et al. (2001) found western snowberry can be propagated by cattle since nearly 70% of consumed seeds found in cattle feces are viable. Western snowberry is adaptable to a wide range of conditions and has been observed growing on both northern and southern slopes, and in wet and dry conditions (McCarty 1967). The growth characteristics and resiliency of this woody shrub make it a very competitive plant on rangelands (Sbatella et al. 2011).

Understanding how to manage western snowberry is essential in terms of increasing biodiversity and agricultural usability in the NGP. With a diet consisting of up to 90% grass, cattle are an important domestic grazer for producers across the Great Plains (Benavides et al. 2009, Hillenbrand et al. 2019). Cattle rarely browse on woody species; therefore, in woody species encroachment can greatly diminish herbaceous plant production potential (Adams and Bailey 1983, Celaya et al. 2007).

The invasion of woody species is largely the result of the modification of historic prairie ecosystems to largely agricultural systems (Grant et al. 2020). Western snowberry is one woody shrub that has caused a reduction in quality grazing lands throughout the NGP (McCarty 1967, Manske 2006, Bai et al. 2009, Sbatella et al. 2011). Through understanding the life history of western snowberry and shrubs like it, we can improve management techniques to help reduce the extent of woody invasion while subsequently increasing agricultural production. Being one of the most abundant shrubs in the region, western snowberry has been the subject of many studies seeking to find effective control methods (McCarty 1967, Defelice 1991, Bowes and Spurr 1996, Johnson et al. 2019).

Rangeland forage quantity can be increased through chemical control of western snowberry (Bowes and Spurr 1995, Bowes and Spurr 1996, Sbatella et al. 2011). Chemical herbicides such as metsulfuron methyl (Bowes and Spurr 1995, Sbatella et al. 2011), 2,4-Dichlorophenoxyacetic acid (Bowes and Spurr 1996, McCarty 1967), and aminopyralid (Sbatella et al. 2011) have been shown to control or reduce western snowberry. Overall, these studies did show that chemical herbicide is a land management technique that can successfully reduce western snowberry while increasing forage production for cattle. However, chemical application can be time consuming, expensive, and can reduce the population of desirable rangeland plants.

Mobilization of chemical application equipment can also be problematic in adverse terrain conditions.

While mature woody stems are generally unpalatable to cattle, some research has attempted to reduce colonies of western snowberry by grazing with alternative livestock such as goats (Smart et al. 2006). Because they have a smaller body than cattle and more malleable mouth parts, goats can consume a higher quantity of shrubs and forbs (Mellado and Olvera 2008, Benavides et al. 2009). Smart et al. (2006) found that browsing of western snowberry with goats greatly reduced colony heights and increased grass coverage. In terms of livestock production, goats are not as common in the Great Plains as cattle.

Additional methods of control have incorporated the use of grazing strategies (Kirby et al. 1988, Smart et al. 2006, Johnson et al. 2019), prescribed fire (Anderson and Bailey 1979, Scasta et al. 2014) and mechanical mowing (Adams and Bailey 1983, Manske 2006). Scasta et al. (2014) found that length of shoots of coralberry (*Symphoricarpos orbiculatus*) were much shorter following prescribed fire as opposed to unburned plants. While height of plants may decrease, fire disturbances increased stem density as the colonizing roots increase vegetative production in the form of new stems (Anderson and Bailey 1979). Although stem density tends to increase following fire, new stems are more palatable to cattle than mature, woody stems. Johnson et al. (2019) found the use of a patch-burn grazing increased the amount of western snowberry grazed by cattle.

In order to understand why patch-burn grazing can be effective, it is necessary to understand how shrubs and broadleaf plants respond to defoliation. Research has shown that evolutionary facilitation between grasses and herbivores was unlikely, yet grasses are better adapted to grazing disturbances than forbs and shrubs (Belksy 1986, Strauss and Agrawal 1999).

Herbivores on grasslands generally graze from the top of the plant down. The growing point of grasses is strategically located at or just above ground level, which protects it from defoliation. The growing point of broadleaf plants is located at the end of the stem, which inherently makes them more easily accessible to foraging herbivores. Due to the location of the growing point, land managers can take advantage of this growth characteristic and use mechanical treatments to control western snowberry (Adams and Bailey 1983). Repetitive removal of the growing point can lead to death of the plant (Manske 2006).

Research Objectives

Research objectives for the brine pond reclamation project are to (1) see how our novel reclamation technique alters EC, SAR, and Cl in the soil and (2) see which treatment is best at reducing the negative effects of salinity associated with historic brine ponds. In addition, our study into restoring native rangeland from woody encroachment, we aim to (1) re-establish historic disturbances on native rangeland with western snowberry colonies, (2) understand which how burning and grazing affect forage production and ecosystem biodiversity in rangeland where western snowberry has encroached.

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2. RECLAIMING BRINE-POND SITES IN NORTH-CENTRAL NORTH DAKOTA WITH THREE SOIL AMENDMENTS

Abstract

Produced water or brine, is a highly saline aqueous solution that is the primary byproduct of oil and gas production. The Williston Basin in North Dakota is a major oil producing region in the United States. During an early boom in oil production in the Williston Basin, brine was set in shallow evaporation pits near well pads, these sites are now subject to extreme soil salinity and sodicity. We selected six brine pond contaminated sites with differing electrical conductivity levels in northcentral North Dakota. We used amendments to create a barrier from salts, increase organic matter (manure and hay), and increase calcium (gypsum) in the soil. We removed the A-horizon of the soil and incorporated five amendment treatments (gypsum, hay, manure, gypsum + hay, gypsum + manure) and a control using a randomized block design with six replicates. The A-horizon was re-spread and amendments applied on the same sub-plots after receiving 5 cm of rain. We collected soil samples pre-treatment, and four, 11-, and 23-months post-treatment to assess changed in soil chemical properties. Sodium adsorption ratio (SAR) was reduced 23 months post-treatment for all treatments from 0-15 cm. Electrical conductivity (EC) had an overall decrease in EC 23 month's post-treatment, with hay and manure treatments the most different from the control. Our reclamation method can be used to effectively lower EC in the A-horizon soil which can enable vegetative growth on historic brine ponds.

Introduction

The Williston Basin is a geologic region associated with oil production that covers parts of Montana, North Dakota, and South Dakota in the United States, and Saskatchewan and Manitoba in Canada (Gleason et al. 2014). The region associated with the Williston Basin was created during the Ordovician period after a shear between the Brockton-Froid fault zone and the Transcontinental arch (Gerhard and Anderson, 1988). The resulting geographic action formed a depression where the Williston Basin lies today. Since the Ordovician period, the Williston Basin has comprised of multiple formations that produce oil, including the Three Forks, Bakken, and Old Madison Formations (Anna et al. 2008, Gaswirth et al. 2015). Oil production first began in 1951 and has historically been an important source of revenue for the state of North Dakota (Murphy et al. 1988, Gleason et al. 2014, Gaswirth et al. 2015). Today, North Dakota is ranked second to Texas in oil and natural gas production, with drilling and its associated activities contributing $1.6 billion to the state's annual tax revenue (USEIA 2020).

Brine is a solution of water and dissolved solids (predominantly salts e.g., NaCl) often with a total dissolved solids (TDS) concentration of greater than 35,000 mg/L (Kalkhoff 1993, Veil and Clark 2011). Brine is the primary byproduct of oil and gas production, and in some cases, 18 barrels of brine are produced for each barrel of oil during the early stages of the well's life (Murphy et al. 1988, Ahmadun et al. 2009, Veil and Clark 2011, Gregory et al. 2011, Green et al. 2019). The TDS metric of brine found in the Williston Basin can be greater than 450,000 mg/L, which is some of the most highly concentrated brine in the United States (Otton 2006, Klaustermeier et al. 2017). Over 90% of the dissolved solids within Williston Basin brine is sodium chloride (NaCl) (Veil and Clark 2011), a salt which has a high solubility in water (Haynes 2014, Day et al. 2019).

Historically, brine was recognized as something that could inflict serious environmental harm if not dealt with properly (Knox and Cantor 1980). Brine spills, where soil is exposed to brine unintentionally, can cause severe immediate and chronic detriments to the environment and have been a problem throughout the history of oil production (De Jong 1982, Murphy et al. 1988, Gleason et al. 2014, Green et al. 2020a). When oil production first began in North Dakota, brine disposal was not highly regulated, as it was predominately disposed of in evaporation pits or brine ponds (Murphy et al. 1988, Gleason et al. 2014). The advantage of this type of brine disposal was that oil and gas production companies could dispose of brine close to where it was extracted at relatively low cost (DeWalle and Galeone 1990). The brine ponds would then be covered with soil and left with relatively little effort towards monitoring or remediation. Brine ponds are no longer an acceptable form of disposal, but these historic brine ponds still cause problems today.

In a semi-arid climate, evaporation is often greater than precipitation (Jurinak 1990, Alberti et al. 2009). The high osmotic potential of the salts draws up water from deeper within the soil profile (Jambhekar et al. 2015), further exacerbating the salinity and even forming hard crusts on the soil surface (Kieffer and Ungar 2002, Qadir et al. 2007). The increased presence of NaCl in the soil can cause problems for ground water in the interior United States (Boyce 1935). Sodium Chloride is easily moved through the soil profile making the negative effects of chloride more widespread than initial soil contact (Richardson et al. 1988, Murphy et al. 1988) (Figure 2.1). The impact of brine ponds on the landscape makes for chemical and physical conditions similar to saline-sodic soils (De Jong 1982, He et al. 2015).

Plants vary in their response and tolerance to salinity. However, high rates of salinity can increase osmotic stress (Thapa et al. 2017), reduce soil water holding capacity (He et al. 2015), reduce root penetration (Wamono et al 2016), increase soil erosion (El Hasini et al. 2019) and negatively impact soil stability (Pils et al. 2007). These physical changes in the soil structure have a negative impact on the edaphic properties of soils. It is widely reported that salinity negatively affects seed germination (Munn and Stewart 1989, Neumann 1997, Askari et al. 2016, Dantas et al. 2019, Dornbush et al. 2020, Green et al. 2020a). High levels of salinity also reduce grain yield (Dang et al. 2006), limit plant available water (Bauder et al. 2008), reduce photosynthesis in plant tissue (Neumann 1997) and eventually lead to death (Bui 2013). This means brine ponds and the areas they affect can remain unvegetated unless remediation is attempted.

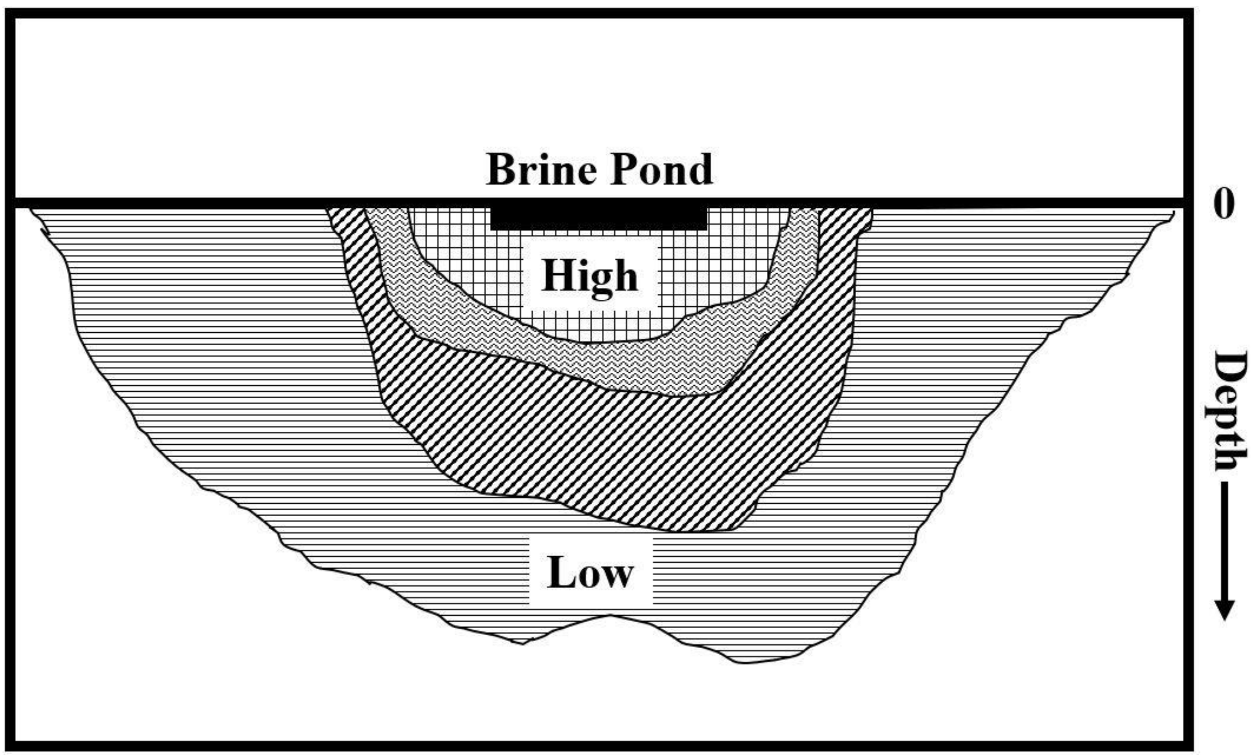

Figure 2.1. The effects of salts around a brine pond are much wider reaching than the initial brine pond itself (source: Murphy et al. 1988). High concentrations of NaCl are shown closer to the brine pond with low concentrations further away. The image shows how NaCl can leach through the soil profile vertically and horizontally negatively impacting plant ecology.

In previous research, methods of soil amendment application have varied, but there has been a focus on the small-scale research due to limited space (Chavez-Garcia and Siebe 2019, Day et al. 2019). One study even proposed a new reclamation method that used a moisture wicking material to draw salts out of the soil (Green et al. 2019). Again, this study was a small-scale project, with foreseen problems associated with expanding on larger land areas. Green et al. (2020b) performed a comprehensive review of past reclamation methods both in-situ and ex-situ.

A relatively cost-effective form of in-situ reclamation is performed by removing the soil A-horizon and blending in soil amendments to alleviate negative effects of Na (Dornbusch et al. 2020).

Various amendments used to reduce soil salinity and sodicity have been used and studied. Manure, hay, char and compost are some of the most widely used biological amendments while common chemical amendments include elemental sulfur, langbeinite, and gypsum (De Jong 1982, Wahid et al. 1998, Oster et al. 1999, Chavez-Garcia and Siebe 2019, Cheng et al. 2019, Day et al. 2019, El Hasini et al. 2019, Dornbusch et al. 2020). As an amendment, gypsum's high Ca concentration allows for the displacement of Na and other soluble minerals to leach further in the soil profile (Qadir et al. 2001). Organic amendments can provide plants with soil nutrients and reinvigorate soil microbiology while acting as a barrier between brine affected soils below (Chavez-Garcia and Siebe 2019, Green et al. 2020b)

Historic brine ponds continue to be obstacles for farmers in oil producing regions (Aschenbach and Kindscher 2006, Zhang et al. 2008). Golder Associates Inc. found 216 historic brine ponds in Bottineau, Renville, and Ward Counties, North Dakota that ranged in size from ten to thousands of square meters (Golder 2018). These brine ponds cover 21 hectares of land and very few of them have been reclaimed. The soils found on these brine ponds are poor options for agricultural production due to the high levels of salts and sodium (Isla et al. 1998, Pils et al. 2007, Thapa et al. 2017, El Hasini et al. 2019). The negative effects of brine on the soil can reach great depths (Figure 2.1) and reclaiming the soil to eliminate these effects is extremely costly. Our hypothesis is that reclaiming the soil to rooting depth can help revegetate legacy brine ponds and improve productivity for farmers in oil producing regions. The objectives of this study were to (1) examine how our novel reclamation process plays a role in reclaiming soils effected by brine pond sites and (2) determine which amendment works best at reducing EC, SAR, and Cl.

Methods

<u>Site Description</u>

Six brine pond sites in near Glenburn, North Dakota (48.5131° N, 101.2207° W) were systematically chosen based on EC_e levels to represent the gradient from low to high brine concentration. Two sites for each of the following EC_e levels were chosen: low EC_e (maximum of 16 dS/m), mid EC_e (maximum of 28 dS/m) and high EC_e (maximum of 56 dS/m). Glyndon soil series was prevalent and taxonomically classified as coarse-silty, mixed, superactive, frigid Aeric Calciaquolls before reclamation efforts. Common agricultural crops in the area include canola (*Brassica spp.*), spring wheat (*Triticum aestivum*) and soybeans (*Glycine max*). The region surrounding our brine pond sites is characterized as being semi-arid. Average air temperature is 5°C while average rainfall is 37.36 cm per year (NDAWN) (Table

Table 2.1. Yearly average air temperature and total rainfall in Glenburn, ND for duration of the study as well as 30-year average.

Year	Avg. Air Temp	Total Rainfall
2018	4°C	26.42 cm
2019	3°C	47.32 cm
2020	6°C	20.42 cm
Average	5°C	37.36 cm

<u>Experimental Design</u>

Treatments

We tested five amendments (gypsum, gypsum + manure, gypsum + hay, manure, hay) and a non-treated control. Manure was from stockpiled cattle manure less than a year old. Hay was from round grass bales 1.75 x 2 m in size and at 87 percent dry matter ground to create hay segments 2.5 to 5 cm long. Gypsum ($CaSO_4*2H_2O$) was transported from a coal powerplant near Washburn, ND.

Brine Ponds

All study sites were previously in crop production prior to the onset of this experiment. In May 2018, six 18.3 x 36.6 m sites were established within the center of brine ponds and removed from crop production. A 15.2 x 30.5 m block was established in the center of each site and divided into six sub-plots measuring 7.3 x 9.8 m (71 m^2). These sub-plots were larger than previous reclamation research: 0.24 m^2 (El Hasini et al. 2019), 0.28 m^2 (Day et al. 2019) and 1.0 m^2 (Chavez and Siebe 2019). Experimental treatments were randomly assigned to each sub-plot. Each site was classified as a replicate and extended either north to south, or west to east depending on the brine pond orientation (Figure 2.2).

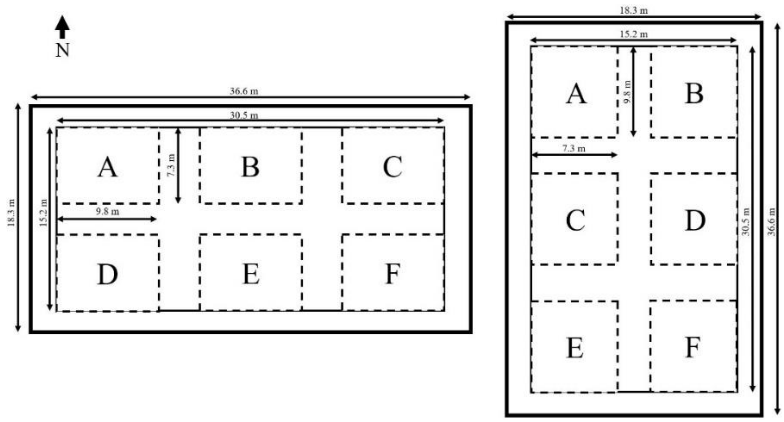

Figure 2.2. Site layout with plots oriented west to east on the left and north to south on the right. Each treatment (gypsum, gypsum + manure, gypsum + hay, manure, hay, control) was assigned randomly on each sub-plot (A-F).

Reclamation Process

All sub-plots were randomly assigned an amendment treatment and control for each study site prior to starting the reclamation process. Sub-plots were spaced half a meter apart to ensure there was no treatment spill-over (Figure 2.2). After the initial soil samples were collected from each sub-plot (mid-May, 2018), the A-horizon (0-20 cm) was removed from each study block using a bulldozer (Figure 2.3). Treatment amendments were applied to their respective sub-plot after removal of the A-horizon. Amendments were applied at a rate of 9,000 kg/ha for both manure treatments, 9,000 kg/ha of gypsum on all three gypsum treatments, and 1,100 kg/ha grass hay on both hay treatments (Table 2.2). Application rates remained the same when two different amendments were applied (e.g. hay + gypsum treatment would = 9,000 kg/ha gypsum + 1,100 kg/ha hay). Each treatment was applied directly to their respective sub-plot using a skid-steer tractor (Figure 2.3) immediately following delivery to research site. A rotary cultivator was used to incorporate the amendments into the soil (exposed B-horizon; Figure 2.3). The goal was to apply each treatment to a depth of about 25 cm. After receiving 3.78 cm of rainfall (NDAWN) on all the blocks to help incorporate the amendments, the A-horizon was re-spread using a skid-steer, leveled and harrowed mid-June 2018. Setting water on each site was allowed to dissipate, leaving the soil dry and ready for the next step in the reclamation process.

Amendments were applied for a second time (on the A-horizon) to their corresponding sub-plot at the same rates as the first application (Table 2.2). Following the application of treatments using a skid-steer tractor, the amendments were dug into the soil profile using the rotary soil cultivator attachment. The sites were again left undisturbed for four weeks after the second amendment was applied for 10 cm of rainfall (NDAWN) to incorporate amendments into the soil (Figure 2.3). After the reclamation process was completed, there were two layers of amendments encompassing the A-horizon and upper level of the B-horizon (Figure 2.4).

Figure 2.3. Top left image showing the removal of A-horizon using a bulldozer. Top right depiction of how amendments were applied to the treatment sub-plots (amendment pictured here is gypsum). Bottom left shows tilling in the amendments to the B-horizon. Bottom right shows a plot after the reclamation process with plots staked and ready for planting of cover crop.

Table 2.2. Application rates for each of the amendments. Rates were the same for both first (on B-horizon) and second (on A-horizon) applications. Amendments were applied on six Legacy brine sites in northcentral North Dakota in 2018.

Treatment	Application Rate
Manure only	9,000 kg/ha
Hay only	1,100 kg/ha
Gypsum only	9,000 kg/ha
Gypsum + Hay	9,000 kg/ha + 1,100 kg/ha
Gypsum + Manure	9,000 kg/ha + 9,000 kg/ha

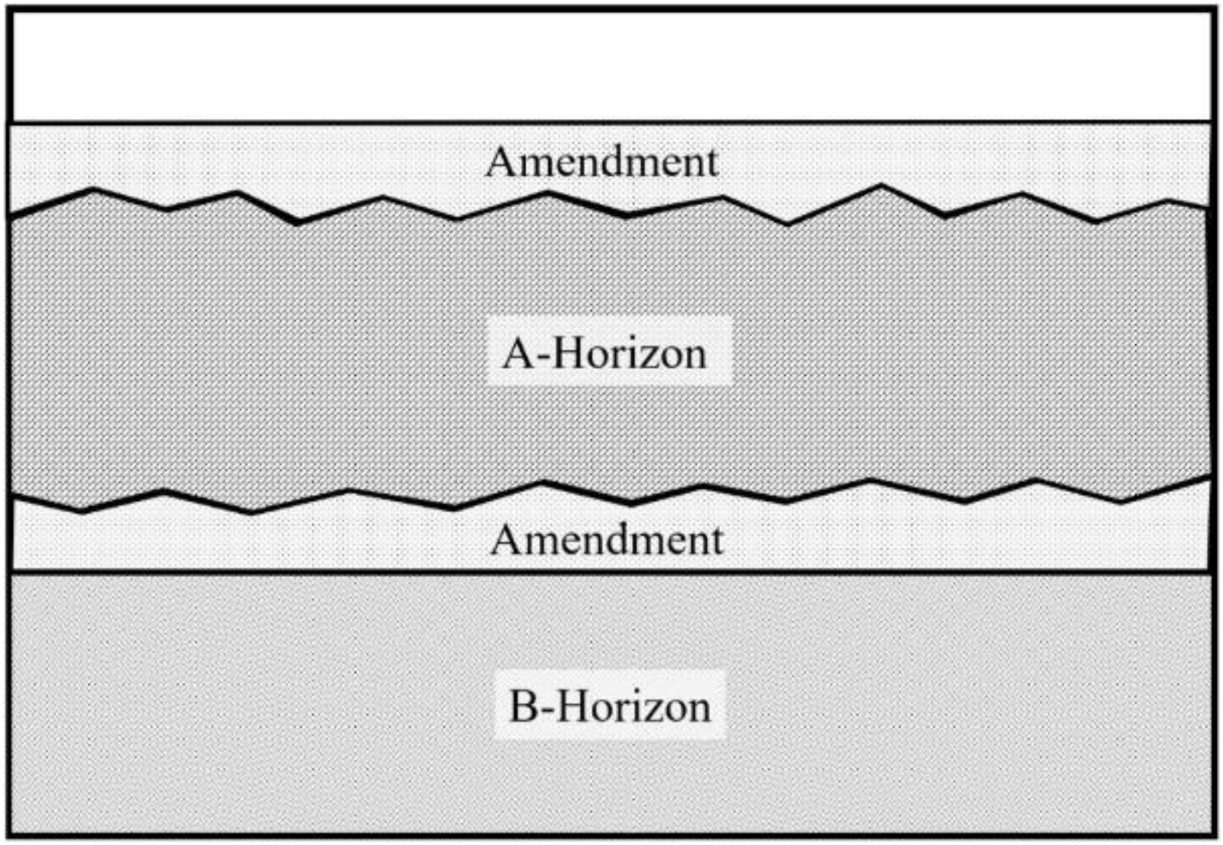

Figure 2.4. Diagram dictating the application of amendments related to soil horizons.

Soil Sampling

Soil samples were collected in a five-point grid within each sub-plot (A-F) at all six brine pond sites in mid-May 2018 (Figure 2.2) at 0-15 and 15-61 cm to provide baseline measurements prior to application of treatments and again at three subsequent time periods (October 2018, May 2019, May 2020) after treatments were applied to determine change from pre-treatment collection. Soil samples were collected from the same grid locations on all four sampling dates (May 2018, October 2018, May 2019, May 2020) (Figure 2.5). Five soil samples collected from sub-plots were combined to create one composite soil sample for each of the 36 sub-plots (six treatment sub-plots per six sites). Soil samples were analyzed at the North Dakota State University soil testing lab.

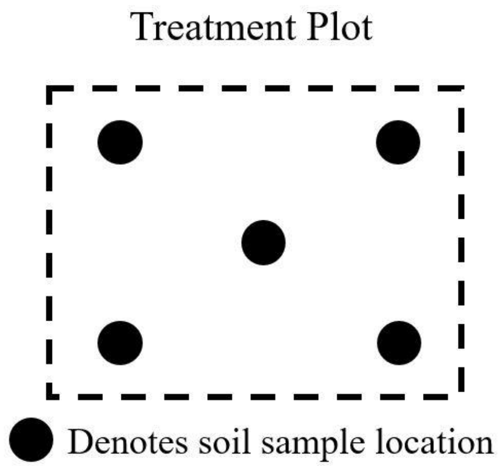

Figure 2.5. Five soil probes were collected using a five-grid layout from each sub-plot for each legacy brine sites.

Soil samples were analyzed for EC, SAR, and chlorine (Cl). Electrical Conductivity (EC_e) was calculated using the saturated paste method as developed by Michigan State University (Warncke 2009). A 600 mL beaker was filled two-thirds of the way full with soil, and then water was deionized water was gradually added to the soil until the soil was saturated. The sample was mixed and allowed to set for 1 hour. After 1 hour idle, pH for the paste was determined. The paste was then added to a Buchner funnel lined with filter paper that was attached to a vacuum. The sample was vacuumed for 15 minutes before a solu-bridge was used to determine the EC_e. Sodium adsorption ratio was calculated using methods described in Elbashier et al. (2016). The determination of Cl was made using a spectrophotometer with the Mercury (II) Thiocyanate Method found in Adriano and Doner (1982). Ten grams of crushed soil was added to a 50 mL Erlenmeyer flask, 25 mL of extracting solution was added to the soil in the flask. Four mL of thiocyanate and ferric nitrate were then added to the flask and set for 10 minutes. A standard curve was created with known solutions and Cl (mg/kg) was determined by aligning the reading of the soil solution with the standard curve.

Data Analysis

The experimental design was a completely randomized block design with six blocks, six treatments and four time periods (initial and three post treatment times) using a significance level of 0.05. Treatment is a fixed factor and time after treatment is treated as a repeated measure. The statistical model is a repeated measures model with a one-way treatment structure and blocking. Time was modeled as a first order autoregressive coefficient. We used the Proc Mixed procedure in the SAS software system (Version 9.4, SAS Institute Inc., 2008) evaluate the effect of time and treatment on EC, SAR, and Cl. All data was log transformed prior to analysis, and a Tukey test was used for multiple comparisons.

Results

We observed a decrease ($P \leq 0.05$) in average EC and SAR over time and an increase ($P \leq 0.05$) in Cl when comparing soil constituents' values 0 MAT with 23 MAT (Table 2.3, 2.4). On average across all six sites, EC from 0-15 cm had the largest average decrease ($P \leq 0.05$) at 23 MAT, with an average decline of 15 dS/m (Table 2.3). From 15-61 cm, the average decline in EC was 8 dS/m (Table 2.4). Similar results were observed for SAR, although the initial SAR value was not as high as the EC and decrease in SAR was not as substantial as EC (Table 2.3, 2.4). Sodium adsorption ratio dropped by 7 on average from 0-15 cm, and by 3 on average from 15-61 cm (Table 2.3, 2.4). Chloride from 0-15 cm was not different ($P > 0.05$) when comparing 0 MAT and 23 MAT, although 4 MAT was different ($P \leq 0.05$) from both 0 MAT and 23 MAT (Table 2.3). Chloride at 4 MAT, 11 MAT, and 23 MAT was different ($P \leq 0.05$) from 0 MAT from 15-61 cm (Table 2.4).

All treatments, including the control, declined in EC over time from 0-15 cm (Figure 2.6). Treatment was a significant effect ($P \leq 0.05$) for EC from 0-15 cm (Table 2.3). The control also had a significant decrease over time according to our model. All treatments containing amendments declined at a greater rate than the control (Figure 2.6). The interaction between treatment and time was significant ($P \leq 0.05$) for EC from 0-15 cm (Table 2.3). At 23 MAT, all treatments were different ($P \leq 0.05$) from the control but, none of the treatments containing amendments were different ($P > 0.05$) from each other.

Table 2.3. Effect of treatment and time after treatment on EC, SAR and Cl at 0-15 cm soil depth.

Effects	Variables	EC* dS/m 0-15 cm	SAR* 0-15 cm	Cl* mg/kg 0-15 cm
Months After Treatment (MAT)	0 MAT	26.2 ± 2.0^{a}	16.4 ± 2.2^{a}	804 ± 51^{a}
	4 MAT	20.9 ± 1.9^{b}	14.5 ± 1.9^{a}	2227 ± 131^{b}
	11 MAT	13.8 ± 1.5^{c}	8.8 ± 1.1^{b}	--
	23 MAT	11.0 ± 1.5^{d}	9.7 ± 1.5^{b}	1266 ± 195^{a}
	P-value	<0.0001	<0.0001	<0.0001
Treatment (T)	Control	26.6 ± 2.9^{y}	14.7 ± 2.5	1735 ± 264
	Gyp+Hay	17.0 ± 2.2^{z}	12.0 ± 2.2	1338 ± 222
	Gyp+Man	16.5 ± 2.2^{z}	12.2 ± 2.1	1399 ± 215
	Gypsum	17.7 ± 2.3^{z}	12.4 ± 2.3	1651 ± 320
	Hay	15.0 ± 2.3^{z}	12.3 ± 2.2	1208 ± 207
	Manure	15.1 ± 2.2^{z}	10.4 ± 1.8	1265 ± 193
	P-value	0.0018	ns	ns
MAT x T	P-value	0.0014	ns	ns

*P-values represent significance of time after treatment and treatment. P-values for Time and Treatment interaction were also given, (ns) means the P-value was not significant ($P \geq 0.05$). Superscript letters (x, y, z for Year; a, b for Treatment) indicate significance among individual variables. Variables with the same letter in a column are not statistically significant.

Table 2.4. Effect of treatment and time after treatment on EC, SAR and Cl at 15-61 cm soil depth.

Effects	Variables	EC* dS/m 15-61 cm	SAR* 15-61 cm	Cl* mg/kg 15-61 cm
Months After Treatment (MAT)	0 MAT	22.3 ± 1.4^{a}	16.2 ± 2.2^{a}	1960 ± 115^{a}
	4 MAT	19.1 ± 1.4^{b}	14.0 ± 1.7^{ac}	5919 ± 396^{b}
	11 MAT	16.2 ± 1.4^{c}	11.1 ± 1.5^{b}	6577 ± 511^{b}
	23 MAT	12.8 ± 1.2^{d}	13.5 ± 1.9^{c}	5923 ± 586^{b}
	P-value	<0.0001	<0.0001	<0.0001
Treatment (T)	Control	20.6 ± 2.3	15.6 ± 2.7	5792 ± 801
	Gyp+Hay	17.5 ± 1.7	12.9 ± 2.2	5181 ± 603
	Gyp+Man	17.2 ± 1.6	13.6 ± 2.1	4831 ± 649
	Gypsum	18.3 ± 1.9	14.1 ± 2.3	5318 ± 694
	Hay	15.7 ± 1.6	13.8 ± 2.5	4645 ± 609
	Manure	16.3 ± 1.6	12.2 ± 1.9	4799 ± 567
	P-value	ns	ns	ns
MAT x T	P-value	ns	ns	ns

*P-values represent significance of time after treatment and treatment. P-values for Time and Treatment interaction were also given, (ns) means the P-value was not significant ($P\geq0.05$). Superscript letters (x, y, z for Year; a, b for Treatment) indicate significance among individual variables. Variables with the same letter in a column are not statistically significant.

Electrical conductivity from 0-15 cm was the only time treatment was a significant effect ($P\leq0.05$) in our repeated measures model. Thus, it was also the only time that there was a significant interaction between time and treatment.

Cover crop forage production after the reclamation process was lowest on the control in 2018 and yielded less than the plots with an amendment treatment (Table 2.5). None of the treatments were significantly different ($P>0.05$). Gypsum + hay treatment yielded the highest average forage production, but this was not different ($P>0.05$) due to the high variability of soil constituents when comparing production within all brine pond site.

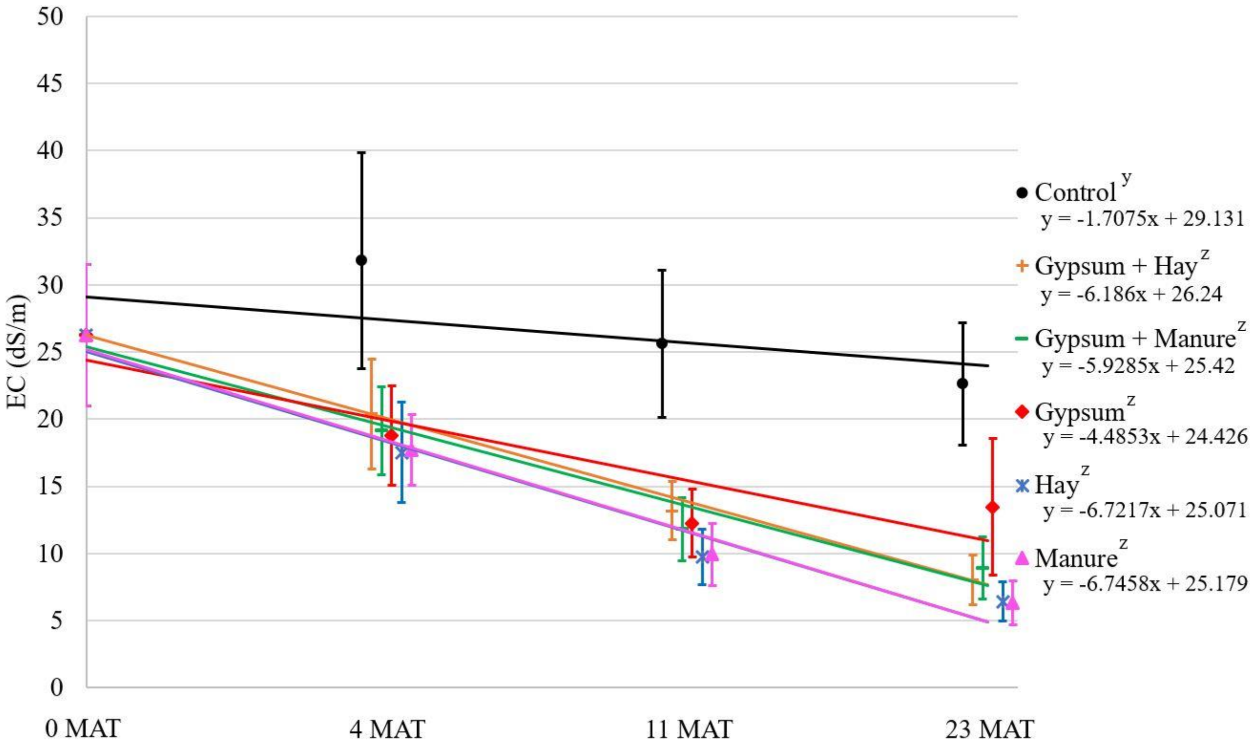

Figure 2.6. Change in EC (0-15 cm) over time by treatment. Points represent average EC for each treatment within a time period (MAT), error bars show standard error of each treatment at given time period (MAT). Regression line (y=mx+b) models were fitted for each treatment, and equations are displayed below corresponding treatment. Letters behind each treatment (y, z) signify significant difference, treatments with the same letters are not significantly different.

Table 2.5. Effect of treatment on cover crop production (mean ± SE; kg/ha) during the 2018 cropping year.

	Control	Gypsum	Manure	Hay	Gypsum + Manure	Gypsum + Hay
2018	32.5±13.4	311.7±161.3	440.8±226.9	564.2±313.9	598.3±261.2	709.2±334.0

Discussion

The average EC levels for all plots was 24 ds/m prior to treatment application; however, the plots averaged 12 ds/m 23 months post-treatment. Our treatments reduced EC levels by leaching salts down the soil profile 23-months after treatment (MAT). All treatments containing amendments had lower EC 23 MAT compared to the control at 0-15 cm. Among the treatments gypsum alone, manure alone, hay alone, gypsum + manure, and gypsum + hay, none were found to be different from each other. This means that using the most readily available or cheapest of these amendments will be the best option for land owners seeking to reclaim brine ponds. At 15-61 cm, only the gypsum alone had higher EC than the control; however, the difference in treatments was not significant at this depth.

Other studies have used amendments in a similar way and found positive results. El Hasini et al. (2019) found gypsum alone was the best amendment for reducing extremely high EC levels compared to sugarcane compost and green waste (general compost). Zhang et al. (2008) used wheat straw that was incorporated into the soil and reduced soil EC, similar to our findings.

The control decreased from 0-15 cm, although it did not decrease as much as the treatments containing amendments. This was because we disturbed the control plots in the same way as we disturbed plots containing amendments. The removal of the A-horizon and occurrence of rain on all plots allowed for salts to percolate down. The re-application of the A-horizon may have created pores in the soil allowing for water to move more easily through the soil. Other studies found that creating heterogenous distribution of salts in the soil allowed for decreased overall salinity and increased plant growth (Chen 2016, Chen 2019, Chavez-Garcia and Siebe 2019). While the control did decrease and produce cover crop forage, all treatments with amendments had higher decrease in salinity and produced more cover crop forage.

High EC can make it difficult for most plants to survive (Ogle and St. John 2009), however, there are other effects it has on the soil. Amatya et al. (2002) looked ex-situ at the effect of salinity on oil and gas degradation and found that higher EC in the A-horizon of soil reduced the soils ability to decontaminate against oil and gas spills. In addition, they found that higher EC in the soil was directly correlated with lower levels of CO_2, which is a sign of reduced soil bacteria activity. In addition, high salinity soils can develop a hard crust on the soil surface as water evaporates, leaving solids behind (Qadir et al. 2007). Incorporating biological and chemical amendments into the A-horizon can help revegetate soils and reduce other negative effects of high soil salinity.

Sodium Chloride (NaCl) is the predominant salt in Williston Basin brine (Veil and Clark 2011). The initial average SAR for all brine ponds was 16% at both depths. At 23 MAT, the average SAR for all treatments was 10% from 0-15 cm and 13% at 15-61 cm. No treatments within our study were different from each other at 0-15 or 15-61 cm soil depths. Chloride in our study dramatically increased from pre-treatment to 23 MAT at 15-61 cm. Gypsum has proven in other studies that it can reduce the effect of sodium on the topsoil (Li and Wang 2018, Day et al. 2019). Qadir et al. (2001) showed replacing Na with Ca from gypsum in the soil helps leach Na further down into the soil profile. Day et al. (2019) found sodium increased in the lower soil profile on plots that used gypsum as an amendment, probably a function of Na from the upper profile leaching down. In an attempt to keep Na and Cl from causing problems lower in the soil, Harris et al. (2005) used hay as a soil amendment in addition to a subsurface drainage system that resulted in lower concentrations of Na and Cl deeper in the soil profile.

On brine pond plots treated with amendments in our study, there was higher plant biomass production of a cover crop when compared to the control (Table 2.5). While these differences in production were not significant, other studies have pointed to the importance of revegetating salt affect areas (Shaygan et al. 2018). Phytoremediation is the use of plants to reduce the negative effects of salt on the soil (Qadir et al. 2007). Greenberg et al. (2012) found that using plants to remediate saline soil resulted in a 15% reduction in dS/m each year. In an ex-situ experiment, Krishnapillai and Sri Ranjan (2005) found that *Atriplex patula* could lower Cl by 0.25 kg/m^3 and Na by 0.06 kg/m^3 over 150 days of growth. Reducing the effects of salts on the soil will increase vegetative growth, therefore vegetative growth begets vegetative growth.

Plant tolerance to salinity depends on stage of growth. With an average of 12 ds/m, many more plants are able to grow on these brine ponds (Ogle and St. John 2009). In fact, being barren before we started this trial, all of the plots had kochia (*Kochia scoparia*) growing on them. Chen et al. (2019) found that heterogeneous spread of salinity can help in revegetating brine ponds. Our study also showed with displacement of salinity down the soil profile, plants were able to grow on brine ponds. The layering of amendments within the soil profile has been shown by others (Zhang et al. 2008, Chavez-Garcia and Siebe 2019, Day et al. 2019, El Hasini et al. 2019) to effectively limit the effects of saline-sodic soils on re-vegetative plants.

Our statistical model showed that EC from 0-15 cm was the only time that treatment effected the soil properties. This is because there are some variables in our experiment that were not recorded, and thus were not included in the repeated measures model that we used. It would be beneficial to have a rain gauge at each brin pond in future experiments in order to record precipitation at each site over time. It would also be valuable to compare how annual crops compare to perennial crops when performing reclamation work on brine ponds.

Conclusion

Historic brine ponds have caused problems for farmers in oil producing areas for half a century, and without reclamation efforts these problems will continue. Our research shows that the use of soil amendments can effectively lower EC enough for vegetative growth to occur. While our treatments reduced EC levels at 0-15 cm greater than the control, no treatment containing soil amendments was different from another. We recommend using amendments that are readily available to producers or amendments that are the most cost effective in order to reclaim brine ponds.

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3. INFLUENCE OF LAND MANAGEMENT STRATEGIES ON WESTERN SNOWBERRY (*SYMPHORICARPOS OCCIDENTALIS*) COMMUNITIES: ASSESSING PRECISION AGRICULTURE TECHNIQUES

Abstract

Woody encroachment has occurred throughout the Great Plains of North America due to the reduction of burning, poor grazing management, and climate change. Western snowberry (*Symphoricarpos occidentalis*) is a woody shrub that can often expand into dense colonies resulting in a reduction of grassland biodiversity. This study used precision agriculture and traditional methodology to assess the impact of prescribed spring fire and continuous season-long grazing on mixed-grass prairie invaded with dense patches of western snowberry communities. We used two different forms of data collection to monitor change in western snowberry populations with different disturbances. (1) We DJI Phantom drone with an 84° field of view, 8.8mm/24mm, auto-focus camera in a grid pattern across eight field sites to collect imagery for analysis. Image analysis was performed using Python coding language and ArcGIS analysis techniques in order to compare the two. (2) We used a one-meter by one-meter square on transects to collect on the ground data for mature plants, new stems and forbs. We assessed how plant communities changed over time post-treatment using both techniques. Prescribed fire reduces ($P \leq 0.05$) mature live plant density compared to un-burned treatments. Prescribed fire also increased ($P \leq 0.05$) sucker density. Image analysis was not different between the two analysis techniques in canopy cover of western snowberry. To date, grazing alone or no disturbance did not reduce western snowberry colonies. Our study shows that reintroducing prescribed fire can help reduce woody encroachment on temperate grasslands. In addition, we

did not get significant results comparing our different imagery analysis techniques to each other and to traditional methods.

Introduction

Temperate grasslands have been severely altered by human activity, which has led to ecosystem conversion and diminishing biodiversity (Sher and Primack 2019). Temperate grasslands are an important contributor to agriculture and an area of economic interest, covering 27% of earth's terrestrial land (Henwood 1998, Geaumont et al. 2019). Historic grasslands are easily converted to anthropogenic systems such as cropland and pasture (Sher and Primack 2019). Consequently, many grasslands have experienced a change in ecosystem function, as areas have been transformed (Kaskie et al. 2019). Much of the converted grasslands provide food for a growing global population. Historically, evolution and upkeep of grassland systems was maintained through natural abiotic disturbances such as fire (Canadell et al. 1991, Gross and Romo 2010, Scasta et al. 2014) and grazing (Fuhlendorf and Engle 2001, Bai et al. 2009, Scasta et al. 2016). Research has shown that removal of grazing and fire disturbances on temperate grassland has led to woody species encroachment (Van Auken 2000, Knapp et al. 2008, Johnson et al. 2019, Kaskie et al. 2019).

Encroachment of woody species onto temperate grassland ecosystems has significant ramifications in terms of reduced biodiversity and forage production (Bowes and Spurr 1995, Ratajczak et al. 2012, Teleki et al. 2020). The transition from graminoids to woody species results in an unnatural level of carbon and nitrogen, altering soil health (McKinley and Blair 2008, Bai et al. 2009). Some woody species tend to colonize through rhizomatous reproduction and sprouting (Defelice 1991, Nesmith et al. 2006). Reduction of sunlight and decreased heat below canopies of woody species also reduces graminoid presence on encroached areas (Gehring and Bragg 1992). The change in species composition associated with woody encroachment on rangelands has reduced productivity of grazable forage (Bowes and Spurr 1995). Temperate grassland that has experienced woody species encroachment produces less forage than grassland that has not been invaded (McCarty 1967, Defelice 1991, Van Auken 2000).

The Northern Great Plains (NGP) comprise the area from Nebraska in the United States north to Alberta and Manitoba in Canada (Hendrickson et al. 2019). This region largely formed as the result of glaciation, most recently the Wisconsin Glaciation, which ended about 10,000 years ago (Coleman 1930, Hobbs 1945). Much of this region has been converted to farmland, although a large portion is still classified as native range and makes up a significant portion of North America's rangeland (Barker and Whitman 1988). Samson and Knopf (1996) described the Great Plains as the continent's most endangered ecosystem. Historically, these areas were grazed by large charismatic ungulates like bison (*Bison bison*), elk (*Cervus canadensis*) and bighorn sheep (*Ovis canadensis*), but have since been converted, in large part, to grazing lands for domestic livestock (Matthiessen 1959, Augustine et al. 2019). Change in grazing disturbance and reduction in fire frequency has resulted in an increase of many native shrubs and woody plants on these grasslands, of which western snowberry is one.

Western snowberry (*Symphoricarpos occidentalis*), also known as buckbrush or wolfberry, is a perennial shrub that has benefited from the alteration of grasslands in the NGP (McCarty 1967, Bai et al. 2009). It is a deciduous shrub measuring 30 to 100 cm in height with an extensive distribution ranging from the Canadian territories, south to Utah and east to Michigan (Pelton 1953). Western snowberry has two main types of reproduction, including rhizomatic growth which creates the establishment of large colonies (Sbatella et al. 2011). Stems of western snowberry can form relatively close together and form canopies with up to 93%

canopy cover (Manske 2006). The growth characteristics and resiliency of this woody shrub creates a competitive advantage over other perennial plants on rangelands.

Managing western snowberry is essential if increasing biodiversity and livestock forage for cattle is desired in the NGP. Cattle are the dominant grazer across the NGP. However, livestock use and desire to consume western snowberry is low (Adams and Bailey 1983, Celaya et al. 2007). Western snowberry has caused a reduction in quality grazing lands throughout the NGP (McCarty 1967, Manske 2006, Bai et al. 2009, Sbatella et al. 2011).

Forage production and quality on rangelands can sometimes be increased through the reduction of western snowberry using herbicides (Bowes and Spurr 1995, Bowes and Spurr 1996, McCarty 1967, Sbatella et al. 2011), grazing (Kirby et al. 1988, Smart et al. 2007, Johnson et al. 2019), prescribed fire (Anderson and Bailey 1979, Scasta et al. 2014) and mechanical mowing (Adams and Bailey 1983, Manske 2006). Chemical application and mechanical mowing can be time consuming and expensive options to implement. Fire can increase stem density through new stem (sucker) production (Lura et al. 1987, Lura et al. 1988) that is much more palatable to cattle (Anderson and Bailey 1979). Johnson et al. (2019) found that the use of patch-burn grazing increased the amount of western snowberry consumed by cattle. If adding grazing following a burn, cattle producers may have a sustainable control technique using patch-burn grazing.

The study objectives include: 1) compare changes in canopy cover of western snowberry patches using the same treatments with ground data and drone imagery, and 2) assess the impacts of continuous grazing with cattle, spring burning, spring burning followed by continuous grazing with cattle, and no disturbance (control) on western snowberry plant density. Our study hypotheses include: 1) cattle grazing following a prescribed spring burn will reduce western snowberry plant density greater than cattle grazing alone or prescribed burning alone, and 2) imagery collected from drones will provide a new technique to interpret treatment effects compared to traditional on-the-ground data collection techniques. By comparing each trial using multiple techniques, it will help us make recommendations as to best management practices for controlling the spread of western snowberry in temperate grasslands.

Methods

Site Description

This study was conducted at the North Dakota State University, Central Grasslands Research Extension Center (CGREC) located in Stutsman and Kidder Counties northwest of Streeter, North Dakota USA (46°45′N, 99°28′W). The station lies within the Missouri Coteau ecoregion (USDA-NRCS, 2006) and dominated by fine-loamy mollisols and characterized by irregular rolling plains resulting from the collapse of super glacial sediment (Bluemle 1991). The climate is continental, with the majority (73%) of precipitation occurring between May and September (North Dakota Agriculture Weather Network 2021). The CGREC receives an average 342-mm of precipitation during the growing season (May 1 through October 1; North Dakota Agriculture Weather Network 2021). August (20°C) is the warmest and January (−12°C) coldest months based on the 30-yr average (North Dakota Agriculture Weather Network 2020).

The vegetation is classified as mixed-grass prairie (Whitman and Wali 1975; Limb et al. 2018) dominated by Kentucky bluegrass (*Poa pratensis*), western wheatgrass (*Pascopyrum smithii*), green needlegrass (*Nassella viridula*), and blue grama (*Bouteloua gracilis*), with other important species including sedges (Carex spp.), sages (*Artemisia* spp.), goldenrods (*Solidago* spp.), and western snowberry (*Symphoricarpos occidentalis*).

Experimental Design

Grazing treatments using mature cross-bred Angus cow/calf pairs to determine change in western snowberry density and canopy cover include continuous grazing (CG), patch-burn grazing (PBG), spring burning only (BO), and no disturbance (CONT) using a split-plot design. Each treatment was replicated four times within eight pastures ranging from 44 to 64 hectares.

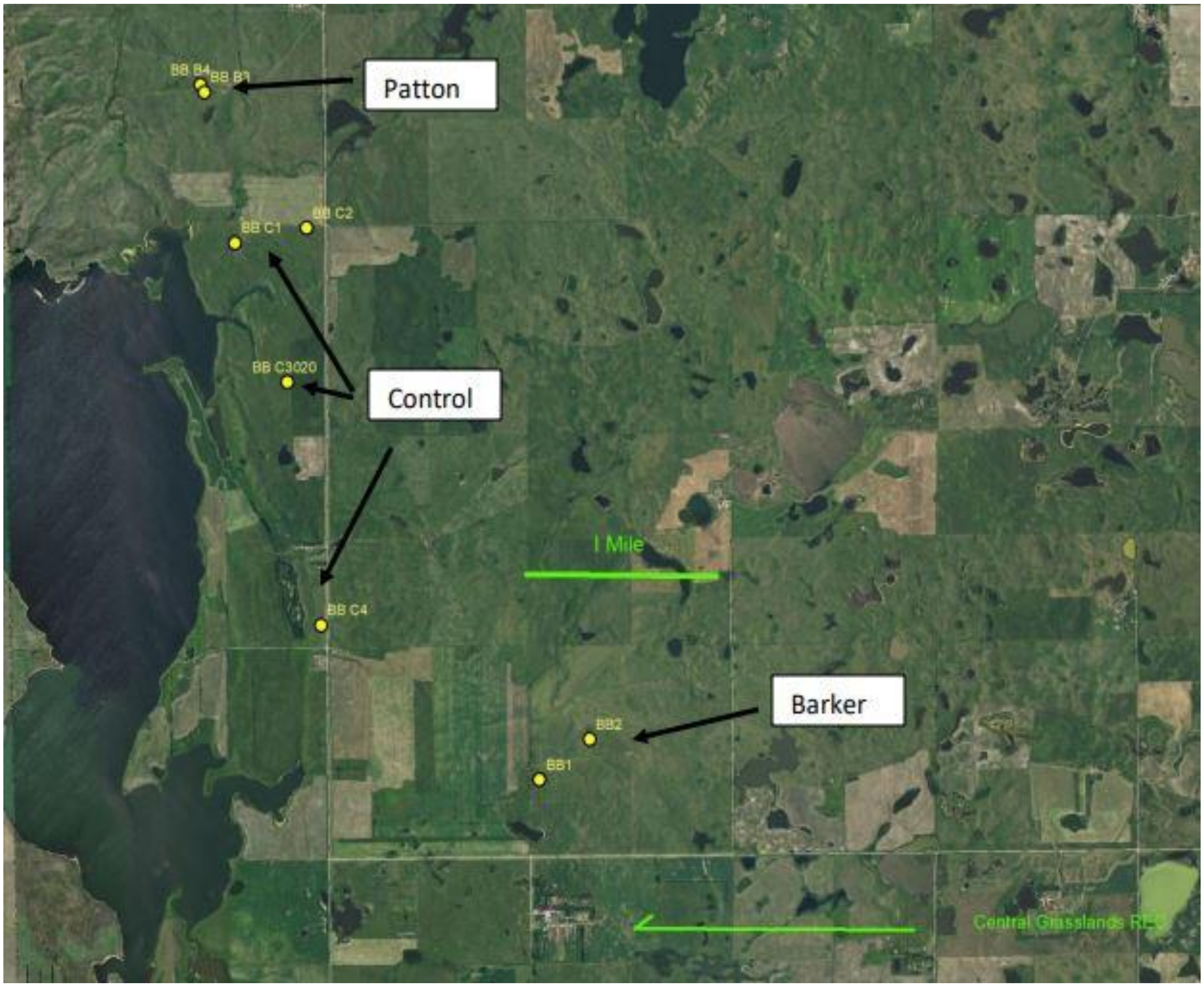

Figure 3.1. Image shows the location of each of the study sites with both the Barker and Patton pastures burned using a prescribed spring burn and the control pastures unburned. All sites were split in half to create a grazed and un-grazed split plot.

Sites were systematically selected by searching for large western snowberry patches with a minimum of 2,000 kg/ha of standing herbaceous litter in each of the eight pastures that were a minimum size of 40 x 20 m^2 (Figure 3.1). Each patch was split, with one split grazed and one split non-grazed. Four of the pastures were burned in early May after western snowberry plants started leaf growth, and four pastures remained unburned. A head fire was used with the average wind speed at 3.2 mph with wind coming from 130° (NE) with the average dew point of 3°C and a temperature of 17°C (NDAWN). The burn through the western snowberry patches was complete, leaving blackened mature western snowberry plants behind. Each pasture had a unique set of cow/calf pairs with pasture considered the experimental unit and was stocked at 2.4 animal unit months/ha and grazed from mid-May to late-October. The study site areas used for the burn treatments had no past history of fire. Cattle grazed freely within each pasture for the entire grazing season.

Two 25 m transects were placed in each treatment plot using an X pattern with 12.5 m the center point where each transect crossed. We estimated snowberry density along each transect by recording the number of individual mature live stems and new stems within the 1 x 1 meter quadrat pre-treatment and four months post burn treatment. Mature growth was considered any stem material that was covered in bark while a sucker considered any new growth with leaf material on stem portion from the current year and not having bark. Mature stems and new growth were collected every 2-m along each transect using a 1 x 1 m quadrat. The plant community within the western snowberry patch were also described for each treatment by collecting density of forb species on the same transects every 2-m using a 1 x 1 m^2 quadrat pre-treatment and four months post burn treatment.

Imagery data was collected at the same time periods (early May and mid-September) as the on-the-ground data collection using an unmanned aerial vehicle (Figure 3.2). The DJI Phantom 4 drone was flown at a height of 30 meters and was equipped with an 84° field of view, 8.8mm/24mm, auto-focus camera that shot color (Red, Green, Blue) imagery with 0.25 x 0.25 m resolution. The UAV was flown in a grid pattern to cover the entire plot. Two image analysis techniques (Python and ArcGIS) were used to describe canopy cover of western snowberry.

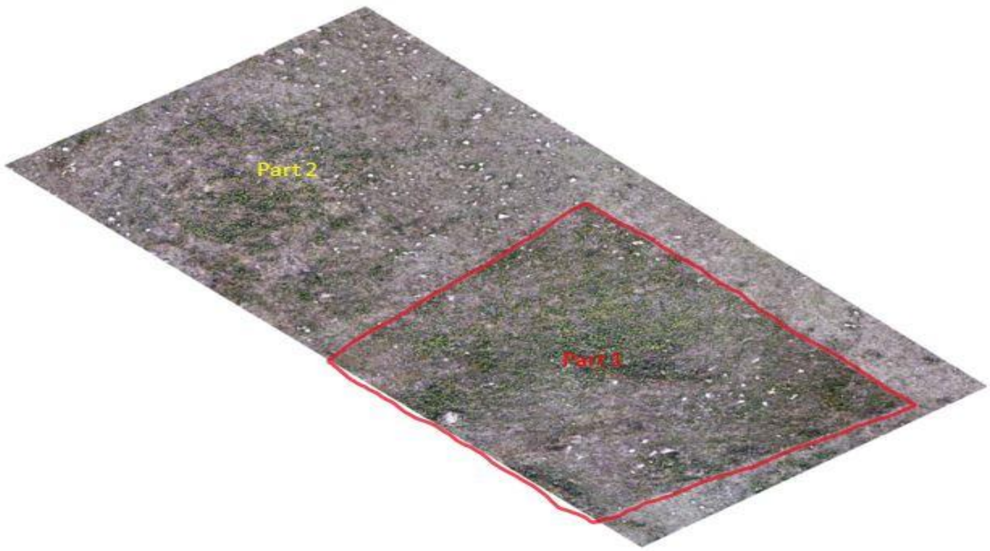

Figure 3.2. Image showing outline of the non-grazed/fenced area (Part 1) and grazed/unfenced area (Part 2). These two parts of the image were cropped and analyzed separately to attain canopy cover of western snowberry on the grazed and non-grazed areas.

Image Analysis-Python

The Python (PSF 2020) method used coding language with Open CV, numpy and matplotlib as python libraries. We compressed and resized the images taken from the drone to a proper dimension that could be read by the program (Python) for processing. Each image has two parts that are of interest (the grazed and non-grazed areas). The smaller region cropped from Figure 3.2 will be referred to as Part 1 (marked by red boundary, non-grazed area) and the left-out region after cropping of the original image will be referred as Part 2 (grazed area).

We calculated the percentage of green cover in the area by using the ratio of *Total Green Pixels* and *Total Pixels of the image.* An image consists of pixels that are stacked together. We can imagine it as smaller square boxes of different color placed together to form a bigger rectangle. The area occupied by each color in that bigger rectangle can be taken as area of one square into number of squares of specific color. Similarly, in case of an image, the dimensions are the number of pixels in height and width. So, an image with dimension 1920 x 1080 has area of 2,073,600 units (i.e., total number of pixels in the image). The green area coverage can be calculated as number of green pixels in the total image.

The image given is skewed, which means it has a white background and cannot be directly use as the dimension of the image for calculating total area. To address this issue, we first took all the pixels that comprise the actual image and classify it as the total area. Out of this total area, we calculated the green pixels in this image and took the ratio for the percentage green cover. The green in the image was obtained by using the excess green value as given in equation "Excess Green = 2 * Green – Red – Blue". Green, red and blue represents the value of green, red and blue channel at a given pixel.

We employed two methods to determine the result for Part 2 of our image. First method employs manually cropping Part 1 out of the image and substituting it with a white color. Then repeat the same process as done for Part 1 and the full image. For the second method, we use the calculated values from the full image and part image. We took the actual area (i.e., the total pixels of the original image and subtract the actual area of Part 1) to get the meaningful pixels of Part 2. In a similar fashion, we do the same for the green pixels, then taking the ration of green area over total area.

<u>Image Analysis-ArcGIS</u>

The ArcGIS (ESRI 2020) procedure processes and creates RGB orthomosaic imagery and selected western snowberry imagery from the drone flights using AgiSoft image processing software and ArcGIS mapping software. The first step was to project the RGB imagery from the native or original WGS 84 Coordinate System to NAD 1983 UTM Zone 14 N in order to measure square meters, hectares, and percent of the western snowberry to the remaining study areas. Using the native or original WGS 84 Coordinate System or Geographic Coordinate System will not allow for accurate area measurements. Projected Coordinate Systems are required to accurately measure areas.

Second step in creating the selected western snowberry areas was to use the ArcGIS Raster Calculator to calculate the Excess Green Index (ExG) or vegetative indices. We used color to separate plant from soil to distinguish green plants from soil. In order to demonstrate good segmentation, the RGB is converted to alternative colors. We added the three-color bands (Red, Green, Blue) from each image into ArcGIS and opened the Raster Calculator. The band names will have the same name as the image in ArcGIS. For instance, the name of the image - Band 1. Band 1 is Red, Band 2 is Green, and Band 3 is Blue. The formula written into the Raster Calculator is 2* image name Band 2 – image name Band 1 – image name Band 3 and then run the script to create the ExG image. This ExG image will have a value of each individual pixel in the image and each value will have a count or number. The following step after creating the imagery was to view the RGB with the ExG image and determine which values were the western snowberry and which values were not. After determining the value, we then reclassified the ExG image into two classes. One being the western snowberry area and the other being the non-western snowberry area.

On the reclassified image, we added attribute fields: SqM, AreaAcres, PerCent and calculated the new attribute fields values using the ArcGIS Field Calculator. The SqM was calculated by multiplying the count times the pixel area. The pixel value was determined by opening the image properties and viewing the Cell Size under the source tab and calculating the area. The AreaAcres was calculated by dividing the SqM by 4047. The PerCent was calculated by the count of the selected areas and divided by total count of both areas and taking that number times 100.

We then created three shapefiles, which were the fenced study area, the non-fenced study area, and total study area including both areas to which we used the ArcGIS mask tool to clip areas of the reclassified imagery into three images, with the areas described as above. Once the study area images were created, we calculated the attribute values into each areas image. We can then view the RGB images with the study area images in ArcGIS or other GIS software to verify the western snowberry areas and locations. Using the ArcGIS swipe tool or changing the transparency of an image we can then verify the western snowberry areas. Future studies may want to use high resolution imagery flown at an elevation in which the western snowberry may be clearly visible.

Ground Data Analysis

Due to the initial range in mature plants present across all plots, data was converted into percent change in order to compare all plots based on their treatment. New growth in most samples were initially zero, so percent change would not work for analysis of new stem growth. Rather than using percent change as with mature plants, we used the actual change in new growth for data analysis.

The 640 samples for mature plants and new growth were analyzed in a mixed effects model using the lme4 package in the R statistical environment. Means and standard errors were recorded for each treatment at both collection dates. We compared the results for the mixed effects model to determine treatments compared to the control. We used the multcomp package in the R statistical environment to determine treatment effects. This package also enabled us to compare all treatments against each other to see which of the treatments were different from each other.

Forb data was analyzed by calculating average species/meter^2 and plants/meter^2 for each treatment. The Shannon-Weiner Diversity Index (SWDI) was calculated (Formula 2) for each treatment. P_i is equal to the proportion of each species when compared to the total number of forbs observed for a given treatment.

$$Formula\ 2.\ \mathrm{SWDI} = -\sum P_i * \ln P_i$$

Results

Image analysis was only performed on the September 15, 2020 imagery, as there were insufficient color differences to detect the differences between western snowberry and graminoid species in the May imagery. Due to the high standard deviations of the canopy covers found between replicates, there was no difference ($P>0.05$) in canopy cover of western snowberry treatments using the imagery analysis.

Image Analysis

Both grazing treatments had the lowest western snowberry canopy cover. Western snowberry canopy cover was 4.4 and 8.6 percent using the Python and ArcGIS techniques; respectively, on the PBG; and 3.9 and 7.8 percent using the Python and ArcGIS techniques; respectively, on the CG (Table 3.1). Western snowberry canopy cover was greatest on the BO, with a canopy cover of 11.0 and 19.0 percent using the Python and ArcGIS techniques; respectively (Table 3.1).

Table 3.1. Western snowberry canopy cover and SE using drone images and analyzed with Python coding language and ArcGIS by treatment from study sites at the Central Grasslands Research Extension Center near Streeter in 2020.

a) Python				b) ArcGIS			
Burn	Graze	Canopy Cover	St. Dev.	Burn	Graze	Canopy Cover	St. Dev.
Y	Y	4.4%	5.4	Y	Y	8.6%	7.7
Y	N	11%	11.0	Y	N	19%	12.7
N	Y	3.9%	2.2	N	Y	7.8%	5.6
N	N	6.9%	5.2	N	N	10%	6.8

Ground Data

The BO, PBG, and GO treatments averaged nine mature plants/m^2 pre-treatment, while CONT treatments averaged 10 mature plants/m^2 pre-treatment. All treatments averaged less than one sucker per square meter prior to the burn and graze treatments on 4 May 2020.

There was no difference (P>0.05) in percent change in mature live western snowberry plants between the GO and CONT treatments four months after treatment (Figure 3.3a). Both burn treatments (BO, PBG) reduced ($P \leq 0.05$) mature western snowberry live plant density after four months. However, there was no difference between the BO and PBG treatments (Figure 3.3a).

There was no (less than 1) new growth found on either treatment prior to implementing the burn or grazed treatments. Both BO and PBG treatments had a greater ($P \leq 0.05$) number of new stems compared to the CONT treatment four months after the burn and had an increase ($P \leq 0.05$) in new growth four months after the prescribed spring burn (Figure 3.3b). There was no difference (P>0.05) in the number of new stems between the GO and CONT treatments, and no difference (P>0.05) in the number of new stems on either GO and CONT treatments four months after the initiation of the treatments (Figure 3.3b). There was no difference (P>0.05) in numbers of new stems between the BO and PBG four months after the prescribed spring burn (Figure 3.3b).

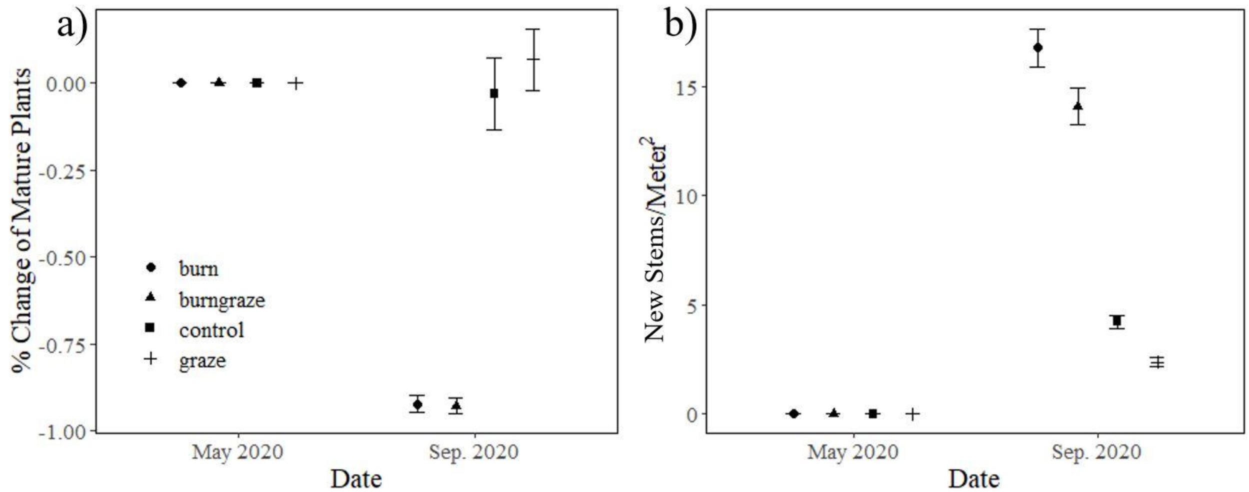

Figure 3.3. Pre-treatment (May 2020) and post-treatment (September 2020). (a) Percent change in mature plants and (b) new stems per meter^2 by treatment at the Central Grasslands Research Extension Center near Streeter, ND.

Forb density was collected near the end of grazing season and four months after the prescribed burns. There was no difference (P>0.05) in species diversity among any treatment four months after treatment. We observed a trend (P=0.091) showing the BO and PBG treatments had more forb species/meter^2 and forb plants/m^2 compared to the GO and CONT treatments four months after the prescribed burn (Table 3.2).

Table 3.2. Forb diversity (Shannon-Weiner Index), number of forb species/m^2 and number of forb plants/m^2 by treatment at the Central Grasslands Research Extension Center near Streeter in 2020.

Burn	Graze	*Species/Meter^2	*Plants/Meter^2	*Shannon-Weiner Index
Y	Y	2.6[a]	10[a]	-2.0997[a]
Y	N	2.6[a]	14[a]	-2.2084[a]
N	Y	0.9[b]	2.7[b]	-1.9428[a]
N	N	0.8[b]	2.4[b]	-1.6546[a]

* Treatments with the same letter (a, b) within a column were not different (P>0.05)

Discussion

The temperate grassland landscape in the NGP has been severely altered, resulting in reduced biodiversity and change in ecosystem function (Sher and Primack 2019, Kaskie et al. 2019). Encroachment of woody species such as western snowberry has negatively altered the plant community (Bowes and Spurr 1995, Bai et al. 2009). Our findings show that burning reduced the density of mature live western snowberry plants four months after treatment. However, grazing following a spring-applied burn did not reduce percent of mature live stems compared to burning alone. Similarly, Scasta et al. (2014) showed a prescribed spring fire reduced western snowberry cover. Bailey et al. (1990) performed an extensive study on the response of western snowberry to fire and grazing and found that four years post-burn, western snowberry densities were greatly reduced compared to pre-burn concentrations. Differences between our study and Bailey et al. (1990) may be explained by study duration. Bailey et al. (1990) evaluated effects of fire and grazing on western snowberry over a four-year period versus one year in the current.

Both the BO and PBG increased western snowberry new stems. Lura et al. (1988) also showed burning increased new western snowberry shoots the first year following a spring burn. Resprouting is a way woody plants increase biomass following extreme defoliation or destruction by disturbances such as fire (Bellingham and Sparrow 2000, Bond and Midgley 2003). Our study, along with Anderson and Bailey (1979), Lura et al. (1988), and Bailey et al. (1990), showed prescribed spring burns increase regrowth of western snowberry.

While our results were similar to past studies in terms of western snowberry response to fire, our findings were not as clear in terms of the effects of grazing on western snowberry density. New stems are more palatable and greater in nutritional quality to cattle and other browsing animals (Smart et al. 2007, Johnson et al. 2019). Other studies have found that grazing reduces the height and density of western snowberry colonies (Bailey et al. 1990, Smart et al. 2007); however, only Bailey et al. (1990) showed a reduction of western snowberry density when comparing early and late season grazing with early season grazing alone. In our study, we did not find any difference in number of new stems at the end of the grazing season between grazed and un-grazed burned areas. This is probably due to cattle having access to free choice to browse in burned or unburned areas for the entire season.

Our aerial imagery was less conclusive when compared to the on-the-ground data. This is mainly due to the standard deviations being large, as we had a large variation in canopy cover among replicates. Pre-treatment imagery was not analyzed due to no observable difference between western snowberry and other green vegetation. Grazing with cattle appears to reduce the canopy cover of western snowberry based on image analysis. Both types of analysis (Python and ArcGIS) show less canopy cover on grazed areas compared to non-grazed areas. However, these observations are not statistically different ($P>0.05$). In some cases, findings from our imagery analysis contradicted results from our ground data. This may be because our imagery analysis techniques were unable to distinguish mature plants from new stems of western snowberry. Gillan et al. (2020) found similar discrepancies between ground data and aerial imagery. Barnas et al. (2019) found that drone imagery overestimated barren land when compared to ground data. Other studies (Perez et al. 2020, Oldeland et al. 2021) have shown similar results when comparing ground data and drone imagery. Perez et al. (2020) comparing drone imagery to field data, found that field data was similar to drone imagery outputs in an arid environment that had less vegetative cover, making it easier for imagery analysis to distinguish species. Lyons et al. (2019) found drone use to be superior to ground data because of the ease at which drones can analyze vast landscapes.

We found the prescribed spring burn increased forb richness and number of forb plants, irrelevant if cattle grazed the burns or not. However, we found no differences in species diversity between the burn treatments (BO, PBG) and unburned treatments (GO, CONT). Scasta et al. (2014) showed a reduction in height of in coralberry (*Symphoricarpos orbiculatus*) following prescribed fire. Smart et al. (2007) and Bailey et al. (1990) found grazing also reduced the height of western snowberry. The increase in sunlight may possibly create a shorter and more open canopy and may explain why the burned areas had greater species richness and number of forbs/m^2 than the unburned areas. Bailey et al. (1990) showed a marked increase in vegetative production in areas with shorter shrubs. Although Miles and Knops (2009) showed fire increased species diversity in the NGP, our study did not show this increase in burned western snowberry patches four months post-fire.

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