Evaluating impacts of high voltage transmission line construction on Dry Mixedgrass prairie in Alberta

by

Seyedeh Faezeh Najafi

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Rangeland and Wildlife Resources

Department of Agricultural, Food & Nutritional Science
University of Alberta

Abstract

Native grassland provides productive rangeland for livestock grazing and valuable habitat for wildlife. However, remaining Canadian prairie in southern Alberta, and its integrity, has been changed by urban-industrial development, including pipeline and electrical transmission line construction. Although not widespread in area, high voltage transmission line construction is an important disturbance within the mixed grass prairie, and necessitates the need for best management practices to maintain these grasslands despite development. Access mats are recommended as an alternative practice to soil stripping, replacement and revegetation, and thereby decrease the effects of contemporary industrial activity on soil and vegetation resources.

This study looked at the *in-situ* monitoring of high voltage transmission tower construction using two different methods, 1) high disturbance sod-stripping of soil, including stockpiling, releveling and reseeding; and 2) low disturbance practices using surface matting to protect existing soil and vegetation during construction. While sod-stripping and access matting both altered soil and vegetation, greater reductions in plant cover, particularly native vegetation and perennial grasses, were evident with sod-stripping, which also increased soil bulk density, and decreased organic matter as well as nitrogen concentrations. In contrast, smaller changes were evident in soil and vegetation with the use of matting, with recovery occurring more rapidly. The value of access mats in protecting mixedgrass prairie also appeared to be particularly high on loamy soils. Recovery in all areas, including soil stripped towers, occurred by the third year post-treatment. Results from this study suggest that different types of construction methods can alter soil and vegetation dynamics, and that low disturbance methods (using access matting) are a viable tool to reduce impacts to mixedgrass ecosystems.

To my beloved parents, lovely husband, for
all their loves and supports throughout my life.

Acknowledgements

This M.Sc. thesis has been carried out since I joined the rangeland research group at the University of Alberta. I have worked with a great number of people who have contributed in various ways to the research in this thesis and deserve special mention. It is a pleasure to convey my gratitude to them with my humble acknowledgment. I would like to extend my thanks first and foremost to my super co-supervisors Drs. Edward Bork and Cameron Carlyle, for their supervision and advice from the early stages of this research. Above all, they provided me with constant encouragement and support and helped me to understand the different scientific aspects of this research and to develop new ideas which have enriched my growth as a researcher. I also would like to thank Dr. Sylvie Quideau for serving on my supervisory committee, and Dr. Dean Spaner for kindly agreeing to be my external examiner. In the process, these individuals offered valuable feedback and suggestions for improvement to the thesis.

This study would not have been possible without the help of many people who assisted with sample collection in the field, the preparation of soil and vegetation materials, and sample processing for lab analyses. These individuals include Dr. Karen Thompson, Dr. Barry Irving, Lisa Raatz, and Don Armitage. Laboratory staff members who provided help throughout included Robin Miles, Drs. Kelvin Lien and Urmila Basu. My thanks to fellow graduate students including Kassia James, Lysandra Pyle, Carly Moore, Sean Chuan, Nicky Lasink, Ekaterine Stolnikova, Caroline Martin, Ashton Sturm and Angela Phung. I am particularly grateful to my field assistants Leah Rodvang, Erica Schell, Christian Kentz, Megan O'Neill, Hanna Schoenberg, Danielle Mai and Kara Doerksen, such that it is almost impossible to thank everyone working in this project appropriately.

This project would not have been possible without the generous financial and technical support from the following institutions and organizations, for which I am grateful: ATCO

Energy Ltd. and the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Rangeland Research Institute (RRI) at the University of Alberta.

Last of all but not least, I would like to thank my family, especially my mother Maryam and my husband Mohsen, for their support and encouragement which helped me carry out this research. They always motivated and encouraged me to persevere in the face of my own doubts and reservations.

Table of Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

°C – Degrees Celsius
AEP – Alberta Environment and Parks
ASRD- Alberta Sustainable Recourse Development
Al- Aluminum
ADF- Acid Detergent Fiber
ATCO- Air Traffic Control Officer
BD- Bulk Density
B- Boron
CTAB- Cetyl Trimethyl Ammonium Bromide
C – Carbon
Cu- Copper
CO_2 – Carbon Dioxide
CO- Colorado
Ca- Calcium
cm- Centimeters
CP- Crude Protein
DSCP- Digital Static Cone Penetrometer
EG&S – Ecological Goods and Services
EC- Electrical Conductivity
Fe- Iron
g- grams
HD- High Disturbance
ha- Hectare
Hr- Hour
IL- Illinois
LD- Low Disturbance
IR- Infiltration Rate
KV- Kilovolt
K- Potassium
Kg- Kilogram
m – meter
mm- millimeter
mm hour- millimeter per hour
MGP- Mixedgrass Prairie
MRR- Mattheis Research Ranch
Mg- Magnesium
Mn- Manganese
MAP- Mean Annual Precipitation
NC- North California
NE- North East
N- Nitrogen
NJ- New Jersey
OM – Organic Matter
P – Phosphorus
pH – Potential of Hydrogen
PRS- Plant Root Simulation
PSI- Pound per Square Inch
PR- Penetration Resistance

SE – Standard Error
SE- South East
SOM – Soil Organic Matter
S- Sulphur
USA – United States of America
UK- United Kingdom
µprobe – microprobe
Zn- Zin

Chapter 1: An Overview of Industrial Impacts on Mixedgrass Prairie and the Need for Research

Grasslands are important for sustaining essential ecosystem goods and services for society, including providing forage and livestock production, wildlife habitat and biodiversity, carbon sequestration and greenhouse gas reduction, as well as water storage and purification (Havstad et al., 2007; Hooper et al., 2005). However, grasslands are also among the most threatened ecosystems in the world (Samson and Knopf 1994), being exposed to urban-industrial development and expanding intensive agriculture (Pitt and Hooper 1994), together with woody cover encroachment (Bailey and Wroe 1974), climate change (IPCC 2013), and overgrazing (Coughenour 1985; Milchunas et al. 1988). As a result, interest is growing in the development of strategies to assist with the conservation of remaining grasslands, particularly those that remain non-cultivated and provide a key source of biodiversity and habitat for species at risk.

Over the past century, since European settlement, the Canadian prairie has been changed substantially by crop agriculture and urban development, with remaining native grasslands dominated by complex mixtures of grasses and forbs found disproportionately more commonly within less arable semi-arid regions (Coupland 1961; Willms and Jefferson 1993). Today, as little as 31% of native grassland remains in the province of Alberta, a figure that varies from less than 10% in the Parkland to 43% in the Dry Mixedgrass Prairie (Hill et al. 2000). Grassland loss continues today (Ceballos et al., 2010) and reflects a growing population base and associated exploitation of natural resources, including the creation of industrial infrastructure necessary to support modern society. Given the need to balance ongoing resource extraction and industrial development, as well as the conservation of ecological goods and services (EG&S) from grasslands, developing management strategies to help maintain and conserve existing grasslands is an important management objective, both on public and private lands.

1.1 Background

Grasslands cover approximately 40% of the world's surface, and Canada is one of five countries with the largest area of grassland (Shorthouse 2010). Alberta's grasslands comprise 14.5 % of the province (6 M ha), with the Dry Mixedgrass subregion covering 7.1 % (Alberta Environmental Protection 1997) that supplies a variety of ecological goods and services. Changes in land use have resulted in decreased native grassland in many regions, including the Mixedgrass Prairie (MGP) of southern Alberta.

1.1.1 Mixedgrass Prairie

The Mixedgrass Prairie has a semi-arid climate with the warmest summer temperatures, longest growing season and lowest precipitation amounts of all natural subregions in Alberta (Adams et al. 2005). This region represents the northern portion of the Great Plains in North America (Willms and Jefferson 1993). The Dry Mixedgrass has a marked moisture deficit in mid to late summer. Soil texture is a major determinant of vegetation composition and biomass production in North America (Epstein et al. 1997) and different types of soil may exhibit variable plant recovery. For example, sandy soils are often more sensitive to disturbance than fine textured (clay-based) soils (Hulett et al. 1966). Soils from Mixedgrass Prairies are typically classified as Orthic Brown Chernozemic soils (Willms and Jefferson 1993). Dominant grass species include needle-and-thread (*Hesperostipa comata)*, western wheatgrass (*Pascopyrum smithii*), Junegrass (*Koeleria macrantha*), blue grama grass (*Bouteloua gracilis*) and sand grass (*Calamavilfa longifolia*).

Grassland conversion into other uses (e.g. urban-industrial, cropland) has reduced mesic regions of the MGP to 31% of its original size (Adams et al., 2013). These trends highlight the need to retain those native grasslands that remain. Loss of native grassland is associated with the decline of several EG&Ss, including rare, threatened and endangered wildlife (Alberta

Environmental Protection 1997). Maintenance alone is unlikely to conserve existing grasslands, as the ability of these areas to provide EG & S will depend on disturbances such as cattle grazing (Willms and Jefferson 1993) in combination with managing ongoing industrial disturbance.

1.2 Disturbance

Different types of natural disturbance (grazing, fire) have been important for grassland and the evolution of species within them. However, some disturbance may of a severe enough nature to cause marked changes in ecological function. Grazing by wildlife and environmental fire ignitions would be the natural equivalent of these disturbances.

1.2.1 Grasslands and Grazing

Range management is the practice of optimizing the production and long-term sustainability of rangelands. The connection between livestock, plant health and soil is important as it allows for a deeper exploration into the roles of herding animals (Voisin 1960). Livestock grazing is one of the main disturbances ongoing in grasslands, in part because fire has been widely suppressed (Baker 1992). The effects of grazing on the structure and functioning of grasslands and shrublands have been debated in the literature. Livestock are also a major source of greenhouse gas emissions in rangelands, largely through enteric methane production. Climate change and increasing atmospheric CO_2 concentration have been implicated in the post-industrial development of woody and invasive species into grasslands. Considerable work has been done to date examining the impact of grazing in MGP (Smoliak et al. 1972)

1.2.2 Carbon Storage in Grasslands

There are many goods and services possible from rangelands that can supply ecosystem services demanded by society, such as clean water and carbon storage. Rangelands represent a large store of C both in soil and vegetation. A potential pitfall in evaluating the benefits of disturbances occurs when the latter leads to invasive species, including woody plants, which can nevertheless sequester carbon (Asner et al. 2004). Dormaar (1984) found that grazing increases C in the MGP, while Naeth et al. (1991) indicated grazing decreased C. Furthermore, Henderson (2004) found grazing resulted in no changes in C within the MGP of Alberta.

1.2.3 Fire

Next to grazing, fire is the next most common natural disturbance that maintained North American grasslands. Indigenous peoples used fire for different purposes such as increasing food production, enhancing hunting success, and to create travel corridors (Sauer 1950). Prescribed burning is a recently implemented practice for controlling non-native plant species (DiTomaso et al. 2006). There are some studies that support the idea that burning is an effective tool to control non-native plant species in grasslands. Late spring or early summer is the best time to control non-native plant species because the effects are more detrimental to target plant species (DiTomaso et al. 2006).

Fire disturbance has now been widely suppressed, including in the MGP. There are some studies that show legumes are increased because of fire in northern temperate grasslands (Bork et al. 2002), suggesting that fire may release dormant legume seeds from the seed bank, potentially from favorable post-fire environmental conditions. Fire usually breaks the dormancy of many hard-coated legume seeds (Martin et al. 1975), and is therefore important as a recovery mechanism that allows burned plant communities to recover (Erichsen-Arychuk et al. 2002).

1.3 Industrial Disturbance

By altering soil and vegetation, industrial disturbances such as the construction of pipelines and power transmission lines, are an important factor resulting in a change to the ecosystem (Kaufman et al., 1993). The footprint of industrial disturbance on native grasslands has been rising since European settlement, and increasingly threatens the conservation of these ecosystems (Floate et al., 2011). Consequently, there is considerable interest in reducing these impacts. While rangeland plant communities are typically dominated by native graminoids (Coupland 1961) and adapted to the disturbance of grazing (Coughenour 1985; Milchunas et al. 1988), industrial activities are introducing new and intense disturbances that can detrimentally alter grassland vegetation. Moreover, ongoing changes in land use have resulted in decreased native grassland in many regions, including the MGP of southern Alberta, which historically comprised about 10% of the province. The total area of MGPs left in Alberta is 661,848 km^2.

Recent research shows that industrial development associated with oil and gas extraction may reduce ecosystem services from agricultural lands, including rangelands (Allred et al. 2015). There has been research regarding conventional energy (i.e. oil and gas) extraction on the mixed grass prairies, both in the short-term at construction (Petherbridge 2000) and over the long-term (Ostermann 2001; Hammermeister 2001; Hammermeister et al. 2004; Elsinger 2009; Desserud et al. 2010), although the extent to which this applies to other industrial disturbances, including transmission lines, is unknown.

One of the major impacts resulting from industrial development occurs at construction sites, when the native plant communities and underlying soils are sometimes removed and replaced, after which soil reclamation and vegetation re-establishment can be conducted. A second major impact that occurs during construction is a result of heavy equipment traffic and direct damage to vegetation and soil (Althoff et al 2007, Palazzo et al. 2005, Retta et al. 2013). To alleviate direct impacts to vegetation and underlying soil, industry often uses access mats (also called rig or swamp mats) (ASRD 2010).

Previous research indicates that the use of access mats in construction areas does not negatively impact either the density or canopy cover of grass species (Dollhopf et al. 2007). Some research suggests that the use of access mats protects the underlying plant (native grass and forb) community, and may avoid weed invasion, thereby conserving the original community (Mitchum et al. 2009). Additionally, some research suggests that the benefits of access mats in reducing soil compaction and promoting vegetation recovery are independent of the timing and duration of access mat stay in the field (Dollhopf et al. 2007).

Soil compaction can have a variety of effects. Compaction destroys soil structure and leads to a more massive soil with fewer natural voids. Additionally, soil compaction causes a decrease in large pores (called macropores), resulting in lower water infiltration rates into soil. Root growth in compacted soils can be restricted because roots can be impeded by a maximum soil consistency (i.e., as measured by penetration resistance) above which they are not able to expand (Vorhees et al. 1975; Gerard et al. 1982; Donkor et al. 2002). In theory, access mats reduce damage by limiting (and/or spreading out) physical disturbance to vegetation and soil. However, access mats themselves are also likely to affect vegetation by temporarily crushing plants, reducing light and altering moisture availability. The severity of these effects may depend on the duration and timing that mats are in place.

Contemporary transmission line construction has impacted substantial areas of rangelands in southern Alberta, including the mixedgrass prairie. Areas under and around high voltage transmission lines towers may also be impacted by several forms of alteration to vegetation and soil. Removal and storage of topsoil for even 6 months can contribute to lower organic matter and related nutrient supply in replaced soils on affected well sites (Hammermeister et al. 2006).

1.3.1 Pipelines, Transmission lines, Wind power plants

Pipeline are an important and widely used form of development to efficiently transport large amounts of oil, gas and water. However, pipeline disturbance may provide an invasion pathway for non-native species that have previously established elsewhere in the community (Zink et al. 1995). While electrical transmission lines are linear features like pipeline corridors, and in theory may have similar effects, their nature of construction is also likely to markedly differ. Pipeline construction more directly affects soil characteristics due to the necessary mechanical handling of soil. Soil stripping may reduce organic matter and increase clay content through admixing of topsoil with subsoil (Culley et al. 1982; Naeth et al. 1987). A pipeline right of way (RoW) can be defined by three general areas of construction: topsoil and subsoil storage area, trench and working (traffic) area. The degree of disturbance at any one location further depends on site characteristics. Pipeline construction has effects on both soil and vegetation. Pipeline construction changes soil properties and flora of the area (Kerr et al. 1993). Pipeline construction decrease topsoil thickness and soil organic matter, while increasing soil bulk density in spoil zones, largely because of mixing of topsoil and subsoil (Naeth 1985).

Electrical transmission lines may have less impacts on grasslands because they can be constructed in a way that limits the direct physical removal and replacement of soil by using access matting. Despite this, visual evidence from newly constructed transmission lines indicates this activity can have a significant impact on grassland composition, and thus, potentially impact their short and long-term land use potential. The land use alone includes an extensive grid of transmission lines, including both residential and high voltage lines, distributed across the western Canada prairies, and are increasing at a rate of 3804 km annually.

The Great Plains are increasingly being subject to energy development (Erickson et al. 2001; Obermeyer et al. 2011), which is impacting ecosystem goods and services, including the availability of grassland bird habitat (Coppedge et al. 2001). The direct removal of native vegetation happens when turbine towers are built and most of the time non-native plant species are re-established instead of native species (Coppedge et al. 2001). Soil disturbance and compaction occurs when there is heavy equipment passed over the ground in the process of assembling and erecting towers (Althoff et al., 2009; Raper, 2005) Also, soil erosion can happen if sites are sandy, or have steep slopes or high exposure to wind (Bradley 2010).

1.4 Mixedgrass Revegetation

Different ecosites may differ in their tolerance to disturbance and subsequent vegetation recovery patterns. Sandy areas are more prone to destabilization following disturbance than sites containing more fine textured spo;s (Hulett et al. 1966), thereby altering the specific management practices required to mitigate disturbance. Restoration of native grasslands typically occurs by seeding perennial species as normally dominant in the vegetation. Industrial disturbance in the form of heavy equipment traffic is often associated with the construction of infrastructure (e.g. pipelines, transmission construction) on prairie rangelands. Direct traffic on grasslands creates compacted soil tracks and bare soil where vegetation is ripped out, leading to increased erosion potential (Althoff et al., 2009; Raper, 2005; Thurow et al., 1996; Wilson, 1998). This equipment can directly impact both vegetation and soil, and may alter the provision of beneficial goods and services from grasslands. Re-establishment of vegetation is critical to restore ecosystem processes, and in many cases, meet regulatory compliance. When the destruction of the plant community is nearly absolute, such as in the case of prolonged cover by access mats, severe compaction or direct removal of soil and vegetation, recovery of the plant community requires new propagules to initiate re-vegetation. Planting seedlings can be prohibitively expensive, so the community is often allowed to recover from the seed bank or the addition of broadcast seed. The seed bank is defined as all viable seeds in the soil (Harper 1977). Recovery from the seed bank, in turn, is controlled by seed composition, dormancy, viability, as well as germination and survival (Walck et al. 2011). Some research suggests that seeding native plants can improve forage quality, leading to increased crude protein and lower neutral detergent fiber (McGraw et al. 2004). Unlike native vegetation, the origin of introduced species is likely the seedbank, which is frequently dominated by introduced species that are hyperabundant, even under moderate disturbance regimes (Willms and Quinton 1995) and some research suggests that native seedling density decreased with increasing nitrogen (Wilson and Gerry 1995).

1.5 Research Objectives

In western Canada, common industrial activities include oil and gas extraction and high voltage transmission line construction, both of which likely create significant impacts to native grassland vegetation and underlying soils. As these activities form a key component of the economy in the Canadian prairie provinces, understanding the specific management practices that can mitigate detrimental impacts of energy development, as well as maximize grassland recovery following their completion, are important for the managers of private and public rangelands, together with those industrial users seeking to minimize their environmental footprint.

In this thesis, I examine the effects of different construction methods (high and low disturbance, representing sod-stripping and access mat use, respectively) that represent different severities of disturbance to vegetation and soil characteristics, and examine the recovery of plant communities at these locations. Moreover, I further examine whether the use of low disturbance methods differs in its importance between sandy and loamy ecosites. The overall goal of this research is to understand how vegetation and soils change and recover in response to industrial disturbance associated with high voltage transmission line construction in the mixedgrass prairie. More specifically, I will: 1) investigate vegetation recovery and forage production changes between different construction treatments (including low disturbance access matting, and high disturbance sod-stripping methods); 2) investigate changes in soil physical, chemical and nutrient supply properties; and 3) investigate the role of environment (moisture) and soil properties between highly disturbed and low disturbance tower sites in regulating vegetation recovery. This study will evaluate the short-term recovery of native grassland and understand the beneficial management practices (BMPs) that aid the recovery of vegetation and soil.

At the end of my project, my results will inform other researchers, industry and landowners to understand the consequences of transmission line construction and provide insight into the best construction practices for maintaining mixedgrass vegetation and soil. This information may lead to actions by land managers that reduce the future environmental impact of industrial disturbance in native grassland. The thesis is structured as follows:

- Chapter 2 provides an overview of the contrasting effect of transmission line tower construction methods on soils of the mixedgrass prairies. In this chapter, soil physical and chemical characteristic are assessed under different construction methods.
- Chapter 3 is focused on the impacts of low and high disturbance transmission line construction on mixedgrass vegetation. In this chapter vegetation quality and quantity are assessed and comparisons are made between the two different construction methods, further stratified by different soil types.
- Chapter 4 provides a short synthesis of the key research results, including recommendations for best management practices for industrial development in the mixedgrass prairie. It also identifies challenges associated with the different construction methods along with future research needs.

Tested hypotheses include that soil removal and replacement would lead to less favorable soil characteristics relative to the use of access matting, including increasing soil bulk density and penetration resistance, while decreasing water infiltration. Additionally, soil removal and replacement was hypothesized to decreased soil chemical characteristic such as organic matter and %N.

In terms of vegetation responses, soil removal and replacement was hypothesized to have a greater impact on the pre-existing grassland, leading to a reduction in native vegetation and an increase in weedy species, compared to the use of access mats.

Chapter 2: Contrasting Effects of Transmission Line Tower Construction Methods on Mixedgrass Prairie Soils

2.1 Introduction

Native grasslands provide many ecological goods and services, including forage for livestock, wildlife habitat, and carbon sequestration and storage. However, native grasslands are a threatened ecosystem (Gibson 2009) and are among the most altered and least protected habitats globally (Hickman et al. 2013). Within disturbed grasslands, prompt re-establishment of vegetation is critical to restore ecosystem function, which largely relies on soil physical, chemical and biological characteristics (Gifford et al. 1977). Industrial disturbance such as pipeline and electrical transmission lines may have varying impact on soil characteristics, depending on the intensity and specific nature of disturbance associated with construction activities.

Within the Mixedgrass Prairies of southern Alberta, one common disturbance associated with ongoing land use that has been investigated is the construction of oil and gas extraction infrastructure (Kerr et al. 1993). These industrial activities include the construction of well sites and pipelines. The latter are lengthy linear disturbances, and can alter the vegetation and soils of grasslands across expansive areas. Pipeline construction often involves the removal and replacement of topsoil, with preferred methods reducing the loss of soil organic matter and preventing increases in bulk density (Naeth et al. 1987). Vehicle traffic can damage soil and vegetation during construction (Althoff et al 2007, Palazzo et al. 2005, Retta et al. 2013). As such, there is considerable interest in reducing their impacts where constructed within remaining grasslands. Previous studies have evaluated the effects of pipeline construction on soil quality in loamy textured soils, finding that wet soils were more sensitive to physical disturbances (Gifford et al. 1977). Soil texture is one of the most important factors that determine plant biomass production (Epstein et al. 1997), and different types of soil may exhibit variable plant recovery. For example, sandy soils are often more prone to destabilization to disturbance than fine textured soils (Hulett et al. 1966).

Heavy equipment traffic associated with construction can also alter grassland soils and lead to increases in compaction and erosion (Althoff et al., 2009; Raper, 2005; Thurow et al. 1996, Wilson, 1998). Soil compaction and changes in bulk density are more evident in wet soils, and in fall than spring, because freeze-thaw cycles can reduce the impact of past disturbance, such as grazing (Donkor et al. 2002). Soil compaction occurs when soil is compressed and the proportion of large pore space decreases (Balachowski and Kurek, 2014), in turn resulting in slower water infiltration and lower soil moisture content (Althoff and Thien, 2005; Unger and Kasper 1994). Consequently, less moisture is available for vegetation on soils compacted by pipeline construction (Naeth et al. 1991). Furthermore, root growth in compacted soils is restricted because roots are inhibited by soils with bulk densities above 1.6 Mg m^{-3}, and both vehicular traffic (Vorhees et al. 1975; Gerard et al. 1982) and animal traffic (Donkor et al. 2002) can increase compaction. To mitigate these impacts, industry often uses access mats (also called rig or swamp mats) to reduce the direct impacts of wheeled and tracked equipment on underlying soil and vegetation.

The effect of pipeline construction on soil chemical properties depends largely on the degree of mixing of soil horizons (Jong and Button 1973). Removal and replacement of topsoil contributes to lower soil organic matter and nutrient supply (Hammermeister et al. 2004), likely due to increased aeration and accelerated microbial degradation (Balesdent et al. 2000)

The purpose of ecosystem restoration is to return the disturbed area to a similar or greater ecological function as the non-disturbed state (Kline 1997) and includes the restoration of all soil conditions to those favoring key soil processes and associated plant growth. While the impacts of pipeline construction on Mixedgrass Prairie have been relatively well studied (as reviewed above), no studies have evaluated the impact of high voltage transmission line construction on native Mixedgrass Prairie, or the recovery of these systems following construction. The goal of this study was to understand how soils were altered by different transmission line tower construction activities *in situ*, including high disturbance methods involving conventional soil stripping, storage and replacement, as compared to low disturbance methods using access mats to protect underlying soils during construction. More specifically, this study: 1) evaluates the impact of sod-stripping and access matting construction methods on soil physical characteristics of mixedgrass prairies including soil bulk density, penetration resistance and water infiltration; and 2) assesses the impact of these treatments on soil chemical attributes, including soil organic matter, pH, salinity, soil nitrogen and carbon levels, and plant nutrient supply rates. Results of this study are expected to inform industry and landowners on the consequences of transmission line construction and to aid in the understanding of whether low soil disturbance methods may mitigate negative impacts of transmission line development on soil quality. This information may help land managers reduce the future environmental impact of industrial disturbance on native Mixedgrass Prairie soils.

2.2 Materials & Methods

2.2.1 Study Sites

We assessed the impact of two types of high voltage transmission line construction methods on Dry Mixedgrass prairie soils of varying texture in southeastern Alberta, Canada. A total of 15 high voltage towers were examined on the University of Alberta Mattheis Research Ranch (MRR), located 40 km north of Brooks, Alberta (Table 2-1; Figure 2-1). We assessed soil physical and chemical characteristics in soils of both sandy (n=9 tower sites) and loamy (n=6) textures, where different construction methods were used during transmission line tower construction. The MRR and surrounding landscape are primarily native (i.e. non-cultivated) grasslands, comprised of both stabilized sand dunes (>80% sand) and adjacent loamy prairie (<60% sand) (Table 2-2). The area has a mean annual precipitation of 354 mm and mean annual temperature of 4.2°C (Adams et al., 2013). Growing conditions during the study were drier than normal early in the 2015 growing season, but wetter than normal later that year and through much of 2016 (Appendix 1). Needle-and-thread grass (*Hesperostipa comata* Trin. and Rup.*),* western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve), Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and blue grama (*Bouteloua gracilis* (Willd ex Kunth) Lag. ex Griffiths) are the dominant plant species across the area, with sand grass (*Calamovilfa longifolia* (Hook.) Scribn.) as an additional dominant plant species in sandy textured soils. Individual study sites were classified as either Orthic Brown Chernozemic or Rego Brown Chernozemic soils.

2.2.2 Study Design and Treatments

This study was conducted on a portion of the Eastern Alberta Transmission Line, a 500 kilovolt (KV) direct current transmission line constructed in 2013-2014 by ATCO Energy, connecting the Heartland region NE of Edmonton to SE Alberta. Around 9 km of this transmission line crossed the 4,900 ha University of Alberta Mattheis Research Ranch. The average size of the area directly under the towers was approximately 10 m × 10 m, with the height of each tower specific to the tower design and the footings adjusted to the geologic ground formation. Footings were up to 18 m deep on a standard tower but varied with engineering requirements. The strength and size of the foundations take into account several different stress factors (wind loading, tension on the line, tower style, span length, etc.) and the soil type, which impacts how deep foundations were laid to obtain required compression and strength from the soil. Different foundation types, either caissons or H-piles, were used during tower construction (see Table 2-1). Caissons are concrete pillars reinforced with rebar, that are approximately 18 m deep and one meter wide, though specifications can vary due to local engineering requirements. H-Piles use long iron beams pounded directly into the ground until they hit bedrock and meet engineering resistance values. H-Piles are typically comprised of 9 beams per corner that are each approximately 18 m long (Table 2-1).

Two different tower constructions methods were used to erect the high voltage transmission towers. The access matting method (n=10; tower numbers, 1218, 1219, 1220, 1221, 1222, 1234, 1236, 1243, 1245, 1246) included the use of *in situ* (i.e., surface placed) access mats that left soil intact on site, with sites divided roughly evenly (6 vs 4) between sandy and loamy soils. Mats were put down on the prairie for up to 4 months during construction, and were removed when not in use, but replaced when construction activities resumed. The sod-stripping tower construction method (n=8; tower numbers 1216, 1217, 1223, 1224, 1227, 1230, 1231, 1233) was used at sites where topsoil was stripped from sites to level the topography to create safer construction conditions. During soil stripping the surface and subsoil layers (ca. 40 cm deep) were removed and stored separately. Sod-stripping construction was done largely on sites with more substantial variation in topography and included mostly the sandy dune ecosite areas (6 of 8 sod-stripped towers).

After tower construction was complete on sod-stripping treatments, the subsoil was replaced, then the topsoil, after which the area was subject to revegetation. Access matting treated sites were largely subject to natural recovery. To minimize the risk of erosion of exposed mineral soil, coconut matting was installed (held with metal stakes) over all the sod-stripping treatments and some of the access matting towers where soil had been exposed by repeated mat placement. However, strong winds rolled up the matting on several occasions, which had to be replaced and secured to the ground in the first year of recovery. One year after initial revegetation, the sod-stripping plots and some access matting towers (1218 and 1222) were hydroseeded in late May 2015 with a mix of grass species similar to the pre-existing vegetation (40% *Hesperostipa comata*, 15% *Koeleria macrantha*, 15% *Bouteloua gracilis*, 10%

Pascopyron smithii, and 20% Calamovilfa *longifolia)*. The binding agent for seed during hydroseeding was a mix of water and cellulose mulch, which remained visibly intact for the growing season. Additionally, fences were constructed around all towers in April 2015 after tower construction (and soil replacement in the case of sod-stripping towers) to prevent cattle from disturbing the construction impacted areas undergoing recovery.

Each tower site was further divided into 2 contrasting treatment areas: 1) the area immediately under the tower where construction activities occurred (either access matting or sod-stripping), and 2) a randomly selected 'non-treated' area outside of the tower construction area but on the same ecosite (typically 10-20 m away from the construction site). The latter ensured that pairwise compared plots had similar topographic position, including slope, aspect, and drainage, but the untreated area was not subject to construction activities (and primarily under natural vegetation), which acted as a spatial control.

2.2.3 Sampling and Measurement Methods

Soils within each of the paired subplots at each tower site were assessed for both soil physical and chemical properties during the summer of 2015 (30 subplots), coinciding with the first and second year after construction.

2.2.3.1 Soil Chemistry

In mid-July 2015, 4 randomly situated soil cores (3.2 cm wide × 7.5 cm deep), with a volume of 60 cm^3, were removed per subplot (n = 30) for the assessment of soil pH, electrical conductivity (EC), organic matter (OM). In mid-July 2016, 2 randomly located soil cores (6.3 cm wide x 3.6 cm deep), with a volume of 272 cm^3, were removed per subplot (n=30) for the assessment of soil bulk density (BD). In addition, nutrient supply rates of nitrogen (N) were assessed from plant root simulator (PRS^{TM}) probes. Soil samples were bulked within a subplot for further analysis.

Soil organic matter was quantified by loss on ignition in a muffle furnace for the soils of all sod-stripping and access matting subplots (total n=15 sites; 30 subplots) sampled in 2015. From the soil sampled at each subplot, 10 g of bulk soil was added to a crucible and dried at 110°C for eight hours, then ashed in a 550°C muffle furnace for 4 hr and reweighed in the crucible at 110°C; this was repeated with two replicates. The difference between the final and initial weights was considered the proportion (%) organic matter (Storer 1984).

In July 2015, soil electrical conductivity and pH were assessed for all soils collected from disturbed and control subplots. As soil salinity and pH were not expected to change markedly once reclamation had occurred, these metrics were assessed only one time for each subplot. A 2:1 mixture of 80 g distilled water and 40 g dry soil were combined and shaken for 30 minutes, then measured for soil pH using an Accumet Basic AB150 Benchtop pH/mv meter (Hach, Loveland, CO, USA), with two replicates from each subplot. Each pH sample was then allowed to settle and the soil water solution decanted using a pipet. To determine soil EC, the probe was calibrated with known EC standards. The resultant solution was tested for EC using a Milwaukee Mw80 Smart pH EC meter (Hach, Loveland, CO, USA).

Plant Root Simulator (PRS^{TM}) probes (Western Ag Innovations (WAI) Inc., Saskatoon, SK, Canada) were used to evaluate soil macronutrient and micronutrient supply rates within each subplot. Probes were installed 7.5 cm into the soil on April 25th, 2016, and contained a membrane that absorbs cations and anions while in the soil, which after removal, are then assessed back at the WAI lab for cation and anion uptake. In this study, four PRS^{TM} probe pairs (anion+cation) were installed vertically into random locations of the soil to 10 cm depth within each subplot, and then removed on August 30th, 2016 after 4.2 months in the field. PRS^{TM} probes were placed on May 30th for tower 1231 and removed at the same time with the rest of the probes. After removal, all probes were cleaned with deionized water and sent to WAI for analysis of plant macronutrients N (Nitrogen), K (Potassium), P (Phosphorus), S (Sulfur) and micronutrients Al (Aluminum), Ca (Calcium), B (Boron), Fe (Iron), Mn (Manganese), Zn (Zinc).

2.2.3.2 Soil Physical Properties

Roots and rocks larger than 2 mm were removed from the soil cores described above, after which soil was dried at 105°C for 24 hr. Bulk density was calculated by dividing the weight of the oven dried soil by the known core volume (Blake and Hartge 1986).

In 2015 an additional four soil cores (3.175 cm diameter by 15 cm deep) per treatment (non-disturbed control and disturbed areas under towers) were collected from random locations in all sod-stripping and access matting tower subplots (total n=15 towers), composited by subplot, and then air dried to a stable weight for the assessment of soil texture. Texture was determined manually with the hydrometer method for all subplots (n=30) (Day 1965), which provides quantitative data on the proportion (%) of sand, silt and clay within the top 15 cm (Table 2-2).

In 2015, soil penetration resistance (PR) was measured in mid-July for all subplots within most sod-stripping and access matting plots (15), which was repeated the following year (2016) monthly for all subplots (n=30) from May through August, inclusive. Fifteen towers were measured in the first year of recovery. PR was measured ten times at randomly selected locations per subplot. A Soil Compaction Tester (Dickey John Inc., Auburn, IL, USA) with a 1.27 cm^2 tip was used in 2015, but due to readings that approached maximum instrument sensitivity in some of the controls, this was switched to an HS-4210 digital static cone penetrometer (DSCP) (Humboldt Mfg. Co., Elgin, IL, USA) with a 1.5 cm^2 tip in 2016. The change in instrumentation between years is not expected to influence PR measurements, as Gao et al. (2012) found that PR is not particularly sensitive to cone diameter.

In 2015 and 2016, soil moisture was measured at one time (mid-July) for all sod-stripping and access matting subplots (n=15 towers). Moisture measures the second year were assessed monthly from May to August, inclusive. During each sampling time, six sub-readings were taken at random locations within each subplot and averaged for further analysis. Two different soil moisture probes were used for these assessments. An ML3 ThetaProbe soil moisture sensor (Delta-T Devices, Burwell, UK) was used initially during July of 2015 and May of 2016, to assess moisture in the top 7.5 cm of soil. However, the ThetaProbe broke in May 2016, and subsequently a TDR300 Field Scout Digital Moisture Sensor (Turf-Tec International, Tallahassee, FL, USA) with a sample volume of 53.0 cm^3 (75 mm x 30 mm diameter cylinder) was used.

During 2016, water infiltration rates (IR) were assessed by following the USDA (2001) infiltration testing method. Four 20.3 cm diameter plastic rings were installed to 15 cm along a centrally located transect within each subplot and at least 127 mm deep into the soil with as little soil disturbance as possible. A total of 824 ml of water was then poured into the top of each ring (representing 100 mm of rainfall), and the time required for complete infiltration to occur recorded in minutes. All vegetation, litter and mosses were left in place. IRs for towers 1216 to 1223 were measured from July 10 to14, while IRs for the remaining towers were measured from July 25 to 26.

2.2.4 Data Analysis

All data were analyzed using R software (R Foundation for Statistical Computing, Vienna, Austria). Response variables included soil physical (bulk density, infiltration, moisture and penetration resistance) and chemical (soil OM, N, C:N ratios, and nutrient availability) characteristics. All data were checked for homogeneity of variance and normality with the Shapiro-Wilk test. If not normally distributed the data were log transformed to achieve normality. In the sandy sod-stripping study area, soil OM and EC, together with monthly readings of soil moisture and penetration resistance in 2016 were log transformed, together with the availability of Fe, B, S, Pb, and Cd. In the loamy access matting study area, soil pH and EC, monthly measures of soil moisture and compaction in 2016, as well as the availability of N, Cu, Zn, Pb, and Cd, were log transformed. In the sandy access matting study area, soil OM, pH, and monthly soil moisture and compaction (in 2016), along with soil N, Mn, B, S, Pb, and Cd availability, were all log transformed. Original data are presented here, with transformed data used to conduct all statistical tests.

To facilitate analysis, we first examined the soil texture found at all 15 tower sites. Based on these data, the five sod-stripping towers were found to be located in soils of predominant sandy texture (sand > 80%), while four access matting towers were located in sandy soils (sand > 80%). In contrast, six other access matting towers were located in loamy soils (sand < 60%) (Table 2-2). Based on the marked differences in initial soil texture (and associated ecosite properties such as landscape topography) and the unbalanced design of the disturbance treatments (i.e. the lack of sod-stripped towers on loamy ecosites in 2015), we conducted an independent analysis of each tower construction method × ecosite combination, which was made possible by the inclusion of spatial controls (i.e., non-treated grassland) at each tower site. Consequently, the analysis looked at all combinations except sod-stripping on loam soils.

Analysis of variance (ANOVA) was then used with mixed model procedures using the *lme4* software package in R software to determine whether soil physical and chemical characteristics responded to the sod-stripping and access matting treatments. In this analysis the treatment, disturbance (either sod-stripping or access matting) or control, was a fixed effect, and tower (site) was a random effect. Soil compaction and moisture were also analyzed for both the first and second years of recovery using month of sampling as a repeated measure ANOVA, with time as an additional fixed factor. All analyses were based on least-square means, with differences considered significant at $P < 0.05$ for main effects and interactions.

2.3 Results

2.3.1 Soil Physical Responses

2.3.1.1 Soil Bulk Density

We observed a significant increase in the bulk density of disturbed areas (2.2 ± 0.1 g cm^{-3}) compared to non-disturbed control areas (0.8 ± 0.1 g cm^{-3}) under the sod-stripping towers ($F_{1,4} = 11.3$; $P = 0.02$); soil bulk density was more than 2-fold greater with soil removal and replacement than undisturbed areas in sandy ecosites. We observed no significant differences in bulk density between access mat (1.4 ± 0.09 g cm^{-3}) and control (1.3 ± 0.09 g cm^{-3}) treatments in the low disturbance treatments on loamy soils ($F_{1,5} = 3.12$; $P = 0.11$), with a similar result in matted areas (0.9 ± 0.07 g cm^{-3}) and non-disturbed control areas (1.1 ± 0.07 g cm^{-3}) of sandy ecosites ($F_{1,3} = 2.46$; $P = 0.21$) (Figure 2-2A).

2.3.1.2 Water Infiltration

Results indicate there was a significant increase in water infiltration rates (IR) within matted areas (485.9 ± 58.7 mm $hour^{-1}$) as compared to non-disturbed control areas (325.2 ± 52.5 mm $hour^{-1}$) under the access matted towers of the loamy ecosite ($F_{1,4} = 4.16$; $P = 0.08$). In addition, there was a significant decrease in IR within access matted areas (390.8 ± 31.88 mm $hour^{-1}$) relative to control treatments (489.3 ± 31.88 mm $hour^{-1}$) of the sandy ecosites ($F_{1,8} = 4.77$; $P = 0.06$). Infiltration rates did not differ between sod-stripping (765.2 ± 148.16 mm $hour^{-1}$) and control treatments (419.9 ± 165.65 mm $hour^{-1}$) within the sandy ecosites ($F_{1,8} = 2.41$ $P = 0.16$) (Figure 2-2B), largely due to high variability in responses among individual towers.

2.3.1.3 Soil Moisture and Penetration Resistance

Soil moisture was measured once during mid-July 2015, with no significant differences between the disturbed and control treatments in either the sod-stripping ($F_{1,4} = 1.64$; P = 0.22), or access matting (loamy ecosite: $F_{1,5}$; = 2.13; P = 0.12; sandy ecosite: $F_{1,3} = 2.15$; P = 0.13) experimental treatments (Appendix 2A). Soil moisture was measured monthly from April to August of 2016 in each plot, with no differences between the disturbed areas and controls within the sandy sod-stripped towers for any of the comparisons (Table 2-3). Soil moisture varied monthly within all study sites throughout 2016, regardless of treatment regime. Average soil moisture was overall variable in sod-stripping areas of the sandy sites (3.0 to 2.5 ± 0.08 %) between all months (see Table 2-3, 2-4). Soil moisture also varied between all months in study sites of the access matting treatments in the loamy ecosite (5.8 to 6.1 ± 0.08 %) ($F_{4,40} = 7.20$; P = 0.0002, see Table 2-3, 2-4). In access matted sandy sites, soil moisture was varied (3.6 to 3.7 ± 0.06 %) between all months ($F_{4,24} = 28.1$; P = 0.0001) (see Tables 2-3, 2-4) in access matting sandy sites. Finally, while soil moisture differed between July 2015 and July 2016 in both the sod-stripping and access matting plots within each ecosite, these metrics did not vary further in relation to disturbance treatment (Appendix 3, Appendix 4).

Soil penetration resistance in 2015 was measured once in mid-July, with no significant differences between disturbed and control treatments in either the sod-stripping ($F_{1,4} = 0.91$; P = 0.38), or access matting experimental treatments (loamy ecosite: $F_{1,5}$; = 1.91; P = 0.21; sandy ecosite: $F_{1,3} = 1.91$; P = 0.25) (Appendix 2B). Soil penetration resistance did not vary between July 2015 and July 2016, alone or in relation to treatment, within the sod-stripping and access matting loamy tower construction methods. However, penetration resistance did vary within the access matting sandy sites between the first and second years of recovery (Appendix 3, Appendix 4).

Soil penetration resistance was measured monthly from April to August of 2016 in each subplot. Soil penetration did not differ between disturbed and non-disturbed control areas within either the sod-stripping or access matting towers ($P > 0.05$; Table 2-3). Soil penetration resistance varied monthly within all study sites, regardless of treatment regime, throughout 2016. Mean monthly soil penetration resistance was varied between all months in the sod-stripping method in sandy soil (316.2 to 337.6 ± 0.06 PSI; $F_{4,32} = 13.7$; $P = 0.0001$) (see Tables 2-3, 2-4). In access matted loamy sites; soil penetration resistance was overall varied (387.8 to 353.8 ± 0.1 PSI) between all months ($F_{4,40} = 4.77$; $P = 0.003$) (see Tables 2-3, 2-4). Soil penetration resistance was overall varied between all months in study sites of the access matting treatments in sandy ecosites (401.3 to 403.8 ± 0.06 PSI) ($F_{4,24} = 11.1$; $P = 0.0001$) (see Tables 2-3, 2-4).

2.3.2 Soil Chemistry

We observed no significant differences in soil pH between disturbed areas (6.2 ± 0.05) and control areas (6.4 ± 0.09) under sod-stripping towers ($F_{1,4} = 0.80$; $P = 0.51$). Similarly, in access matting loamy there were no significant differences in pH between soils exposed (6.7 ± 0.1) compared to the adjacent controls (6.8 ± 0.1) ($F_{1,5} = 1.11$; $P = 0.55$) and in access matting sandy, pH was no significant between disturbed areas (6 ± 0.03) relative to their controls (6.1 ± 0.03) ($F_{1,3} = 5.1$; $P = 0.06$) (Appendix 5A).

In terms of electrical conductivity, we observed no significant difference between disturbed areas (76.8 ± 0.3 mS m^{-2}) and control areas (60 ± 0.40 mS m^{-2}) under sod-stripped towers ($F_{1,4} = 2.3$; $P = 0.11$). No differences in EC were evident between soils in access matted plots on loamy soils (124.3 ± 0.7 mS m^{-2}) relative to the control (132.2 ± 0.7 mS m^{-2}) ($F_{1,5} = 0.32$; $P = 0.71$). Soil EC also did not differ between soils in access matted areas in sandy soils (63 ± 6.8 mS m^{-2}) relative to their controls (62.2 ± 6.8 mS m^{-2}) ($F_{1,3} = 0.75$; $P= 0.93$) (Appendix 5B).

2.3.2.1 Soil Organic Matter and N%

The sod-stripping method of tower construction led to a 56% decrease in soil organic matter compared to the adjacent control areas ($F_{1,4} = 25.9$; $P = 0.00001$; Figure 2-3A). In contrast, soil OM remained similar on soils exposed to matting, regardless of soil type ($P \geq 0.05$; Figure 2-3A). Sandy soils also generally had lower soil OM levels compared to the loamy soil (see Figure 2-3A).

Patterns of soil N concentration closely followed those of soil OM, with about half the soil N found in sod stripped disturbed areas relative to control areas on sandy soils ($F_{1,4} = 23.9$; $P = 0.0001$; Figure 2-3B). No differences in soil N were evident due to matting on either the loamy sites ($F_{1,5} = 7.96$; $P = 0.22$), nor the sandy sites ($F=2.41$; $P = 0.14$) (Figure 2-3B).

In terms of the soil C:N ratio, we observed no significant differences between disturbed areas (12.3 ± 0.3 %) and control areas (12.8 ± 0.4 %) under sod-stripping towers ($F_{1,4} = 0.02$; $P = 0.88$). Soil C:N ratio also did not differ between soils in access matted loamy soil (11.6 % ± 0.2) compared to their controls (11.3 % ± 0.2) ($F_{1,5} = 0.98$; $P = 0.33$). Similarly, no significant differences in C:N ratio occurred between soils in access matted sandy soils (11.4 ± 0.2 %) relative to the control (11.6 ± 0.2 %) ($F_{1,3} = 0.65$; $P = 0.43$) (Appendix 5C).

2.3.2.2 Nutrient Availability

During the 2nd growing season of recovery, soil total macro and micro nutrients were assessed. Within the sod stripped sandy areas, the availability of Ca and Fe increased by 38% and 77%, respectively, and the availability of K decreased by 36% during the growing season ($P < 0.08$) on areas with the sod-stripping construction method (Table 2-5) compared to the adjacent controls. In access matted loamy sites, the availability of S, K, Mg, Fe, and Cu declined by 4%, 11%, 15%, 8% and 67%, respectively, within matted sites ($P < 0.09$) (Table 2-6). In access matted sandy sites, the availability of Al and Zn increased by 18% and 25% (Table 2-7), due to the placement of mats on grassland, relative to the control.

2.4 Discussion

2.4.1 Soil Physical Properties

While transmission lines are linear disturbance features similar to pipeline corridors, it remains unknown whether construction of the former leads to similar effects on grassland soils. In the current study, two markedly different construction methods (access matting and sod-stripping) were examined within Mixedgrass Prairie. Between these treatments, stripping and handling of the surface soil under high disturbance towers (to achieve levelling) likely emulates the disturbance effects found along pipeline trenches. Notably, soil bulk density was greater in disturbed areas using the sod-stripping method, but unchanged in grassland soils subjected to access matting. This indicates that the use of low disturbance construction methods is capable of reducing soil surface disturbance impacts during transmission line construction. Although this outcome is consistent with the recommendation that access mats be used in many areas (grasslands, forests, wetlands, etc.) to reduce the physical impact of equipment on vegetation and soils (AEP 2016), it is important to note that the study design employed here did not include a treatment with traffic only (i.e. directly on prairie). As a result, the benefit of the low disturbance treatment in preventing changes in grassland soils must be considered jointly in the context of soils being kept intact in the landscape along with the potential reduced effect of heavy equipment traffic to soils.

Under the sod-stripping method, soil was removed, stockpiled, and later replaced, which may have destroyed soil structure (i.e. aggregates), thereby contributing to the observed increase in bulk density (Kuncoro et al., 2014a). Passing heavy equipment over the soil is known to cause soil macro aggregates to rearrange, hence decreasing soil pore space (Defossez and Richard

2002). Moreover, exposure to heavy equipment traffic, particularly during soil replacement, may have directly contributed to soil compaction and the increased bulk density. Soil compaction occurs when soil particles and pores are compressed under an applied force, deforming soil aggregates (Balachowski and Kurek, 2014), and compressing large soil pores into smaller soil pores. This in turn, increases bulk density from the decrease in air filled pores, and reduces pore connectivity (Kuncoro et al., 2014b). Increases in soil bulk density (i.e., 2.2 g cm^{-3}) can be problematic if these increases lead to levels that exceed limits for plant growth. Vegetation recovery within the sod-stripping treatment was generally slower than that in the low disturbance treatments, particularly of grasses (Chapter 3), and was accompanied by reduced root biomass (and root:shoot ratios), suggesting that the increase in bulk density may have negatively impacted vegetation recovery. Soil bulk densities within the sod-stripping treatment (i.e. as high as 2.2 g cm^{-3}) were above the recommended maximum (1.1 to 1.5 g cm^{-3}) for revegetation (Sheoran et al., 2010).

Despite this, the sod-stripping treated areas were revegetated after as little as three years, indicating any negative effects of sod stripping did not appear to preclude long-term revegetation in this investigation. Bulk density usually takes 1-3 years to recover in the top 10 cm of soil after disturbance (Althoff et al. 2010). Finally, it is notable that neither of the construction methods (sod-stripping vs access matting) examined here resulted in changes to soil penetration resistance, including throughout the 2nd growing season. This was surprising given the initial increase in bulk density observed in the sod-stripping study during the first growing season, and could reflect changes in bulk density from the first to second year. Free-thaw cycles over the winter of 2015-16 could have helped alleviate any compaction arising from heavy equipment (Donkor et al. 2002a), potentially accounting for the lack of differences in PR.

In contrast to the sod stripped areas, the access matting disturbance treatments led to stable soil bulk densities as well as PRs. This indicates the use of matting was able to better conserve soil structural attributes in this mixedgrass prairie, presumably by spreading the load bearing weight of heavy equipment across the ground surface (Gartrell 2009), protecting the underlying soil, and preventing soil structure degradation. This finding is similar to that of other studies reporting that access mats were able to maintain soil physical properties (Gartrell, 2009; Mitchem et al., 2009). Additionally, some evidence suggests the benefits of access mats in protecting soil and promoting vegetation recovery is independent of the timing and duration of access mat placement in the field (Dollhopf et al. 2007).

Although soil bulk densities increased within the sod-stripping treatment, water infiltration rates did not change significantly in this same treatment within the current investigation. This was surprising because soil compaction and reduced pore sizes is known to contribute to reduced water infiltration (Althoff and Thien, 2005; Unger and Kasper, 1994). As the sod-stripping treatments were all conducted on sandy soils, these soils may have remained relatively resistant to changes in infiltration despite soil compaction, suggesting the more disturbed treatment may not have altered hydrologic function of this particular grassland ecosite. In contrast, we unexpectedly found that water infiltration increased on the loamy soils and decreased on sandy soils subject to access matting, which occurred despite no change in soil bulk density or penetration resistance. While reductions in infiltration often reflect decreased macropores (Naeth et al. 1991), the mechanism by which this could have occurred in the matted loams tested here remained unclear, particularly as these soils were not subject to direct wheeled traffic. One possibility is that access mats may have altered the soil surface in some way that otherwise altered infiltration and impaired hydrologic function. For example, access mats were found to reduce microphytic crusts in these soils (Chapter 3), which in turn, may have helped maintain water infiltration. By reducing infiltration, matting on sandy soils could render these ecosites more susceptible to overland flow during heavy rain, evaporation, and hence reduced water availability, which is particularly problematic given that water generally limits production in the mixedgrass prairie (Willms and Jefferson 1993), including within sandy soils where overall moisture holding capacity is lower (Bork and Irving 2015).

Mats were put down in access matting towers for up to 4 months resulting in the vegetation and soil under mats not receiving any light. However, as matting occurred prior to the first growing season of monitoring here, our results are probably more indicative of water use (i.e. by vegetation) rather than water accumulation during mid-summer.

2.4.2 Soil Chemistry

In the current study, sod-stripping of sandy soil, which was then stockpiled for up to four months, led to decreased soil organic matter and soil N concentrations compared to control soils. In contrast, soil organic matter and N levels did not change using the low disturbance construction method (i.e., access matting), regardless of ecosite type. Soil stripping likely reduced organic matter, potentially through admixing of topsoil with subsoil (Culley et al, 1982; Naeth et al, 1987). Removal of topsoil and storage for even 6 months can contribute to lower organic matter and related nutrient supply in replaced soils (Hammermeister et al. 2006), likely due to increased aeration and accelerated microbial degradation (Balesdent et al. 2000). Stockpiled soil may be warmer due to its lack of insulation (no litter or mulch, and increased exposure to oxygen). Changes in vegetation and associated soil physical and chemical characteristics under disturbance may markedly change microbial composition and diversity (Brussard and Van Faassen, 1994; Quideau et al., 2013), yet little is known about how substantive these changes are in relation to specific industrial activities. In sod-stripped areas, soil was removed and subsequently replaced and hydroseeded, likely resulting in changes in soil temperature and microbial access to electron acceptors (O_2) through soil aeration, which led to alterations in the composition of the microbial community (Morris and Boerner, 1999; Carletti et al., 2009). According to Chapter 3, these sod-stripping areas would have had bare soil for extended periods, and this would have slowed microbial activity until more inputs were eventually received after revegetation. As a result, soil stripping and replacement is likely to reduce those soil properties critical to maintaining ongoing grassland ecosystem function related to nutrient cycling and hydrology, as well as maintain productivity. Organic matter is one of the most important soil characteristics that changes due to disturbances, with the recovery of organic matter in the dry mixedgrass prairie potentially taking many decades (Dormaar and Willms, 1993).

In the current study, no changes in soil pH or EC were detected in relation to the treatments, even soil stripping. This contrasts several previous studies that have shown the removal of soil during pipeline installation can lead to lower pH and an increase in EC (Elsinger 2009); the latter is associated with the incorporation of subsurface salts into the topsoil and was typically found on loamy texture mixedgrass prairie ecosites. As we did not evaluate the impact of sod-stripping treatments on loamy soils, where salts may be more likely to be near the soil surface, we are unable to conclude that these soil characteristics are immune to sod-stripping treatment, and therefore recommend caution in extrapolating these results to all ecosites.

Changes were detected in the nutrient supply rates using the PRS^{TM} probes in relation to both the sod stripping and access matting treatments, with the latter varying further between loamy and sandy ecosites. The supply of select nutrients (Ca, Fe) increased in the sod-stripped areas of sandy ecosites, while only that of K decreased under the sod-stripping treatment. Within the same sandy ecosite but subject to low disturbance, Al and Zn increased with matting. In contrast, many soil nutrients (K, S, Mg, Fe, Cu) decreased under matting in the loamy ecosite, with no nutrients increasing their supply rates under matting at this location. A combination of treatment effects and ecosite differences likely reflect the observed nutrient supply rates arising in this study. Increases in calcium specifically may also have arisen due to the hydroseeding and use of coconut matting, as coconut matting has 10 % calcium (Commission 2001), which in turn, could have increased the availability of calcium in these areas.

In this study, due to access mats being placed on soils for a couple of months, an increase in zinc and aluminum in access matting sandy sites was observed. Additionally, a decrease in other nutrients (K, S, Mg, Fe, and Cu) under access matting occurred in the loamy site. Observed nutrient supply rates in soils are a function of a combination of factors, including mineralization and plant uptake, the latter of which may have been reduced in the sod-stripping treatment due to the widespread increase in introduced forbs (see Chapter 3), and could therefore have led to the increased supply rates of trace minerals.

2.5 Management Implications

High disturbance (sod-stripping) transmission tower construction, that involved stripping and stockpiling of soil, negatively impacted select soil physical and chemical properties (i.e. increased bulk density, and reduced soil OM and N) within the sandy mixedgrass prairie study sites. In contrast, the use of low disturbance methods (access mats) on both sandy and loamy ecosites was relatively effective at conserving soil physical and chemical properties of the initial grassland, although select soil properties did decline under matting within the loam sites (water infiltration and soil nutrient supply). Thus, the use of low disturbance construction methods, as demonstrated here by access mats overtop of otherwise non-disturbed soil, appears to be a better choice compared to soil removal for the conservation of mixed grass prairie soils during industrial development.

Table 2-1. Summary of different foundation types used during high voltage transmission line tower construction at the Mattheis Research Ranch, situated in the Dry Mixedgrass Prairie of SE Alberta, Canada.

Tower Number	Construction Method	Foundation type
1216	Sod-stripping	Caisson
1217	Sod-stripping	Caisson
1218	Access matting	Caisson
1219	Access matting	Caisson
1220	Access matting	Caisson
1221	Access matting	H-Pile
1222	Access matting	H-Pile
1223	Sod-stripping	H-Pile
1224	Sod-stripping	Caisson
1227	Sod-stripping	H-Pile
1230	Sod-stripping	H-Pile
1231	Sod-stripping	H-Pile
1233	Sod-stripping	H-Pile
1234	Access matting	H-Pile
1236	Access matting	H-Pile
1243	Access matting	H-Pile
1245	Access matting	H-Pile
1246	Access matting	H-Pile

Table 2-2. Summary of soil texture and construction methods, as well as the date of hydro-seeding (where applicable) for all high voltage transmission towers. High disturbance (HD) and low disturbance (LD) represent sod-stripping and access matting, respectively. In all HD and two LD (1218 and 1222) towers surrounded by fences and coconut matting used on the hydroseeding.

Tower Number	Construction Method	%Sand	%Silt	%Clay	Textural Class	Hydroseeding Date
1216	HD	5.6	9.5	88.7	Clay	May 2016
1217	LD	5.7	10.1	87.4	Clay	May 2016
1218	LD	16.3	48.8	30.7	Loamy	April 2015
1219	LD	16.1	51.2	23.6	Loamy	Not seeded
1220	LD	17.9	33.3	33.6	Loamy	Not seeded
1221	LD	20.0	31.2	30.7	Loamy	Not seeded
1222	LD	22.4	26.8	34.7	Loamy	April 2015
1223	HD	80.4	14.3	5.1	Sandy	April 2015
1224	HD	90.5	4.6	4.7	Sandy	April 2015
1227	HD	88.0	0.2	11.6	Sandy	April 2015
1230	HD	84.8	10.1	4.9	Sandy	April 2015
1231	HD	85.6	5.7	4.3	Sandy	June 2016
1233	HD	93.4	2	4.5	Sandy	April 2015
1234	LD	94.2	1.5	4.2	Sandy	Not seeded
1236	LD	84.6	8.4	6.8	Sandy	Not seeded
1243	LD	87.1	6.2	6.5	Sandy	Not seeded
1245	LD	86.7	6.7	6.5	Sandy	Not seeded
1246	LD	50.7	19.7	20.5	Loamy	Not seeded

Table 2-3. Summary of the ANOVA assessment of soil moisture and soil penetration resistance responses across sequential months of sampling during the 2016 growing season.

Source	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
	F	df[1]	*P*	F	df	*P*	F	df	*P*
------------------------------- *Soil Moisture Responses* ------------------------------									
Treatment (T)	0.10	1,4	0.76	0.02	1,5	0.90	0.16	1,3	0.71
Month (M)	8.60	4,32	**0.0001**	7.20	4,40	**0.0002**	28.11	4,24	**<.0001**
T x M	1.60	4,32	0.20	0.08	4,40	0.98	1.30	4,24	0.30
------------------------ *Soil Penetration Resistance Responses* -----------------------									
Treatment (T)	0.95	1,4	0.38	0.70	1,5	0.44	2.01	1,3	0.25
Month (M)	13.7	4,32	**<.0001**	4.77	4,40	**0.003**	11.1	4,24	**<.0001**
T x M	0.70	4,32	0.60	0.28	4,40	0.88	1.6	4,24	0.20

[1] Values represent numerator and denominator degrees freedom, respectively.

Table 2-4. Summary of mean (±SE) soil moisture and penetration resistance (PR) measured following different transmission tower construction methods, throughout the second growing season of recovery (2016). Data were collected monthly from April to August.

Treatment: Ecosite:		Sod-stripping Sandy		Access matting Loamy		Access matting Sandy	
		μ ± SE		μ ± SE		μ ± SE	
Response	Sampling Date	Disturbed	Control	Disturbed	Control	Disturbed	Control
Moisture (%)	April	3.2	2.6	3.6	3.5	2.9	3.0
	May	2.4	2.8	6.1	6.6	3.0	3.1
	June	2.3	3.1	6.4	6.6	3.8	3.3
	July	4.8	5.5	7.0	7.6	5.5	5.7
	August	2.4	4.1	6.0	6.2	3.2	3.1
		(±0.1)		(±0.1)		(±0.07)	
	All Months	3.0 a[1]	2.5 b	5.8 a	6.1 b	3.6 a	3.7 b
		(±0.08)		(±0.08)		(±0.06)	
PR (PSI)	April	210.0	232.0	296.1	232.9	360.0	324.0
	May	279.0	289.0	374.6	357.5	414.0	390.0
	June	484.0	517.0	530.0	565.0	510.0	590.0
	July	305.0	285.0	354.1	268.9	328.5	330.0
	August	303.0	365.0	385.0	345.9	394.0	385.0
		(±0.08)		(±0.1)		(±0.08)	
	All Months	316.2 a	337.6 b	387.8 a	353.8 b	401.3 a	403.8 b
		(±0.06)		(±0.1)		(±0.06)	

---

[1] Means within a treatment and response variable with different letters differ, $P<0.05$.

Table 2-5. Results of the ANOVA analysis evaluating plant macronutrient and micronutrient availability between disturbed and control treatments in sod-stripping sandy ecosites of the Dry Mixedgrass Natural Subregion in Alberta, Canada. Nutrient availability was assessed with PRS^{TM} probes installed from April 21 until August 30, 2016. Comparisons shown in bold are significant ($P < 0.10$).

Nutrient Availability	Disturbed (μg probe^{-1} burial period[1])	Control (μg probe^{-1} burial period[1])	F-stat[1]	P-value	SE
	------------------------- *Plant Macronutrients* -------------------------				
Total N	19.2	15.6	0.60	0.48	3.47
P	16.5	17.1	0.008	0.93	4.71
K	**323.5**	**500.6**	**4.95**	**0.08**	**68.20**
S	39.6	110.6	0.51	0.51	0.60
	------------------------- *Plant Micronutrients* -------------------------				
Ca	**1855.4**	**1343.8**	**8.06**	**0.04**	**135.80**
Mg	431.4	373.4	2.01	0.23	40.66
Mn	5.3	4.3	0.74	0.43	0.75
Fe	**5.3**	**3.6**	**9.50**	**0.03**	**0.30**
Al	11.3	7.7	2.8	0.16	1.50
B	0.95	0.34	2.60	0.18	0.30
Zn	4.0	3.8	0.02	0.90	0.80
Cu	0.06	0.03	1.88	0.24	0.02

[1] Analysis is based on 1 and 4 df for the numerator and denominator, respectively.

Table 2-6. Estimate of plant macro and micro nutrient availability between disturbed and control treatments within access matted loamy sites in the Dry Mixedgrass Natural Subregion of Alberta, with PRS^{TM} probes installed from April 21 until August 30, 2016. Comparisons shown in bold are significant ($P < 0.10$).

Nutrient Availability	Disturbed (μg probe^{-1} burial period^{1})	Control (μg probe^{-1} burial period^{1})	F-stat[1]	P-value	SE
------------------------ *Plant Macronutrients* -------------------------					
Total N	10.4	25.5	0.01	0.92	0.33
P	13.3	13.8	3.85	0.10	1.71
K	**245.7**	**279**	**4.26**	**0.09**	**16.8**
S	**18.0**	**18.7**	**5.8**	**0.06**	**0.55**
------------------------- *Plant Micronutrients* -------------------------					
Ca	1785.2	1976.7	1.88	0.22	101.0
Mg	**344.2**	**404**	**8.92**	**0.03**	**27.3**
Mn	3.2	2.9	0.0003	0.98	0.17
Fe	**3.6**	**3.9**	**0.84**	**0.03**	**0.66**
Al	9.6	13.3	3.01	0.14	1.32
B	0.5	0.7	0.67	0.44	0.16
Zn	3.07	1.4	1.07	0.34	0.48
Cu	**0.03**	**0.09**	**6.17**	**0.05**	**0.03**

[1] Analysis is based on 1 and 5 df for the numerator and denominator, respectively.

Table 2-7. Estimate of plant macro and micro nutrient availability between disturbed and control treatments in access matting sandy sites of the Dry Mixedgrass Natural Subregion. of Alberta, with PRS^{TM} probes installed from April 21 until August 30, 2016. Comparisons shown in bold are significant (P < 0.10).

Nutrient Availability	Disturbed (µg probe^{-1} burial period[1])	Control (µg probe^{-1} burial period[1])	F	P-value	SE
------------------------ *Plant Macronutrients* -------------------------					
Total N	20.5	15.0	0.61	0.50	0.45
P	6.4	10.3	0.08	0.80	2.10
K	61.0	102.6	0.24	0.66	101.1
S	214.0	29.3	0.01	0.91	4.55
------------------------- *Plant Micronutrients* -------------------------					
Ca	1785.2	1976.7	1.1	0.36	144.0
Mg	401.5	470	2.62	0.20	27.6
Mn	1.8	1.7	0.02	0.87	1.15
Fe	4.4	3.3	0.04	0.84	0.92
Al	**11.9**	**10.0**	**6.5**	**0.08**	**1.04**
B	0.5	0.3	2.18	0.23	0.23
Zn	**2.9**	**2.2**	**6.2**	**0.08**	**0.21**
Cu	0.01	0.06	0.92	0.40	0.04

[1] Analysis is based on 1 and 3 df for the numerator and denominator, respectively.

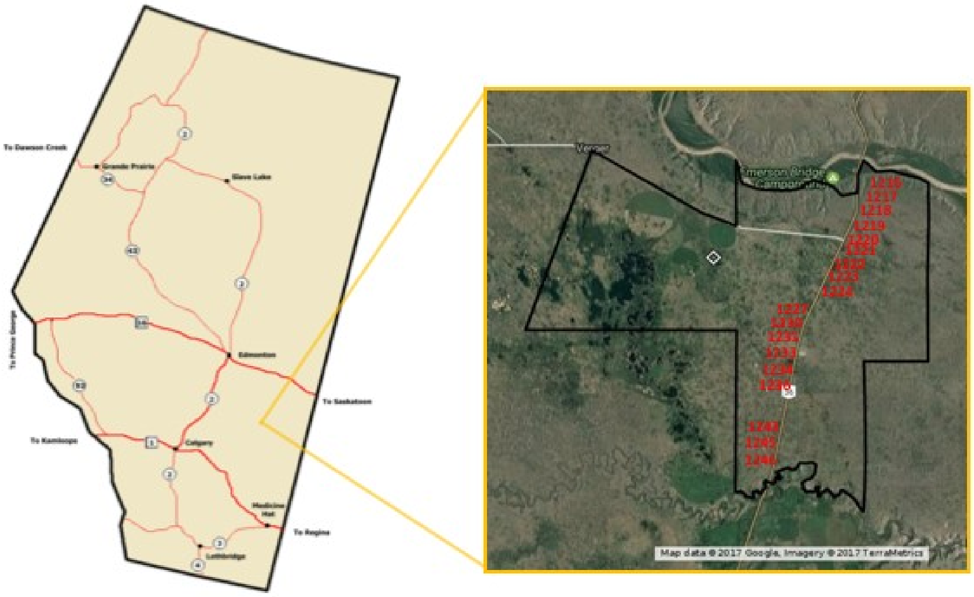
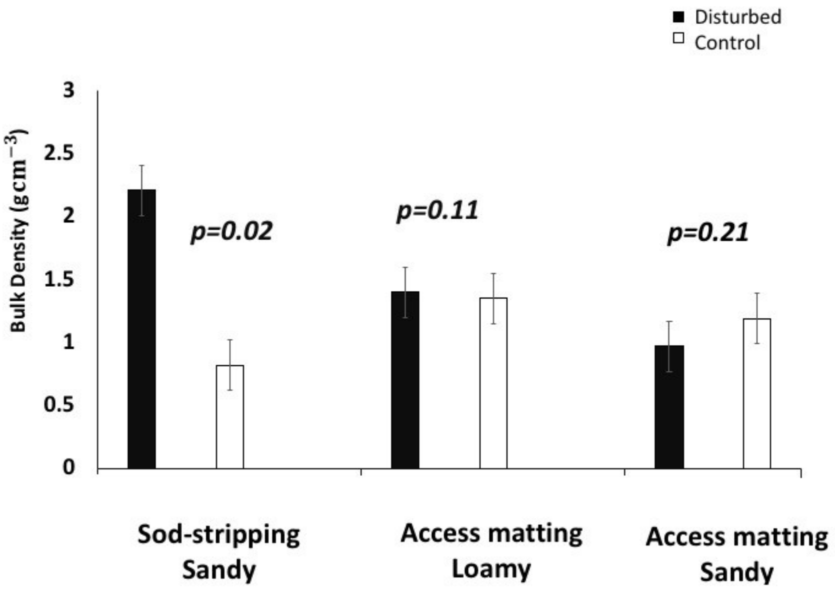


Figure 2-1. Map of the University of Alberta Mattheis Research Ranch, part of the Rangeland Research Institute, situated in the Dry Mixedgrass Prairie of SE Alberta, Canada. Red numbers indicate high voltage tower locations.

A)



B)

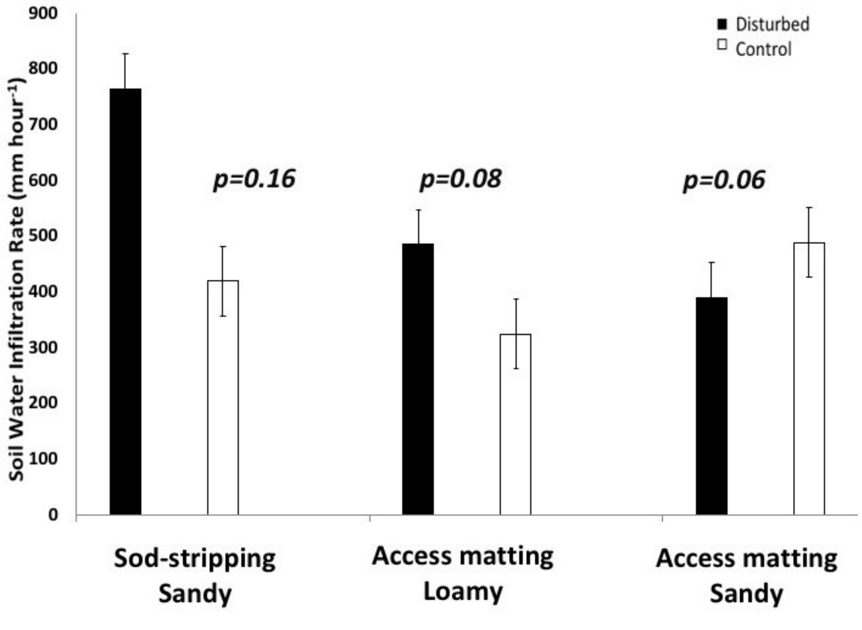
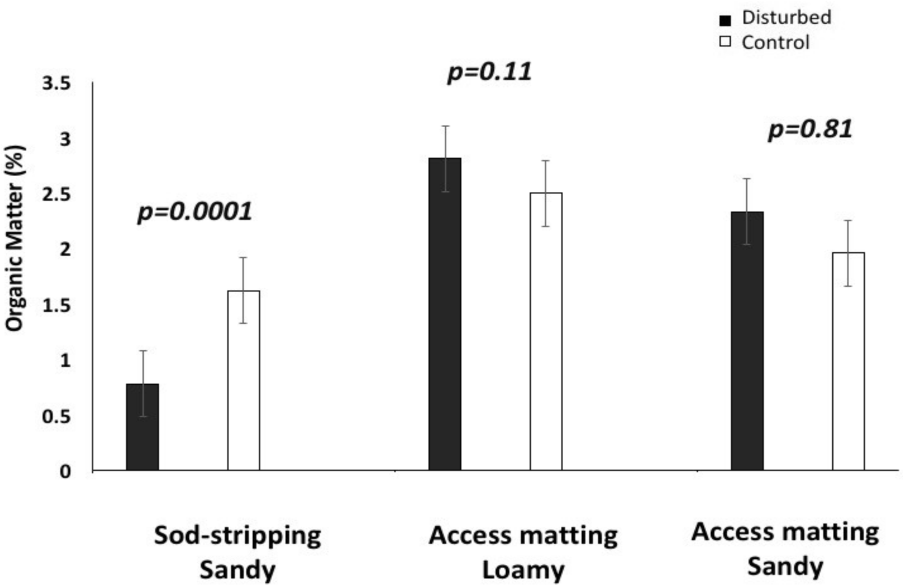


Figure 2-2. Comparison of mean (± SE) A) soil bulk density and B) water infiltration rates, between disturbed areas and adjacent control (non-disturbed) grassland in each of three tower construction type × ecosite combinations during 2016. P-values indicate significant differences between disturbed and control treatments within each pairwise combination.

A)



B)

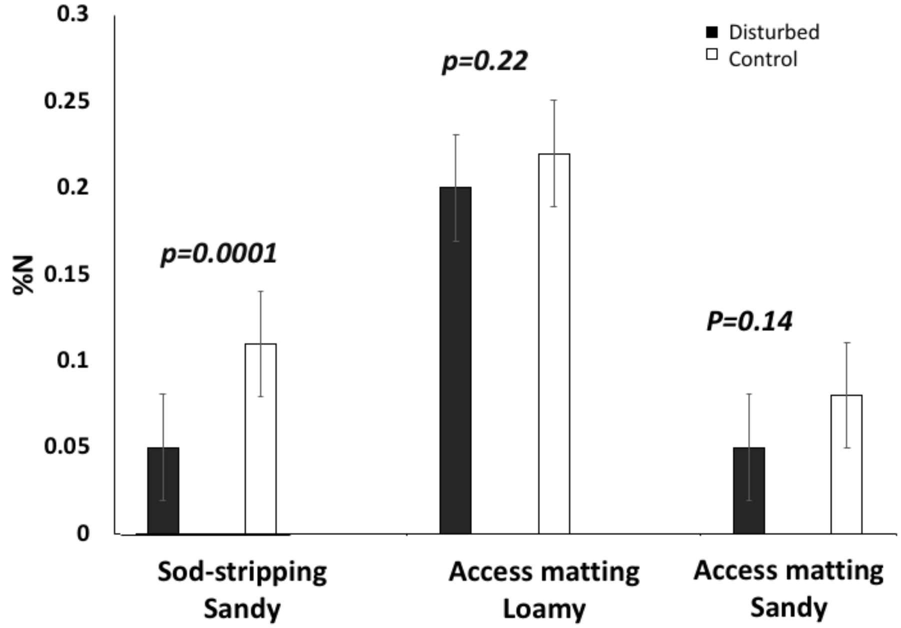


Figure 2-3. Comparison of A) soil organic matter and B) soil N values, between disturbed and control areas in each of three tower construction method × ecosite combinations during 2016. P-values indicate differences between each paired comparison.

Chapter 3: Contrasting Access Mats and Conventional Transmission Line Construction Impacts on Mixedgrass Vegetation Recovery

3.1 Introduction

Native grasslands are among the most threatened ecosystems in the world (Samson and Knopf 1994) because of conversion to other types of land use and degradation from existing land uses, including excessive grazing and industrial development (Adams et al., 2013). Mitigating the effects of disturbance within these landscapes is therefore an important component of conserving grassland ecosystems (ASRD 2010). While industrial developers try to minimize damage through the use of best management practices, the latter's effectiveness in limiting damage have not been rigorously evaluated, especially in temperate grasslands of the Northern Great Plains.

Among the threats to grassland integrity are industrial construction activities such as natural gas and oil well site development, associated pipelines, and the establishment of electrical transmission lines. The latter include an extensive grid of transmission line, including both residential and high voltage transmission lines, situated across western Canada, and are increasing at a rate of 3804 km per year across the western Canadian prairies (Heck, 2007). In Alberta alone, several recently constructed high voltage transmission lines have been established for the purpose of redistributing power regionally across the province, and in doing so, traverse a variety of ecosystems, including the mixedgrass prairie. The total area of mixed grass prairies that remain in Alberta is 661,848 km^2.

Native grasslands provide valuable ecosystem goods and services such as forage for wildlife and livestock, carbon storage and water purification (Hooper et al., 2005). However, exposure to traffic can put these areas at risk during industrial development. Access corridors across prairie may be impacted from repetitive passes by equipment of variable size and weight (up to 40+ tons), with repeated traffic leading to eventual damage to vegetation and soil compaction (Wilson 1988). Frequent equipment passes during sensitive times of the year (e.g. when moisture is high during spring and vegetation is actively growing) may directly damage plants (Wilson 1988). Ultimately, construction activities can crush existing vegetation (Althoff and Thien 2005), reduce forage quantity and quality (Unger and Kaspar 1994), increase soil compaction (Anderson et al. 2007), and lead to enhanced wind and water erosion (Althoff and Thien, 2005; Althoff et al., 2010), with some of these effects lasting for decades (Willms et al., 2011).

Maintaining the ecological integrity of prairie and restoring degraded grassland where they are subject to industrial disturbance have therefore become important conservation issues (Desserud et al., 2016). A common mitigation technique during construction is the use of access mats (also called “rig mats”) to reduce the direct effects of industrial construction activities, particularly vehicle traffic, on underlying soil and vegetation (ASRD 2010). Laid down in a continuous grid, access mats are used to build temporary access roads across prairie landscapes into worksites, and also form a working foundation for equipment within the construction site. Each mat is approximately 0.75 t in weight, with dimensions of 2.43 x 3.65 m in size, and must be individually placed with loaders, and then removed once complete. Larger projects require a significant number of mats, each of which comes at a substantial cost (~$700 a piece), although they are re-used a number of times over their lifetime.

While some evidence suggests that access mats benefit vegetation (Dollhopf et al. 2007), few rigorous studies have been conducted testing the effectiveness of mats in facilitating vegetation recovery, nor on how the latter varies with soil texture. For example, sandy soils exhibit markedly different vegetation composition and growth patterns compared to loamy soils in the mixedgrass prairie (Bork and Irving 2015), which in turn, may alter vegetation susceptibility to matting, including vegetation recovery (i.e. resilience) after mats are removed. Access mats are thought to reduce direct damage to soil and vegetation by limiting physical contact with equipment and spreading out the load bearing weight onto a greater ground surface area, but mats can also inhibit plant growth by blocking light and altering select soil properties for the duration of placement (Dollhopf et al. 2007; Mitchem et al. 2009).

The use of access mats in grasslands represents an alternative to more direct (i.e. conventional) types of disturbance known to cause severe degradation to native grasslands (Andrade et al., 2015), such as the temporary removal of soil. Until recently, much of the industrial development within grasslands has involved sod and soil-stripping into stockpiles, in order to create a level and uniform work area on the subsoil. Once construction of the well-site, pipeline, or transmission tower was complete, the stockpiled soil was later replaced, then revegetated (Strohmayer, 1999). In this situation, areas around transmission towers may be impacted by various forms of physical alteration to vegetation and soil. As a consequence, extensive effort is required for soil reclamation and vegetation re-establishment.

Recovery of plant communities following either soil removal and replacement, or the use of access mats *in-situ* on soils and vegetation, will depend on a number of ecosystem properties. Vegetation regrowth will depend on the availability of surviving plant material or the seed bank (Dollhopf et al. 2007; Mitchem et al. 2009). Litter is an important determinant of both forage production (Willms et al. 1986; Deutsch et al. 2010) and floristic diversity (Lamb 2008) in native grasslands, and its removal with frequent disturbance is associated with reduced plant growth (Naeth et al., 1991).

Additionally, changes in the timing of disturbance to coincide with dormant periods of plant development (winter, or alternatively, late summer after the onset of dormancy with moisture depletion) can reduce traffic impacts on grassland (Wilson 1988), which parallels studies showing more negative effects of cattle grazing on fescue grassland in summer as compared to winter (Tannas 2011). Finally, changes in plant species composition induced by disturbance are likely to alter the production of both above-ground and below-ground vegetation biomass (Coupland 1961; Coupland and Johnson 1965).

The goal of this investigation was to evaluate the recovery of vegetation following high-voltage transmission line (hereafter 'transmission line') construction in the Dry Mixedgrass prairie of SE Alberta over a three year period. The primary objective was to quantify the relative impact of two contrasting construction methods, access matting and sod-stripping, comprised of soil removal and replacement, followed by revegetation. A secondary objective was to determine whether vegetation recovery patterns for areas exposed to access mats differed between soil ecosites, differing primarily in texture. Response variables included vegetation foliar cover (3 years), biomass (2 years), and in the first year, forage quality.

3.2 Material & Methods

3.2.1 Study Design

This field study was conducted at the University of Alberta Mattheis Research Ranch (MRR), located 40 km north of Brooks, Alberta (50° 90' 37'' N; 111° 87' 99'' W). The ranch is located on the Brooks Plain of the Dry Mixedgrass Prairie natural subregion in Alberta, Canada

(Adams et al. 2005). Mean annual precipitation is 343 mm and mean daily temperature is 4.2° C (Adams et al., 2013) (Appendix 1). The MRR and surrounding landscape are primarily native (i.e. non-cultivated) grasslands, comprised of both stabilized sand dunes and adjacent loamy prairie, and are grazed by cattle under an infrequent, rotational grazing system (one or two passes annually) at moderate stocking rates (0.6 animal-unit-months ha^{-1}). Needle-and-thread grass (*Hesperostipa comata* Trin. and Rup.*),* western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve), Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and blue grama (*Bouteloua gracilis* (Willd ex Kunth) Lag. ex Griffiths) are the dominant plant species across the area, with sand grass (*Calamovilfa longifolia* (Hook.) Scribn.) locally abundant in sandy textured soils.

In 2014-2015, a new high voltage (500 KV direct current) transmission line was installed as part of ATCO's Eastern Alberta Transmission Line project, which crossed through 9 km of the MRR (Figure 3-1). Towers supporting the transmission lines were spaced approximately 300 m apart, for a total of 31 towers across the property. Towers were 35 to 40 m in height, and were anchored to the ground using four footings, which were installed using various techniques (e.g. either cemented in Cassions or H bar pilings) under the towers. Footings were approximately 1.5 m x 1.5 m in dimension, with the entire area under the tower representing an area roughly 15 m on each side. The foundation type for each tower was determined by engineering requirements. The strength and size of the foundations take into account several different stress factors (wind loading, tension on the line, tower style, span length, etc.), and the soil type, which impacts how deep foundations were laid to obtain required compression and strength from the soil. Cassions are comprised of concrete pillars poured into a deep hole augured into the ground and containing a rebar frame lowered into the hole to reinforce the concrete that is poured. Cassions were 18 m deep. The H-Pile foundations use a grid of iron footings pounded directly into the ground until they hit bedrock and meet engineering resistance values. H-pilings are roughly 18 m deep in the ground and vary in exact length based on engineering requirements.

Two different tower installation methods were used. The access matting method included the use of surface laid access mats wherein soil was left intact (n=10 sites; tower numbers 1218, 1219, 1220, 1221, 1222, 1234, 1236, 1244, 1245, 1246) (Fig. 3-2), with 6 of these sites (towers 1218-1222, and 1246) occurring on loamy ecosites, while the others were on sandy ecosites (Chapter 2 - Table 2-1). In contrast, sod-stripping methods were used on the remaining sites (n=5; tower numbers 1223, 1224, 1227, 1230, 1233) wherein the top and sub-soil were initially removed from the tower work site, stockpiled for at least 3 months during tower construction, after which soil was replaced and subject to revegetation (Fig. 3-3). All sod-stripping tower sites were on sandy ecosites (Chapter 2 - Table 2-1). Initial revegetation attempts on sod-stripping treatments included drill seeding and the application of coconut matting to help stabilize the soil (i.e. prevent active soil loss) under each sod-stripped tower. However, strong winds frequently removed the coconut matting and led to the loss of seed in the spring of 2015, necessitating reseeding. Subsequent hydroseeding was done on all the sod-stripping treatments, and two of the access matting treatments (1218,1222). The seed mix used in all cases included grass species native to the area (*Hesperostipa comata, Pascopyrum smithii, Calamovilfa longifolia, Bouteloua gracilis* and *Koeleria macrantha*) (Appendix 6).

At each tower, an area 10-15 m from the tower construction site and unaffected by the adjacent disturbance, but on the same ecosite (soil, topographic position), was used as a control to evaluate relative differences in soil and vegetation during the recovery of natural vegetation. Soil responses are reported in Chapter 2. Fences were installed around the sod-stripping towers to prevent cattle from entering the study areas and thereby inhibiting vegetation recovery. On towers built with access matting, where soils remained stable after construction, and on all control areas, four range cages (~ 1 m diameter) were placed in each plant community to enable vegetation sampling without the effects of grazing cattle. Cages were randomly placed, and were moved to new locations at the end of each growing season.

3.2.2 Characterization of Vegetation and Forage Quantity

Plant foliar cover, to the individual species level, was quantified for each of four individual 0.5 x 0.5 m quadrats within each plant community, in order to track overall changes in foliar vegetation cover by growth form. Within non-fenced communities, these assessments were done under range cages to ensure independence of current year cattle use. At the same time, estimates of bare soil and microphytic crust (lichen + mosses) were made, to provide measures of site stability (as per range health guidelines; Adams et al, 2013).

Once foliar vegetation cover had been assessed, we measured forage quantity by harvesting biomass from four 0.25 m^2 quadrats, one under each cage where present, within each of the disturbed areas under each tower, and also on the adjacent control, creating a paired (i.e. blocked) design. Plant biomass was collected between July 22-27, 2015, August 1-10, 2016, and July 22-27, 2017. All biomass was separated into primary growth forms only (grasses, forbs) in 2015. During the second (2016) and third (2017) years of recovery, we further separated forbs into native and introduced species to distinguish between endemic and invasive vegetation. We also collected dead plant material (litter) from each plot given its importance as an indicator of range health (Adams et al. 2013). All samples were dried at 50 °C for a minimum of five days, or until stable mass was reached, and then weighed to determine dry matter mass.

3.2.3 Forage Quality Characterization

Concentrations of crude protein and acid detergent fiber were determined for all grass and forb samples harvested from each treatment in 2015. Biomass samples from that year were first ground in a Resch ball mill (SPEX Sample Metuchen, NJ, USA) to 0.1 mm size. Crude protein was determined from the nitrogen content of 5 mg pellets by combustion and high temperature conversion using a FLASH 2000 HT Elemental Analyzer for Isotope Ratio Mass Spectrometry (Thermo Fisher Scientific, Massachusetts, USA) (Soest and Lewis 1991). The analyzer was calibrated daily using orchard leaves and tobacco leaves (Standard #s 502-055 and 502-082, respectively) to achieve the standards of nitrogen and carbon levels. Standards were run every 10th run and corrections applied if necessary based on drift patterns. Nitrogen concentrations were multiplied by 6.25 (Noel and Hableton 1976) to derive estimates of crude protein concentration (%).

Acid detergent fiber (ADF) was used to provide an estimate of forage digestibility (Van Soest et al., 1991) using an A200 Fiber Analyzer (ANKOM Technology, Macedon, NY, USA), again conducted separately for each biomass sample from each plot. To estimate ADF, 0.5 g of dried ground sample was sealed in an F57 filter bag (25-micron porosity, ANKOM) and digested with 8% sulfuric acid and cetyle trimethylammonium bromide (CTAB). The residual plant material in the filter bag after digestion for 48 hr was reweighed to determine non-digestible mass remaining, including predominately (non-digestible) cellulose and lignin. To evaluate particle loss from the bags themselves and make any necessary corrections, an empty sealed bag was included in each run and weighed before and after digestion.

3.2.4 Root Biomass Quantification

Root biomass was measured by removing roots from soil samples extracted for soil characterization in relation to each treatment in mid - July of both 2015 and 2016 (See Chapter 2). Four randomly located cores were removed from each subplot at 15 tower sites (5 sod-stripping sandy sites, 6 access matted loamy sites, and 4 access matted sandy sites) for a total of 120 soil cores (3.175 cm diameter by 15 cm deep); cores from within each subplot were combined for processing and analysis. After soil samples were dried, roots were carefully removed with tweezers and washed, then dried to constant mass and weighed. Root biomass was calculated using the dried root weight from the sample for all treatments in 2015 and 2016. The total root biomass removed (summed) from all 4 cores (each one 3.175 cm diameter by 15 cm deep) was used to derive root mass values per m^2. Soil physical and chemical metrics were assessed and reported in Chapter 2.

3.2.5 Statistical Analysis

Total grass and forb foliar cover, plant biomass and quality (% CP and ADF), vegetation root mass, as well as the abundance of ground cover components (bare soil, litter, club moss and microphytic crust) were all analyzed using an analysis of variance (ANOVA) with mixed models; a Kenward-Roger correction was used to adjust the degrees freedom for small sample sizes. Individual subsampling quadrats were averaged for each subplot (i.e. community) prior to analysis. Because of the incomplete overall design of ecosites among disturbance treatments (i.e. there were no sod-stripping treatments on loamy ecosites), and the fact that each tower site had a paired spatial control (i.e. non-treated) area, we analyzed each of the treatment by ecosite combinations (sod-stripping on sand, n=5; access matting on loam, n=6; access matting on sand, n=4) separately. Within each analysis, paired treatments (disturbed and control) were fixed effects, with tower sites random in the analysis. Year of sampling was also considered a fixed effect for those variables measured in multiple years, with year treated as a repeated measure. The ANOVA included tests of year, and year x treatment interactions.

Data were assessed with an analysis of variance (ANOVA) in SAS 9.4 (Carlsbad, NC, USA) using a generalized linear mixed model (PROC MIXED). All data were checked for homogeneity of variance and normality with the Shapiro-Wilk test. Total foliar grass cover and ADF concentrations were not transformed. Log transforms were applied to total native forb cover and total root-to-shoot ratio in all studies. Square root transforms were applied to total introduced cover and all ground cover (including bare soil, club moss, lichen and total litter) components, along with total grass and forb biomass, native and introduced forb biomass, and total root biomass in each study. Where data were transformed, original data are presented for all results to facilitate interpretation of the effects. Post-hoc comparisons are conducted at $P<0.05$, unless otherwise stated.

3.3 Results

3.3.1 Plant Foliar and Ground Cover

The total cover of grasses and native forbs ($P \leq 0.05$), as well as introduced forbs ($P = 0.08$), were affected by the sod-stripping construction method on sandy sites, with no further interaction with year of sampling (Table 3-1). Sod-stripping led to lower grass cover and native forb cover, while increasing that of introduced forbs (Table 3-2). Grass and native forb cover were not affected by year of sampling (Table 3-1), while introduced cover was affected ($P = 0.02$), which revealed a lower cover ($P < 0.05$) of introduced forbs in 2017 (23.8 ± 14.1%) compared to both 2015 (56.6 ± 14.1%) and 2016 (63.3 ± 14.1%).

In contrast to the sod-stripping treatments, the access matting treatment on loamy and sandy sites had an effect on grass, native and introduced forb cover (Tables 3-1, 3-2). There was an interaction between the matting treatments and year of sampling on grass and native forb cover within the loamy study sites (Table 3-1). Closer examination of these responses showed no differences in grass biomass between the control and matting treatments on grass cover, though grass cover declined significantly in the controls but not the matted areas (Table 3-3). Native forb cover followed the same pattern, to the point of being higher in the matted area than the control during the final year of sampling (Table 3-3). In loamy sites subject to access matting, introduced forb cover was not affected by sampling year or treatment. Grass cover was generally affected by year of sampling ($P = 0.001$), with lower cover ($P<0.05$) of grasses in 2017 (22.1 ± 2.8 %) than in 2016 (28.8 ± 2.8 %) and 2015 (39.3 ± 2.8), although as noted previously, this decline occurred only in the control area.

The access matting treatment on sandy sites did not alter grass, native or introduced forb cover, either alone or in conjunction with year of sampling ($P > 0.54$; Table 3-1). All three response variables however, were affected by year of sampling ($P \leq 0.001$). Grass cover was significantly different between all three years of recovery ($P \leq 0.001$). Grass cover was lower ($P < 0.05$) in 2017 (25.7 ± 4.4 %) than both 2015 (59.4 ± 4.4 %) and 2016 (144.8 ± 4.4 %), the latter of which also differed from one another ($P < 0.05$). Native forb cover was lower ($P < 0.05$) in 2015 (7.8 ± 3.8 %) than 2016 (26.3 ± 3.8 %), while forb cover in 2017 (9.7 ± 3.8 %) remained similar ($P > 0.05$) to the previous two years. Also within the sandy matted sites, introduced forb cover was greater ($P < 0.05$) in 2016 (13.3 ±1.7 %) than both 2015 (7.4 ± 1.7 %) and 2017 (2.7 ± 1.7 %).

Sod-stripping on sandy ecosites did not alter the extent of bare soil, either alone or in combination with year of sampling ($P > 0.21$; Table 3-4), even though average exposed soil did tend to be elevated in disturbed areas (Table 3-5). However, bare soil was affected by year of sampling ($P = 0.04$; Table 3-4), which revealed a lower cover ($P < 0.05$) of bare soil in 2015 (9.4 ± 8.4 %) compared to both 2017 (20.8 ± 8.4 %) and 2016 (27.7 ± 8.4 %). Club moss was not affected by treatment or year of sampling ($P > 0.26$; Table 3-4) in the sod-stripping study, while microphytic crust and litter were both impacted by the treatment, alone and in combination with year ($P \leq 0.03$). Closer examination of this response indicated microphytic crust was high in the control during 2015, but non-existent in all other periods, including the disturbed area during all three years of recovery (Table 3-6). Finally, litter was lowest in the disturbed area during 2015, and increased over time (Table 3-6). While litter cover was variable in the control of the sandy sod-stripping areas over the study, it remained similar to that of the disturbed area by as soon as the second year of recovery (Table 3-6).

The access matting treatment on loamy sites varied in bare soil, but only in conjunction with year of recovery ($P = 0.0008$; Table 3-4). Similarly, club moss and microphytic crust cover responded to the interaction of matting and sampling year ($P \leq 0.01$; Table 3-4). Bare soil was greater during the first and third years of recovery within areas subject to matting (i.e., compared to controls) on loamy soils (Table 3-7). Both club moss and microphytic crust were generally lower in these same areas under matting (Table 3-5), though closer examination showed the non-disturbed control also had relatively little club moss by the final year of sampling (Table 3-7). Conversely, controls had similar microphytic crust cover to the matted loamy treatment in 2015, but by 2016 and beyond, crust cover was greater in the control than matted areas (Table 3-7).

The access matting on sandy sites did not alter bare soil, club moss, microphytic crust, or litter cover relative to the treatment itself ($P > 0.28$; Table 3-4, 3-5). However, bare soil, microphytic crust and litter cover, were all affected by year of sampling ($P = 0.01$; Table 3-4). Bare soil was lower ($P < 0.05$) in the first year of recovery (2.0 ± 5.3) compared to the second (25.0 ± 5.3 %) and third year (10.7 ± 5.3 %). In contrast, microphytic crust was higher ($P < 0.05$) in 2015 (11.2 ± 1.8 %) than both 2017 (1.4 ± 1.8 %) and 2016 (0.50 ± 1.8 %). Litter cover was generally lower ($P < 0.05$) in 2016 (69.9 ± 6.3 %) than both 2017 (86.6 ± 6.3 %) and 2015 (86.0 ± 6.3 %). Club moss did not vary among years ($P > 0.15$; Table 3-4, 3-5).

3.3.2 Vegetation Biomass

Total grass biomass was affected by the sod-stripping construction method on sandy sites, with a further interaction with year of sampling ($P = 0.06$; Table 3-8). Total grass biomass was 32% lower in disturbed areas (Table 3-9), with marked differences over time (Table 3-10). In general, grass biomass increased in the disturbed area throughout the trial, including in the controls, such that by the end of the monitoring period, total grass biomass was similar between the disturbed and non-treated areas (Table 3-1). Total forb biomass in the sod stripping study was not effected by treatment or its interaction with year ($P > 0.12$; Table 3-8). However, total forb biomass was affected by year of sampling ($P = 0.0006$; Table 3-8), which showed that all three years of recovery were different from each other ($P < 0.05$), with the greatest forb mass in 2017 (236.0 ± 30.8 g m^{-2}), followed by 2015 (156.0 ± 30.8 g m^{-2}) and then 2016 (74.0 ± 30.8 g m^{-2}).

Total native forb biomass was affected by the sod-stripping construction method on sandy sites, but only in combination with year of sampling ($P = 0.03$; Tables 3-11, 3-12). Native forb biomass was lowest in the disturbed areas in 2016, and then increased to the point of being similar to the non-treated controls by the final year of recovery (Table 3-13). Total introduced forb biomass did not respond to treatment or their interaction with year of sampling ($P > 0.67$; Tables 3-11, 3-12). However, total introduced forb biomass varied with year of sampling ($P = 0.04$; Table 3-11), with fewer ($P < 0.05$) introduced forbs in 2016 (66.0 ± 28.4 g m^{-2}) than in 2017 (126.8 ± 28.4 g m^{-2}).

The access matting sites on loamy soil did not affect either total grass biomass or total forb biomass ($P > 0.35$; Tables 3-8, 3-9). However, both total grass and forb biomass were affected by year of sampling ($P < 0.0001$; Table 3-8). Grass biomass at these sites differed among all three years ($P < 0.05$), being greatest in 2017 (209.6 ± 12.0 g m^{-2}), followed by 2016 (122.0 ± 12 g m^{-2}) and then 2015 (62.8 ± 12 g m^{-2}). While total forb biomass also differed among all three years ($P < 0.05$), the pattern was reversed, with the following rank order: 2015 (30.4 ± 25.2 g m^{-2}), followed by 2016 (66.0 ± 25.2 g m^{-2}) and then 2017 (174.8 ± 25.2 g m^{-2}). Access matting sites on loamy soil did not alter total native or introduced forb biomass ($P \geq 0.32$; Table 3-11). However, both forb biomass components varied with year of sampling ($P \leq 0.03$; Table 3-11). Native forb mass was lower ($P < 0.05$) in 2016 (32.0 ± 12.0 g m^{-2}) than 2017 (110.8 ± 12.0 g m^{-2}), with introduced forb biomass following a similar pattern (2016: 34.0 ± 20.0 g m^{-2}, vs 2017: 63.6 ± 20.0 g m^{-2}).

Similar to the loamy matted sites, access matting on sandy soil did not impact total grass or forb biomass ($P > 0.63$; Tables 3-8, 3-9). However, both grass and forb biomass varied with year of sampling ($P < 0.001$; Table 3-8). Grass biomass was lower ($P < 0.05$) in 2015 (60.0 ± 9.6 g m^{-2}) than in 2016 (140.4 ± 9.6 g m^{-2}), which in turn, was lower ($P < 0.05$) than in 2017 (268.8 ± 9.6 g m^{-2}). Total forb biomass was lower ($P < 0.05$) in the first (18.4 ± 19.2 g m^{-2}) and second year (32.4 ± 19.2 g m^{-2}) of recovery than the third (147.2 ± 19.2 g m^{-2}) year of sampling. Access matting sites on sandy soil did not alter native or introduced forb biomass ($P \geq 0.38$; Tables 3-11, 3-12). Both these forb components once again varied with year of sampling ($P \leq 0.04$; Table 3-11). Native forb mass was lower ($P < 0.05$) in 2016 (18.4 ± 20.4 g m^{-2}) than 2017 (100.0 ± 20.4 g m^{-2}), as was the mass of introduced forbs (2016: 14.4 ± 12.0 g m^{-2}; vs 2017: 47.2 ± 12.0 g m^{-2}).

Root biomass was affected ($P = 0.001$) by the sod-stripping construction method on sandy sites, with no further interaction with year of sampling (Table 3-11). Root biomass was 77% lower in sod-stripped areas (Table 3-12). Root-to-shoot ratios were also affected by the sod-stripping construction method ($P = 0.01$), being 73% lower in the soil stripped and revegetated areas (Tables 3-12).

Root biomass was not affected by the access matting construction method on loamy sites (Table 3-11), but interacted with year of sampling ($P = 0.08$; Table 3-11). In general, root biomass increased throughout the trial, but to a larger extent in the controls, such that by the end of the monitoring period root biomass was higher in previously matted areas during the second year of recovery than the same disturbed areas in first year of recovery (Table 3-14). Root biomass also varied with year of sampling on matted loamy sites ($P \leq 0.0001$; Table 3-11). Root biomass was lower ($P < 0.05$) in 2015 (945.7 ± 193.8 g m^{-2}) than 2016 (2163.6 ± 193.8 g m^{-2}). Root-to-shoot ratios were not affected by the access matting treatments on loamy ecosites (Table 3-11, 3-12).

Root biomass was not affected by the access matting construction method on sandy sites, with no further interaction with year of sampling ($P = 0.61$; Table 3-11). Root biomass did vary with year of sampling ($P \leq 0.01$; Table 3-11). Root biomass mass was lower ($P < 0.05$) in 2015 (1604.9 ± 337.1 g m^{-2}) than 2016 (2658.0 ± 337.1 g m^{-2}). Root-to-shoot ratios were not affected by access matting on sandy sites (Tables 3-11, 3-12).

3.3.3 Forage Chemical and Quality Response

Acid Detergent Fiber (ADF) concentrations of grasses and forbs were not affected by either the sod-stripping or accessing matting construction methods on sandy sites ($P > 0.17$; Tables 3-15, 3-16). Within access matted loamy sites however, grass ADF was comparatively 12% higher in the control compared to the disturbed areas ($P < 0.05$; Tables 3-15, 3-16). Crude protein concentrations were not affected by access matting in either the sandy or loamy sites ($P > 0.22$; Tables 3-15, 3-16). Within sod-stripped areas, grasses in the disturbed areas had greater ($P < 0.02$) protein (9.0 ± 0.6 %) relative to the control (6.5 ± 0.6 %), with no difference in the crude protein content of forbs (Table 3-16).

3.4 Discussion

3.4.1 Vegetation Recovery and Ground Cover

The two different methods of high-voltage transmission line tower construction (sod-stripping and access matting) tested here have been widely utilized within industrial development activities on native grasslands in the past. Provincial guidelines for best management practices recommend low disturbance methods (i.e. matting) be used on native grassland in Alberta (e.g., ASRD 2010). The latter appears to be supported here in the current study, as the extent of change to vegetation properties appeared to be lowest, and the magnitude of recovery most successful, within the matted treatments, particularly those performed on sandy ecosites. In contrast, sod-stripping led to greater initial changes in vegetation and slower recovery, though all sites exhibited marked recovery over the 3 year study period.

These results support the notion that where possible, native grassland should be left intact during construction to minimize short-term effects on vegetation and promote recovery. Access mats are thought to reduce direct damage to vegetation by limiting physical disturbance, with subsequent recovery depending on the adequacy of regrowth of vegetation from surviving plant material (Dollhopf et al. 2007 Mitchem et al. 2009). In the current study, access matting generally did not alter total grass or forb cover/mass, with the exception of increasing native forbs in loamy sites during year 3, suggesting a relatively high resilience of grassland exposed to matting. This finding is perhaps surprising given that matted areas were covered for up to three months at a time, and high light restrictions may have been expected to facilitate widespread plant mortality. Although vegetation recovery in matted areas could have occurred from the seed bank, this process is slow, and remains relatively problematic for late seral grassland species, particularly grasses (Tannas 2011). As a result, it is more likely that the observed recovery arose from the perennial bud bank of surviving vegetation. A large proportion of plant biomass (e.g. 85% or more) is belowground in MGP (Sims et al. 1978), and is further supported here by the high root:shoot ratios found, and recovery may only require a small proportion of these roots (and associated plant crowns) to survive matting to facilitate revegetation. While we did not test the direct effects of heavy equipment traffic on grasslands, other studies suggest that frequent equipment passes during sensitive times of the year, as is likely to occur with transmission line construction, may directly damage plants (Wilson 1988).

One interesting aspect of matting on vegetation dynamics was the increase in native forb cover found during the final year of recovery, and likely represents residual effects of short-term release from disturbance. Disturbance to grassland, particularly those with a long evolutionary history of disturbance (Milchunas and Laurenroth 1993), are known to lead to an increase in species diversity (Bai et al. 2001). This appears to be the case based on native grass cover as well (species level data not provided), and may reflect some degree of competitive release of native forbs from grasses, which in the absence of disturbance, are known to reduce species diversity in native grasslands (Bork et al. 2018).

Ecosite conditions also appeared to play at least some role in determining the impact of access matting on these native grasslands, although direct comparisons are not possible in the current study due to the incomplete study design used. More specifically, the negative impacts of access matting were more apparent on loamy than sandy soils, as evidenced by reduced root biomass in the second year, as well as increased bare soil and microphytic crust even after 3 years of recovery. Plant growth in the extended absence of light, termed etiolated growth, uses stored energy in stem bases and roots (Biligetu and Coulman 2011) to produce leaf tissue as the plant elongates its leaves and stems to try to find sunlight to photosynthesize. We observed this here when mats were removed by the extensive presence of chlorotic vegetation remnants. Plant tolerance to disturbance (such as grazing) has previously been found to be reflected by etiolated regrowth, with those species having more total non-structural carbohydrate able to produce more etiolated regrowth than those with lower tolerance (Lardner et al. 2003).

While the current study indicated ample above-ground vegetation recovery shortly after disturbance (both in cover, and biomass – see Section 3.3.1 and 3.3.2), the reduction in root mass in loamy ecosites suggests the longer-term effect of this disturbance may have manifested below-ground rather than above-ground. As root biomass is a major component of mixedgrass prairie vegetation, with the majority of biomass belowground (Dormaar and Willms 1998); R:S ratio was lower in the sod-stripping area and recovery reduced by disturbance. Ensuring root recovery is likely an important indicator of overall vegetation re-establishment. Notably, the reduction in root mass in year 2 occurred despite wet conditions that year, which should have favored vegetation growth (and recovery) as moisture is generally a major limiting factor for plant growth in this region (Willms and Jefferson 1993). It is possible that dry conditions that year could have further impaired recovery at all study locations, and the loamy ecosites in particular due to their sensitivity to low moisture (Willms and Jefferson 1993).

While we are unable to rule out differences in the timing or duration of matting between studies as the cause of these effects, nor differences in the type of vegetation (Bork and Irving 2015) that may have further confounded these responses (i.e., due to inherent differences in adaptation/tolerance to disturbance), this pattern is notable and highlights the need for more research addressing the role of ecosite (and growing conditions overall) in regulating mixedgrass prairie resilience to disturbance (including access matting). Due to their finer texture, we might expect loamy soils to be more prone to soil compaction, though no differences were detected in soil bulk density or penetration resistance from matting at these locations (Chapter 2). However, bare soil was greater following matting (Chapter 2), and could have led to greater subsequent water loss due to the lack of insulating ground cover to prevent evaporation (Willms et al. 1986). Litter cover is particularly important for the growth of cool-season vegetation during the early growing season (Bork and Irving 2015). Additionally, access matted loamy soils tended to have lower rates of water infiltration (Chapter 2), which could have further inhibited vegetation recovery. Reduced infiltration could increase runoff and/or evaporation, decreasing overall water availability, and therefore root growth. The latter is important given that matting was expected to mitigate the impacts of industrial disturbance on mixedgrass soils, including hydrologic function, and therefore warrants further study. Despite the negative impact of initial matting on loamy mixedgrass prairie, the doubling of root biomass in these plots from year 1 to 2 and similarity in accompanying above-ground cover (and biomass) suggests vegetation recovery remained on track in these treatments.

In contrast to the matting treatments, grass biomass and cover were reduced by the sod-stripping treatment, but increased markedly by the 2nd year, again likely aided by the high rainfall conditions that year, with full recovery of biomass relative to controls by the 3rd year. The wholesale removal of native grassland (i.e. bud bank) with soil stripping necessitated revegetation following soil replacement, as the seedbank in stockpiled soil is often altered by soil removal (Naeth et al. 1987). Loss of desirable plant species from the seedbank may have been further exacerbated by the burial of topsoil, which appeared to occur given the decline in soil organic matter (Chapter 2). Top soil burial would make it more difficult for native species to recover, particularly slow establishing perennial grasses, from the seedbank. In the current study, native grass revegetation in soil stripped sites was facilitated by reseeding, although it is unclear how much of the grass recovery took place from the hydroseeding, the initial broad cast seed treatment, or the original seed bank itself.

Sod-stripping in the current investigation led to increased introduced forbs at the expense of native forbs, although native forbs appeared to recover by the 2nd year. Native plant species, particularly grasses, are often slow to re-establish from seed within highly disturbed perennial grasslands (Desserud et al. 2010). An increasing severity of disturbance requires that vegetation recovery increasingly depends on the seed bank, defined as all viable seeds in the soil (Harper 1977). Unlike native vegetation, the origin of introduced species is likely the seedbank, which is frequently dominated by introduced species that are hyperabundant, even under moderate disturbance regimes (Willms and Quinton 1995). Removal/suppression of existing native vegetation then opportunistically releases introduced species (Tyser and Worley 1992). During construction, increasing damage from vehicle traffic crushes vegetation (Althoff et al 2007) and transports invasive species seeds (Althoff et al. 2007). While one pass can damage vegetation

(Grantham et al. 2001), multiple passes further increases damage (Anderson et al. 2007, Ayers et al. 2007). Assessed across all three studies, the current results generally indicate that introduced vegetation was most likely to establish where the soil was directly disturbed physically (i.e. removed) and vegetation altogether removed. Moreover, because industrial traffic may alter vegetation both on access trails, and in areas nearby that are invaded by species that initially established on adjacent disturbed areas and then spread (Tyser and Worley 1992), we are unable to rule out the possibility that the (non-treated) controls may have been influenced by the matting and soil stripping treatments.

Sod-stripping also led to lower root biomass and reduced root:shoot ratios, highlighting the importance of keeping the sod intact to conserve plant propagules (roots, plant crowns) and facilitate recovery of the existing vegetation. A reduction in roots could have rendered the re-establishing vegetation in these areas more susceptible to drought conditions during recovery, thereby making for a 'best case scenario' of recovery. Decreases in root biomass (and associated R:S ratio) in the soil stripped areas also coincides with an increase in introduced forbs, which are often short-lived ruderals (Willms and Quinton 1995). The latter species preferentially develop shoot biomass within the growing season to support seed production. In contrast, an abundance of grasses and native forbs, such as was evident in the non-treated controls, is more likely to maintain greater root biomass over time, thereby providing higher soil stability. Soils in the stripped areas were generally impaired by this treatment, including having lower organic matter, microphytic crust, and surficial litter cover, although the latter was relatively short-lived, presumably due to the large release of introduced forbs during revegetation and the generation of associated litter. As noted earlier, litter is an important determinant of forage production (Willms et al. 1986; Deutsch et al. 2010) in native grasslands. Litter loss in general may impede resource availability (light and water) such as is commonly found in cultivated cropland (Lafond et al. 2011). Vegetation recovery in these areas will ultimately be impacted by soil removal and storage practices, such as the precision of topsoil salvage and the duration of soil storage, and its likelihood to maintain the pre-existing seedbank and bud bank. Conversely, where topsoil removal is not required, recovery is likely to be a function of vegetation tolerance to disturbance combined with recovery from the seedbank. Vegetation monitoring during the three years of recovery here showed that the effect of sod-stripping led to a more detrimental, but short-term impact to native vegetation, as compared to matting.

Finally, it is important to reinforce the context of study conditions assessed here. Wet conditions in the latter part of 2015 and summer of 2016 probably aided vegetation recovery (i.e., increases in grasses and native forbs) on all studies/sites, and possibly accounts for the elevated introduced forb cover throughout the study in the sod-stripping study. During the first and second year of assessment the average precipitation was higher (Appendix 1), and this likely contributed to the improved recovery in 2015 and 2016.

3.4.2 Forage Chemical and Quality Response

Only limited impacts of industrial disturbance on livestock grazing opportunities were observed to forage quality, largely due to rapid increases in vegetation regrowth, regardless of disturbance type (matting and soil stripping). All treatments produced large amounts of biomass post-recovery, suggesting total herbage availability was not a constraint for livestock production. However, as cattle prefer grasses, the short-term reduction in grass biomass following sod-stripping are likely to limit short-term grazing opportunities in these areas, particularly if the forbs (esp. introduced forbs) were low in palatability for livestock (Milchunas et al. 1988).

Some evidence existed that disturbance (sod-stripping on sand; access matting on loam) increased forage quality (CP, digestibility) of grasses during the first year of recovery. The mechanism for this improvement is unclear, and is surprising given that soil stripped areas were associated with decreased N and OM levels (Chapter 2). One possibility is that the initial compositional shift from grasses to introduced forbs, as shown by the cover data, may have led to improvements in forage quality. Further to this, plant phenology may have been delayed during the growing season in the 'disturbed' treatments, with the relatively younger vegetation following disturbance accounting for the increase in quality the first year.

3.5 Management Implications

Transmission line construction within grasslands of southeastern Alberta is extensive, and can impact large areas of existing native vegetation. While mitigation practices are thought to substantially reduce disturbance impacts during and after transmission line construction, few data test this directly in grassland ecosystems in an operational context. Access mats are thought to reduce the physical impact of equipment on vegetation. Here we utilize a large-scale study examining vegetation responses to different operational methods to achieve transmission line construction on soils of varying texture. Our results show that the use of access matting can limit the overall negative impacts of development on the plant community, particularly within loamy ecosites. In this study, we found access mats had less impact on the composition, quantity and quality of vegetation, while the removal of topsoil altered the plant community to a greater extent. Recovery occurred quite quickly regardless of method or ecosite, and was aided by high rainfall.

Access matting construction methods that conserve the topsoil and at least part of the original plant community (soil seed/bud-bank) are therefore more likely to achieve rapid vegetation recovery. Thus, despite their high cost, access mats appear to be a better choice compared to soil removal for mixed grass prairie conservation during industrial development. An understanding of the rate and extent of vegetation recovery after physical disturbance (including heavy construction traffic) is important to understand the longevity of these impacts, and to separate real from perceived impacts on grassland ecological function, as well as identify best management practices during construction that may minimize initial impacts and/or aid the recovery of vegetation and soils.

Table 3-1. Summary ANOVA results (F-stats, df and P-values) evaluating different transmission tower construction methods and adjacent controls on measures of total foliar cover, including that of grasses, native forbs and introduced forbs (%), for the first three years of recovery. Significant disturbance impacts (P<0.10) are bolded.

Cover Response	Treatment: Ecosite:	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
		F	df[1]	*P*	F	df	*P*	F	df	*P*
Grass (%)										
	Treatment	6.21	1,8	**0.03**	0.09	1,10	0.77	0.37	1,6	0.56
	Year	0.92	2,16	0.41	9.33	2,20	**0.001**	193.5	2,12	**<.001**
	T x Y	1.96	2,16	0.17	3.27	2,20	**0.06**	2.22	2,12	0.15
Native Forb (%)	Treatment	28.61	1,8	**<.001**	0.30	1,10	0.60	0.16	1,6	0.70
	Year	0.47	2,16	0.63	2.12	2,20	0.15	5.12	2,12	**0.02**
	T x Y	0.54	2,16	0.59	3.44	2,20	**0.05**	0.45	2,12	0.65
Introduced Forb (%)	Treatment	3.76	1,8	**0.09**	0.25	1,10	0.63	0	1,6	0.95
	Year	4.44	2,16	**0.03**	0.90	2,20	0.42	7.81	2,12	**0.007**
	T x Y	0.22	2,16	0.80	0.15	2,20	0.86	0.68	2,12	0.53

[1] Values represent the numerator and denominator degrees freedom, respective

Table 3-2. Summary of mean (±treatment SE) grass, native forb, and introduced forb foliar cover (%) following different transmission tower construction methods, over the initial three years (2015-2017) between disturbed and control treatments. Data were collected at peak biomass in late July. Sod-stripping and access matting indicate high disturbance and low disturbance, respectively.

Response	Treatment: Ecosite:	Sod-stripping Sandy		Access matting Loamy		Access matting Sandy	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
Grass Cover (%)							
		18.3 a[1]	37.3 b	29.6	30.6	78.22	75.11
	SE	(±5.4)		(±2.3)		(±3.6)	
Native Forb Cover (%)							
		32.2 a	122.5 b	28.2	27.6	14.3	14.9
	SE	(±13.2)		(±3.2)		(±3.1)	
Introduced Forb Cover (%)							
		63.8 a	32.0 b	7.4	8.2	7.4	8.2
	SE	(±12.4)		(±1.4)		(±1.4)	

[1] Means within a treatment and response variable with different letters, P<0.08.

Table 3-3. Summary of mean (±SE) total grass and native forb cover (%), following transmission tower construction using access matting on loamy ecosites over a three-year period (2015-2017). Data were collected at peak biomass in late July.

Response	Treatment:	Access matting	
	Ecosite:	Loamy	
		μ ± SE	
		Disturbed	Control
Grass Cover (%)	2015	35.6 ab[1]	43.1 a
	2016	25.6 b	32.1 ab
	2017	27.6 b	16.7 b
	SE	(±4.0)	
Native Forb Cover (%)	2015	28.1 ab	38.4 a
	2016	26.7 ab	26.9 ab
	2017	29.8 a	17.6 b
	SE	(±8.9)	

---

[1] Within a response variable, means with different letters differ, $P<0.05$.

Table 3-4. Summary ANOVA results (F-stats, df and P-values) evaluating different transmission tower construction methods and adjacent controls on measures of total ground cover, including bare soil, club moss, microphytic crust and litter cover (%), during the initial three years of recovery. Significant grazing impacts (P<0.07) are bolded.

Cover Response	Treatment: Ecosite:	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
		F	df[1]	*P*	F	df	*P*	F	df	*P*
Bare soil (%)	Treatment	1.84	1,8	0.21	1.90	1,10	0.20	0.16	1,6	0.71
	Year	3.94	2,16	**0.04**	0.43	2,20	0.66	5.91	2,12	**0.02**
	T x Y	0.76	2,16	0.49	6.21	2,20	**0.008**	0.15	2,12	0.86
Club moss (%)	Treatment	1.42	1,8	0.27	36.2	1,10	**0.0001**	0.17	1,6	0.70
	Year	0.80	2,16	0.47	25.9	2,20	**<.0001**	2.18	2,12	0.16
	T x Y	0.80	2,16	0.47	14.8	2,20	**0.0001**	0.26	2,12	0.78
Micro crust (%)	Treatment	5.12	1,16	**0.04**	9.35	1,10	**0.01**	0.04	1,6	0.84
	Year	5.12	2,16	**0.02**	1.08	2,20	0.36	21.6	2,12	**<.0001**
	T x Y	5.12	2,16	**0.02**	5.40	2,20	**0.01**	1.41	2,12	0.28
Litter cover (%)	Treatment	19.13	1,8	**0.002**	0.19	1,10	0.67	0.03	1,6	0.87
	Year	3.06	2,16	**0.08**	2.13	2,20	0.14	3.43	2,12	**0.07**
	T x Y	4.34	2,16	**0.03**	1.73	2,20	0.20	0.06	2,12	0.94

[1] Values represent the numerator and denominator degrees freedom, respectively.

Table 3-5. Summary of mean (± SE) cover (%) of various ground cover components (%) during each of the first three years (2015-2017) after transmission tower construction. Sod-stripping and access matting indicate high disturbance and low disturbance, respectively.

Response	Treatment:	Sod-stripping		Access matting		Access matting	
	Ecosite:	Sandy		Loamy		Sandy	
		μ ± SE		μ ± SE		μ ± SE	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
Bare Soil (%)		28.8	9.90	12.0	6.9	12.5	12.6
	SE	(±10.4)		(±4.4)		(±4.4)	
Club moss (%)		0.00	6.7	0.44 a	15.3 b	0.43	1.3
	SE	(±4.5)		(±2.4)		(±0.97)	
Microphytic crust (%)		0.00 a	1.5 b	0.4 a	15.3 b	5.0	3.70
	SE	(±0.6)		(±2.4)		(±1.8)	
Litter Cover (%)		23.30 a	81.84 b	75.90	65.0	80.5	81.1
	SE	(±9.1)		(±9.0)		(±6.6)	

[1] Means within a treatment and response variable with different letters differ, $P \leq 0.07$.

Table 3-6. Summary of mean (±SE) total microphytic crust and litter cover (%) following transmission tower construction using sod-stripping on sandy ecosites over a three-year period (2015-2017). Data were collected at peak biomass in late July.

Response	Treatment: Ecosite:	Sod-stripping Sandy	
		μ ± SE	
		Disturbed	Control
Microphytic Crust (%)	2015	0.0 a	4.4 b
	2016	0.0 a	0.0 a
	2017	0.0 a	0.0 a
	SE	(±1.0)	
Litter Cover (%)	2015	0.0 b	89.8 a
	2016	24.2 a	62.9 a
	2017	45.7 a	92.8 a
	SE	(±8.9)	

---

[1] Within a response variable, means with different letters differ, P<0.05.

Table 3-7. Summary of mean (±SE) total bare soil, club moss and microphytic crust (%) following transmission tower construction using access matting on loamy ecosites over a three-year period (2015-2017). Data were collected at peak biomass in late July.

Response	Treatment: Ecosite:	Access matting Loamy	
		μ ± SE	
		Disturbed	Control
Bare Soil (%)	2015	13.4 a	1.0 b
	2016	7.0 ab	19.1 a
	2017	15.6 a	0.4 b
SE		(±6.3)	
Club moss (%)	2015	0.1 b	19.4 a
	2016	1.2 b	25.6 a
	2017	0.0 b	0.0 b
SE		(±3.6)	
Micro Crust (%)	2015	2.1 bc	6.2 bc
	2016	0.3 c	10.6 b
	2017	0.0 c	24.4 a
SE		(±5.3)	

---

[1] Within a response variable, means with different letters differ, P<0.05.

Table 3-8. Summary ANOVA results (F-stats, df and P-values) evaluating different transmission tower construction methods and adjacent controls on measures of total grass and forb (native and introduced) biomass (g m^{-2}) during the initial three years of recovery. Significant grazing impacts (P<0.06) are bolded.

Biomass Response	Treatment: Ecosite:	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
		F	df[1]	*P*	F	df	*P*	F	df	*p*
Grass (g m^{-2})	Treatment	8.82	1,8	**0.007**	0.94	1,10	0.35	0.05	1,6	0.82
	Year	25.8	2,16	**<.001**	79.8	2,20	**<.0001**	171.2	2,12	**<.0001**
	T x Y	3.15	2,16	**0.06**	0.34	2,20	0.71	0.47	2,12	0.63
Total Forb (g m^{-2})	Treatment	1.60	1,8	0.24	0.71	1,10	0.42	0.01	1,6	0.91
	Year	12.3	2,16	**0.0006**	75.0	2,20	**<.0001**	27.7	2,12	**<.001**
	T x Y	2.36	2,16	0.12	0.30	2,20	0.74	0.31	2,12	0.74

[1] Values represent the numerator and denominator degrees freedom, respectively.

Table 3-9. Summary of mean (± SE) total grass and forb (including native and introduced forb) biomass (g m^{-2}) during each of the first three years (2015-2017) after transmission tower construction. Sod-stripping and access matting indicate high disturbance and low disturbance, respectively.

Response	Treatment:	Sod-stripping		Access matting		Access matting	
	Ecosite:	Sandy		Loamy		Sandy	
		μ ± SE		μ ± SE		μ ± SE	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
Grass (g m^{-2})		99.2 a	145.6 b	141.6	121.2	156.8	156.4
	SE	(±13.2)		(±14)		(±9.2)	
Forb (g m^{-2})		183.6	127.6	114.0	66.8	64.4	67.6
	SE	(±28.8)		(±32.8)		(±18.8)	

[1] Means within a treatment and response variable with different letters differ, P≤0.06.

Table 3-10. Summary of mean (±SE) total grass biomass (g m^{-2}) following transmission tower construction using sod-stripping on sandy ecosites over a three-year period (2015-2017). Data were collected at peak biomass in late July.

Response	Treatment: Ecosite:	Sod-stripping Sandy	
		μ ± SE	
		Disturbed	Control
Grass (g m^{-2})	2015	17.2 d	86.8 c
	2016	56.6 c	144.4 bc
	2017	215.6 a	206.4 ab
	SE	(±23.2)	

[1] Within a response variable, means with different letters differ, $P<0.05$.

Table 3-11. Summary ANOVA results (F-stats, df and P-values) evaluating different transmission tower construction methods and adjacent controls on measures of total native and introduced forb biomass (g m^{-2}) over two years of recovery (2016-2017), and total root biomass and Root-to-Shoot ratios over two years (2015-2016). Significant impacts (P<0.10) are bolded.

Cover Response	Treatment: Ecosite:	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
		F	df[1]	*P*	F	df	*P*	F	df	*P*
Native Forb (g m^{-2})	Treatment	0.06	1,8	0.82	0.01	1,10	0.92	0.04	1,6	0.84
	Year	26.5	1,8	**0.0009**	91.8	1,10	**<.0001**	41.5	1,6	**0.0007**
	T x Y	7.25	1,8	**0.03**	0.03	1,10	0.87	0.90	1,6	0.38
Introduced Forb (g m^{-2})	Treatment	0.53	1,8	0.49	1.61	1,10	0.23	0.01	1,6	0.93
	Year	5.76	1,8	**0.04**	6.93	1,10	**0.03**	6.04	1,6	**0.05**
	T x Y	0.18	1,8	0.68	0.25	1,10	0.63	0.87	1,6	0.38
Root Biomass (g m^{-2})	Treatment	22.8	1,8	**0.001**	1.2	1,10	0.30	0.27	1,6	0.62
	Year	1.23	1,8	0.30	39.1	1,10	**<.0001**	10.5	1,6	**0.01**
	T x Y	0.95	1,8	0.35	3.5	1,10	**0.08**	0.28	1,6	0.61
Root: Shoot Ratio	Treatment	10.9	1,8	**0.01**	1.68	1,10	0.22	0.07	1,6	0.79
	Year	2.60	1,8	0.14	0.32	1,10	0.58	1.11	1,6	0.33
	T x Y	0.0	1,8	0.96	0.04	1,10	0.84	0.08	1,6	0.78

[1] Values represent the numerator and denominator degrees freedom, respective.

Table 3-12. Summary of mean (± SE) native and introduced forb biomass (g m^{-2}) measured during the second and third years of recovery, and total root biomass (g m^{-2}) and Root:Shoot ratios (g m^{-2}) over two years of monitoring (2015-2016).

Response	Treatment Ecosite:	Sod-stripping Sandy		Access matting Loamy		Access matting Sandy	
		μ ± SE		μ ± SE		μ ± SE	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
Native Forb (g m^{-2})		66.4	52.0	72.0	70.8	55.2	62.8
	SE	(±17.2)		(±15.6)		(±24.8)	
Introduced Forb (g m^{-2})		102.0	90.8	72.8	24.8	30.0	31.2
	SE	(±90.8)		(±24.4)		(±13.6)	
Root Biomass (g m^{-2})		780.9 a	3366.2 b	1357.0	1752.3	1968.5	2294.5
	SE	(±453.9)		(±237.6)		(±405.0)	
Root:Shoot Ratio		4.3 a	15.9 b	4.9	7.0	7.6	10.2
	SE	(±4.2)		(±0.9)		(±3.1)	

[1] Means within a treatment and response variable with different letters differ, P≤0.08.

Table 3-13. Summary of mean (±SE) total native forb biomass (g m^{-2}) following transmission tower construction using sod-stripping on sandy ecosites over a two-year period (2015-2017). Data were collected at peak biomass in late July.

Response	Treatment: Ecosite:	Sod-stripping Sandy	
		μ ± SE	
		Disturbed	Control
Native Forb (g m^{-2})	2016	1.2 c	17.2 bc
	2017	131.6 a	86.8 ab
	SE	(±22.4)	

[1] Within a response variable, means with different letters differ, P<0.05.

Table 3-14. Summary of mean (±SE) total root biomass (g m^{-2}), following transmission tower construction using access matting on loamy ecosites over a two-year period (2015-2016). Data were collected at peak biomass in late July.

Response	Treatment: Ecosite:	Access matting Loamy	
		μ ± SE	
		Disturbed	Control
Root biomass (g m^{-2})	2015	960.5 c^{2}	931.0 c
	2016	1753.6 b	2573.6 a
	SE	(±274.1)	

[1] Within a response variable, means with different letters differ, P<0.10.

Table 3-15. Summary ANOVA results (F-stats, df and P-values) evaluating different transmission tower construction methods and adjacent controls on measures of vegetation quality and chemical response in the first year of recovery (2015). Significant grazing impacts (P<0.06) are bolded.

	Treatment Ecosite:	Sod-stripping Sandy			Access matting Loamy			Access matting Sandy		
		F	df[1]	*P*	F	df	*p*	F	df	*P*
ADF (%)	Grass	0.04	1,8	0.84	4.49	1,10	**0.06**	0.69	1,6	0.43
	Forbs	0.31	1,8	0.59	1.81	1,9	0.21	2.37	1,6	0.17
Crude Protein (%)	Grass	7.00	1,8	**0.02**	0.29	1,10	0.59	0.22	1,6	0.65
	Forbs	0.93	1,8	0.36	0.29	1,10	0.59	1.80	1,6	0.22

[1] Values represent the numerator and denominator degrees freedom, respectively.

Table 3-16. Summary of mean (±SE) biomass of total vegetation quality responses within various transmission tower construction methods in the first year of recovery (2015).

Response	Treatment: Ecosite:	Sod-stripping Sandy		Access matting Loamy		Access matting Sandy	
		μ ± SE		μ ± SE		μ ± SE	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
ADF (%)	Grass	47.3	46.3	42.2 a	47.8 b	43.7	39.9
		(±3.4)		(±1.8)		(±3.3)	
	Forbs	46.4	49.7	39.0	43.8	39.5	43.6
		(±4.1)		(±2.4)	(±2.6)	(±1.9)	
Crude Protein (%)	Grass	9.0 a	6.4 b	7.5	7.0	7.5	6.9
		(±0.6)		(±0.6)		(±0.8)	
	Forbs	13.2	11.0	10.3	11.0	9.8	12.0
		(±1.6)		(±0.9)		(±1.7)	

[1] Means within a treatment and response variable with different letters differ, P<0.05.

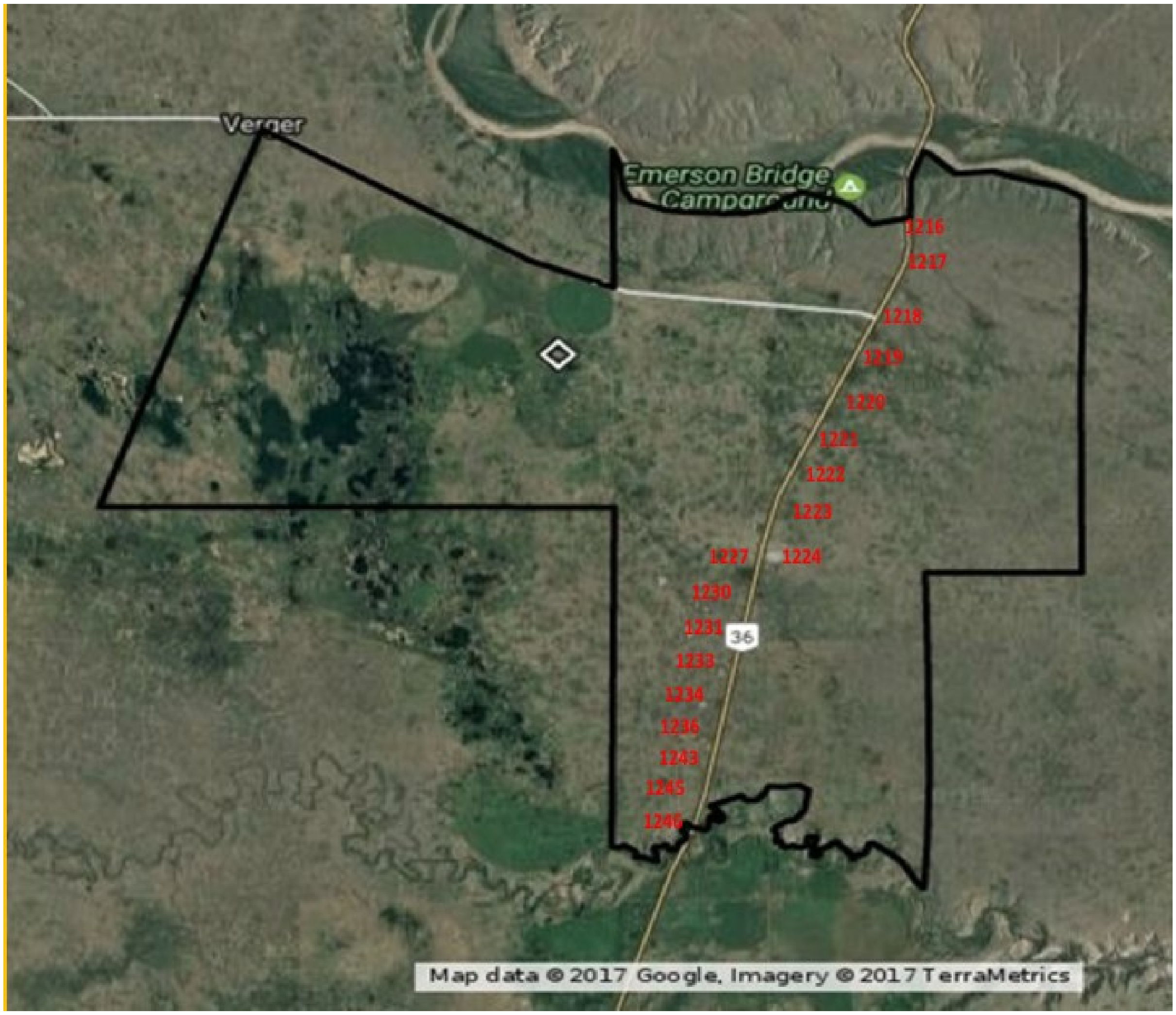


Figure 3-1. Map of the University of Alberta Mattheis Ranch, part of the Rangeland Research Institute. Red numbers indicate tower locations.

Figure 3-2. Access matting transmission tower construction where access mats (bottom) were used to build access trails into the tower sites (top), as well as establish a working area directly below the tower to facilitate tower assembly and erection.

Figure 3-3. Sod-stripped tower site where soil was initially removed and replaced after tower construction (top), and vegetation was then re-established using a hydro-seeding treatment (bottom).

Chapter 4 Synthesis

4.1 Introduction

Native grasslands provide many ecological goods and services, including forage for livestock, wildlife habitat, and carbon storage and sequestration (Havstad et al., 2007; Hooper et al., 2005). However, in the past one hundred years of settlement, the Canadian prairies have been changed by agriculture and urban development. While rangeland vegetation communities are dominated by native graminoids (Coupland 1961) and are adapted to the disturbance of grazing (Coughenour 1985; Milchunas *et al.* 1988) industrial activities are introducing new and intense disturbances that can detrimentally alter grassland vegetation.

Industrial activities such as high voltage transmission line construction can alter vegetation and soils in the Mixedgrass Prairie of western Canada. Re-establishment of vegetation is critical to restore ecosystem function and meet regulatory compliance. Two different methods of high-voltage transmission line tower construction are sod-stripping prior to construction followed by soil replacement and wholesale re-revegetation (i.e. high disturbance method), or laying wooden access mats on prairies (i.e. low disturbance method) to minimize heavy equipment impacts to the underlying grassland (ASRD 2010). Access mats are thought to reduce direct damage to soil and vegetation by limiting physical disturbance, but subsequent recovery depends on regrowth of vegetation from surviving plant material or the seed bank (Dollhopf et al. 2007 Mitchem et al. 2009). While the use of access mats is widely recommended on public land in Alberta, limited data exist on the effectiveness of mats in facilitating vegetation recovery, particularly in comparison to conventional high disturbance methods; in addition, very little is known on how this varies with soil texture. This study reports on the first several years of recovery of high-voltage transmission line towers constructed in Mixedgrass Prairie using two contrasting construction methods.

4.2 Soil Responses

Both sod-stripping and access matting had a significant effect on soil physical and chemical characteristics. Soil stripping and replacement was less able to maintain key soil properties, including leading to a reduction in organic matter and soil nitrogen, presumably through admixing of topsoil with subsoil (Culley et al, 1982; Naeth et al., 1987). In this study, soil bulk density increased, and organic matter and N decreased in response to the removal and replacement of soil within the sod-stripping method, while no such changes were observed under access matting. Access matting had more effect on loamy than sandy sites by reducing soil water infiltration and ground cover. Soil nutrients were changed under both sod-stripping and access matting. The disturbance of sod-stripping generally increased nutrients to a greater extent compared to access matting.

4.2 Vegetation Recovery

Grass and both native and introduced forbs were changed under high disturbance sod-stripping. Sod-stripping led to less initial grass, and more introduced forbs, which eventually recovered after three years. Changes in grass cover and biomass were not as dramatic in the access matted plots, where grasses recovered more quickly, leading to a community more representative of the adjacent controls, regardless of ecosite. However, most of the disturbance effect was reclaimed by the third year of recovery. Grass cover and vegetation biomass was changed mostly by sod-stripping, and access matting within the loamy site.

4.3 Future Direction/ BMP

Our study has strong relevance to industry through the development of better management practices on the proper construction methods of high voltage transmission lines in grasslands, with low disturbance methods capable of minimizing the detrimental impacts of energy infrastructure construction on grassland soil and vegetation. Additionally, where grasslands are disturbed, this study provides information on the resilience (i.e. recovery dynamics) of these ecosystems, including the role of different types of industrial activity (soil removal and replacement, spoil pile storage, access matting use, etc.). These impacts were examined using not only vegetation metrics, but also soil conditions. Collectively, this information will allow industry to refine their best management practices for managing prairie grasslands exposed to industrial disturbance, including identifying both mitigation measures prior to and during construction, and subsequent activities that will promote recovery after completion and during restoration. In addition to benefiting industry, this information will also provide greater confidence to land owners and land managers that the construction of infrastructure such as high voltage transmission lines can be done in a manner consistent with grassland conservation. In doing so, the information provided by this research will add to the social license necessary for the energy sector to continue to sustainably operate on private and public grasslands in Canada.

Lastly, future research should also consider evaluating how transmission line disturbance impacts seed bank composition and displacement of mixedgrass prairies. This would provide better comparisons among native and introduced vegetation and help to identify management practices more beneficial for construction activities. Examine the effect of these two different construction methods on soil and vegetation in different areas, such as mesic foothills grassland, forest, and aspen parkland. Also, examine how microbe functional activity changes under two different construction method.

4.4 Conclusion

Industrial activity in grasslands is extensive, but our results show that some types of management practices on certain ecosites can limit the overall impact on the plant community and underlying soil. Throughout this thesis, we have heavily emphasized that both sod-stripping and access matting can have a significant effect on soil and vegetation. However, sod-stripping (i.e. high disturbance) construction more negatively impacted soil and vegetation properties in mixedgrass prairies, in turn necessitating longer recovery times. In contrast, access matting construction helped protect soil and vegetation to a greater extent, and therefore despite their high cost, access mats appear to be a better choice compared to soil removal for mixedgrass prairie conservation. The value of access mats in protecting mixedgrass prairie also appeared to be particularly high on loamy soils.

Overall, my research results serve to better inform industry, landowners, and rangeland managers, on the consequences of high voltage transmission line construction. Additionally, the study undertaken here provides more details on the type, magnitude and duration of construction practice impacts to mixedgrass vegetation (biomass, composition, and forage quality) and soil (physical and chemical characteristics). This information has the potential to reduce the future environmental impact of industrial disturbance in native grassland.

Bibliography

Alberta Sustainable Resource Development. 2010. Industrial activity in foothills fescue grasslands. Guidelines for minimizing surface disturbance. Report prepared by Alberta Sustainable Resource Development, Lands Division, Edmonton, Alberta. 17 pp

Alberta Environment and Parks (AEP). 2016. Principles for minimizing surface disturbances in native grassland – principles, guidelines, and tools for all industrial activity in native grassland in the prairie and parkland landscapes of Alberta. Alberta Environment and Parks Policy, Land Policy Branch, Edmonton, AB

Alberta Environmental Protection. 1997. The grassland natural region of Alberta. Draft report for Special Places 2000 coordinating committee. Alberta Environmental Protection, Natural Resources Services, Recreation and Protected Areas Division, Natural Heritage Protection and Education Branch 229 pp

Allred, B.W., W.K. Smith, D. Twidwell, J.H. Haggerty, S.W. Running, D.E. Naugle, and S.D. Fuhlendorf. 2015. Ecosystem services lost to oil and gas in North America. Science **348**: 401-402

Andrade, B.O., C. Koch, I.I. Boldrini, E. Vélez-Martin, H. Hasenack, J.M. Hermann, J. Kollman, V.D. Pillar, and G.E. Overbeck. 2015. Grassland degradation and restoration: a conceptual framework of stages and thresholds illustrated by southern Brazilian grasslands. Journal of Natureza and Conservação **13**: 95–104

Adams, B.A., J. Richman, L. Poulin-Klein, K. France, D. Moisey, and R.L. McNeil. 2013. Rangeland plant communities of the Mixedgrass Prairie Natural Subregion of Alberta. 2nd approximation. Rangeland Management Branch, Policy Division, Alberta Environment and Sustainable Resource Development. Lethbridge, Alberta 103pp

Althoff, D.P., P.S. Althoff, N.D. Lambrecht, P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2007. Soil properties and perceived disturbance of grasslands subjected to mechanized military training: Evaluation of an index. Land Degradation and Development **18**:269-288

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics **42(3)**:159-176

Althoff, P.S., S.J. Thien, and T.C. Todd. 2010. Primary and residual effects of Abrams tank traffic on prairie soil properties. Journal of American Soil Science **74(6)**:2151-2161

Ayers, P.D. 1994. Environmental damage from tracked vehicle operation. Journal of Terramechanics **31(3)**:173-183

Balachowski, L., and N. Kurek. 2014. Deep compaction control of sandy soils. Studia Geotechnica et Mechanica **36(2)**:3-8

Blake, G.R., and K.H. Hartge. 1986. Bulk density. Pp. 363-376, In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, 2nd ed. Agron. Monogr. 9. ASA. Madison, WI

Bork, E.W. and B.D. Irving. 2015. Seasonal availability of cool- and warm-season herbage in the Northern Mixed Prairie. Rangelands **37(5)**:178-185

Baker, W.L. 1992. Effects of settlement and fire suppression on landscape structure. Journal of Ecological Society of America **73(5)**: 1879-1887

Bork, E.W., B.W. Adams, and W.D. Willms. 2002. Resilience of foothills rough fescue, Festuca campestris, rangeland to wildfire. Canadian Field-Naturalist **116(1):** 51-59

Bailey, A.W., and R.A. Wroe. 1974. Aspen invasion in a portion of the Alberta parklands. Journal of Range Management **27(4)**: 263-266

Bradley, C., M. Neville. 2010. Minimizing Surface Disturbance of Alberta's Native Prairie Background to Development of Guidelines for the Wind Energy Industry. Foothills Restoration Forms pp 19

Bai, W., Y. Fang, M. Zhou, X. Ting, L. Li, and W-H. Zhang. 2015. Heavily intensified grazing reduces root production in an Inner Mongolia temperate steppe. Agriculture, Ecosystems and Environment **200**:143-150

Biligetu, B. and B. Coulman. 2011. Etiolated regrowth of three brome grass (Bromus) species after defoliation at different developmental stages. Journal of Japanese Society of Grassland Science **57**:198 – 203

Carletti, P., E. Vendramin, D. Pizzeghello, G. Concheri, A. Zanella, S. Nardi, and A. Squartini. 2009. Soil humic compounds and microbial communities in six spruce forests as function of parent material, slope aspect and stand age. Journal of Plant and Soil **315**: 47-65

Culley, J.L.B., B.K. Dow, E.W. Presant, and A.J. MacLean. 1982. Recovery of productivity of Ontario soils disturbed by an oil pipeline installation. Canadian Journal of Soil Science **62(2)**: 267-279

Coughenour, M.B. 1985. Graminoid responses to grazing by large herbivores: adaptations, exaptation's, and interacting processes. Journal of the Missouri Botanical Garden **72(4)**: 852-863

Commission, U.S.F.E.R., 2001. Algonquin Gas Transmission Company and Texas Eastern Transmission Corporation: Environmental Impact Statement, Phase III/Hubline Project. Northwestern University, United States, 99 pp

Coupland, R.T., and T. Brayshaw. 1953. The fescue grassland in Saskatchewan. Journal of Ecological Society of America **34(2)**:386-405

Coupland, R.T. 1961. A reconsideration of grassland classification in the Northern Great plains of North America. Journal of Ecology **49**: 135-167

Coupland, R.T., and R.E. Johnson. 1965. Rooting characteristics of native grassland species in Saskatchewan. Journal of Ecology **53**: 475-507

Coppedge, B. R., D. M. Engle, R. E. Masters, and M. S. Gregory. 2001. Avian response to landscape change in fragmented southern great plains grasslands. Journal of Ecological Applications **11**:47–59

Ceballos, G., A. Davidson, R. List, J. Pacheco, P. Manzano-Fischer, G. Santos-Barrera, and J. Cruzado. 2010. Rapid Decline of a Grassland System and Its Ecological and Conservation Implications. Journal of Public Library of Science **5(1)**: 137-856

Chanasyk, D.S., and M.A. Naeth. 1995. Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. Journal of Canadian Soil Science **75**: 551-557

Donkor, N.T., J.V. Gedir, R.J. Hudson, E.W. Bork, D.S. Chanasyk, and M.A. Naeth. 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. Journal of Canadian Soil Science **82(1)**: 1-8

DiTomaso, J.M., M.L. Brooks, E.B. Allen, R. Minnich, P.M. Rice, and G.B. Kyser. 2006. Control of invasive weeds with prescribed burning. Journal of Weed Science Society of America **20(2)**: 535-548

Dormaar, J.F., A. Johnston, and S. Smoliak. 1984. Seasonal changes in carbon content, and dehydrogenase, phosphatase, and urease activities in mixed prairie and fescue grassland Ah horizons. Journal of Range Management **37(1)**: 31-35

Dormaar, J.F., and W.D. Willms. 1998. Effect of forty-four years of grazing on fescue grassland soils. Journal of Range Management **51**: 122-126

Dormaar, J.F., and W.D. Willms. 1993. Decomposition of Blue Grama and Rough Fescue Roots in Prairie Soils. Journal of Range Management **46**(3):207-213

Dollhopf, D.J., M.D. Mitchem, C.S. McWilliams, and S.J. Gundlach. 2007. Effect of oak matted drill pads on plant and soil resources. Report prepared by KC Harvey, Soil and Water Resources Consulting, for US Bureau of Land Management, Pinedale, WY 82 pp

Desserud, P., C.C. Gates, B. Adams, and R.D. Revel. 2010. Restoration of foothills rough fescue grassland following disturbance in southwestern Alberta. Journal of Environmental Management **91**: 2763–2770

Desserud, P. 2016. Alberta Environment and Parks: Industrial activity in the central Parkland and northern fescue native grasslands: strategies for minimizing surface disturbance. Edmonton, Alberta, pp 22

Defossez, P. and G. Richard. 2002. Models of soil compaction due to traffic and their evaluation. Journal of Soil and Tillage Research **67**:41-64

Elsinger, M.E. 2009. Reclamation status of plains rough fescue grasslands at Rumsey block in central Alberta, Canada after oil and gas well site and pipeline disturbance. MSc Thesis in Land Reclamation and Remediation. University of Alberta 232 pp

Epstein, H.E., W.K. Lauenroth, and I.C. Burke. 1997. Effects of temperature and soil texture on ANPP in the U.S. Great Plains. Journal of Ecology **78**: 2628-2631

Erickson, W. P., G. D. Johnson, M. D. Strickland, D. P. Young, K. J. Sernka, and R. E. Good. 2001. Avian collisions with wind turbines: a summary of existing studies and comparisons to other sources of avian collision mortality in the United States (No. DOE-00SF22100--822418). https://doi.org/10.2172/822418

Floate, K.D., and K.D. Floate. 2011. Arthropods of Canadian grasslands: vol. 2. Biological Survey of Canada, Ottawa, Ontario pp 479

Fukushima, R.S., M.S. Kerley, M.H. Ramos, J.H. Porter, and R.L. Kallenbach. 2015. Comparison of acetyl bromide lignin with acid detergent lignin and Klason lignin and correlation with in vitro forage degradability. Journal of Animal Feed Science and Technology **201:** 25 -37

Gerard, C., P. Sexton, and G. Shaw. 1982. Physical factors influencing soil strength and root growth. Journal of Agronomy **74:** 875-879

Gibson, D.J., 2009. Grasses and grassland ecology. Oxford University Press, Oxford, United Kingdom pp 314

Gifford, G.F., R.H. Faust, and G.B. Coltharp. 1977. Measuring soil compaction on rangeland. Journal of Range Management **30:** 457-460

Gartrell C.A., J.K. Newman, and G.L. Anderton. 2009. Performance measurements of pavement matting systems by full-scale testing over differing soil strengths. Journal of Materials in Civil Engineering **21**:561-568

Grantham, W.P., E.F. Redente, C.F. Bagley, and M.W. Paschke. 2001. Tracked vehicle impacts to vegetation structure and soil erodibility. Journal of Range Management **54(6)**:711-716

Henderson, D.C., B.H. Ellert, and M.A. Naeth. 2004. Utility of ^{13} C for ecosystem carbon turnover estimation in grazed mixed grass prairie. Geoderma **119(3)**: 219-231

Harper, J.L. 1977. Population Biology of Plants. Academic Press, London pp 892

Hill, M.J., W.D. Willms, R.J. Aspinall. 2000. Distribition of Range and Cultivated Grassland Plants in Southern Alberta. Journal of Plant Ecology **147(1)**: 59-76

Hammermeister, A.M., T. Astatkie, E.A. Jeliazkova, P.R. Warman, and R.C. Martin. 2006. Nutrient supply from organic amendments applied to unvegetated soil, lettuce and orchardgrass. Journal of Canadian Soil Science **86(1)**: 21-33

Havstad, K.M., D.C. Peters, R. Skaggs, J. Brown, B.T. Bestelmeyer, E.L. Fredrickson, J.E. Herrick, and J.E. Wright. 2007. Ecological Services to and from Rangelands of the United States. Journal of Ecological Economics **64**: 261-268

Hammermeister, A.M., M.A. Naeth, J.J. Schoenau, and V.O. Biderbeck. 2004. Effectiveness of five soil reclamation and reforestation techniques on oil and gas well sites in northeaststern British Columbia.Journal of Canadian Soil Science **83**: 507-519

Hamza, M.A. and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Journal of Soil and Tillage Research **82**:121-145

Hammermeister, A.M. 2001.An ecological analysis of prairie rehabilitation on petroleum wellsites in Southeast Alberta. PhD Thesis in Water and Land Resources. University of Alberta 121 pp

Hickman, L.K., P.A. Desserud, B.W. Adams, and C.C. Gates. 2013. Effects of disturbance on silver sagebrush communities in dry mixed-grass prairie. Ecological Restoration **31**: 274-282

Hutchings, M.J., and K.D. Booth. 1996. Studies on the feasibility of re-creating chalk grassland vegetation on ex-arable land. Journal of Applied Ecology **33**: 171-118

Hooper, D.U., F.S. Chapin, J.J. Ewel, A. Hector, P. Inchausti, S. Laborel, J.H. Lawton, D.M. Lodge, M. Loreau, S. Naeem, B.H. Schmid, L.A. Setala, A.J. Symstad, J. Vandermeer, and D. Wardle. 2005. Effects of biodiversity on ecosystem functioning. Journal of Ecological Society of America **75(1)**: 3-35

Hulett, G.K., R.T. Coupland, and R.L. Dix. 1966. The vegetation of dune sand areas within the grassland region of Saskatchewan. Canadian Journal of Botany **44**: 1307-1331

Houghton, J.T.Y., D.J. Ding, M. Griggs, P.J. Noguer, X. Dai. van der Linden, K. Maskell, and C.A. Johnson. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 881pp

Jong, E.D., and R.G. Button.1973. Effects of pipeline installation on soil properties and productivity. Canadian Journal of Soil Science **53**: 37-47

Kerr, D.S., L.J. Morrison, and K.E. Wilkinson. 1993. Reclamation of native grasslands in Alberta: a review of the literature. Alberta Land Conservation and Reclamation Council Report **93(1)**: 205

Kaufman, D.S., L.J. Morrison and K.E. Wilkinson. 1993. Protecting Our Global Environment. Harper Collins College Publishers. 607 pp

Kaufmann, J., E.W. Bork, P.V. Blenis, and M.J. Alexander. 2013. Cattle habitat selection and associated habitat characteristics under free-range grazing within heterogeneous Montane rangelands of Alberta. Journal of Applied Animal Behavior Science **146**: 1–10

Kline, V.M., 1997. The Tallgrass Prairie Restoration Handbook for Prairie, Savannas and Woodlands. Island Press. Washington, D.C 3-21

Kuncoro, P.H., K. Koga, N. Satta, and Y. Muto. 2014. A study on the effect of compaction on transport properties of soil gas and water I: Relative gas diffusivity, air permeability, and saturated hydraulic conductivity. Journal of Soil and Tillage Research **143**:172-179

Lafond, G.P, F. Walley, W.E. May, and C.B. Holzapfel. 2011. Long-term impact of no-till on soil properties and crop productivity on the Canadian prairies. Journal of Soil Tillage Research **117**: 110-123

Lardner, H.A., S.B.M. Wright, and R.D.H. Cohen. 2003. Assessing eight grass species for pasture by measuring etiolated spring regrowth. Journal of Canadian of Plant Science **83(3)**:551-554

Mitchem, M.D., D.J. Dollhopf, and K.C. Harvey. 2009. Reduced-impact land disturbance techniques for natural gas production. American Society of Mining and Reclamation, Billings, MT, Revitalizing the Environment 16 pp

Milchunas, D.G., O.E. Sala, and W. Lauenroth. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. Journal of American Naturalist **132(1)**: 87-106

Milchunas, D.G., and W.K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Society of America **63** (4): 327-366

Martin, R.E., R.L. Miller, and C.T. Cushwa.1975. Germination response of legume seeds subjected to moist and dry heat. Journal of Ecology **56(6)**: 1441-1445

Morris, S.J., and R.E.J. Boerner. 1999. Spatial distribution of fungal and bacterial biomass in southern Ohio hardwood forest soils: scale dependency and landscape patterns. Journal of Soil Biology and Biochemistry **31**: 887-902

McWilliams, C.S., D.J. Dollhopf, K.C. Harvey, and D.J. Dale. 2007. Soil bulk density impacts of an oak mat natural gas drill pad construction technique. Journal American Society of Mining and Reclamation **31**: 3-4

Naeth, M.A., A.W. Bailey, D.J. Pluth, D. Chanasyk, and R.T. Hardin. 1991. Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. Journal of Range Management **44(1)**: 7-12

Naeth, M.A., 1985. Ecosystem reconstruction following pipeline construction through solonetzic native rangeland in southern Alberta. Master of Science Thesis, University of Alberta, Edmonton, Alberta 233 pp

Naeth, M.A., A.W. Bailey, and McGill, W.B., 1987. Persistence of changes in selected soil chemical and physical properties after pipeline installation in solonetzic native rangeland. Canadian Journal of Soil Science **67:** 47-763

Nelson, A.G., S.A. Quideau, B. Frick, D. Niziol, J. Clapperton, and D. Spaner. 2011. Spring wheat genotypes differentially alter soil microbial communities and wheat breadmaking quality in organic and conventional systems. Journal of Canadian Plant Science **91**: 485-495

Noel, R. J., and L. G. Hableton. 1976. Collaborative study of semi-automated method for determination of crude protein in animal feeds. Assoc. Journal of Functional Analysis **59**: 134140

Obermeyer, B., R. Manes, J. Kiesecker, J. Fargione, and K. Sochi. 2011. Development by design: mitigating wind development's impacts on wildlife in Kansas. Journal of Public Library of Science **6(10)**: 26-698

Ostermann, D.K. 2001. Revegetation assessment of a twelve year old pipeline on native rangeland in southern Alberta. MSc Thesis in Land Reclamation and Remediation. University of Alberta 121 pp

Pitt, M., and T.D. Hooper. 1994. Threats to biodiversity of grasslands in British Columbia. Biodiversity in British Columbia: Our Changing Environment. (LE Harding and E. McCullum, eds.) Environment Canada, Canadian Wildlife Service, Pacific and Yukon Region pp 279-291

Prescott, C.E., D.G. Maynard, and R. Laiho. 2000. Humus in northern forests: friend or foe? Journal of Forest Ecology and Management **133**: 23-36

Petherbridge, W.L. 2000. Sod salvage and minimal disturbance pipeline reclamation techniques: Implications for native prairie restoration. MSc Thesis in Land Reclamation and Remediation University of Alberta 218 pp

Palazzo, A.J., K.B. Jensen, B.L. Waldron, and T.J. Cary. 2005. Effects of tank tracking on range grasses. Journal of Terramechanics **42**:177-191

Raper, R.L., 2005. Agricultural traffic impacts on soil. Journal of Terramechanics **42(4)**: 259-280

Retta, A., L.E. Wagner, J. Tatarko, and T.C. Todd. 2013. Evaluation of bulk density and vegetation as affected by military vehicle traffic at Fort Riley, Kansas. American Society of Agricultural and Biological Engineers **56(2)**:653-665

Samson, F., and F. Knopf. 1994. Prairie conservation in north America. Journal of Biological Science **44(6)**: 418-421

Smoliak, S., J.F. Dormaar, and A. Johnston. 1972. Long-term grazing effects on Stipa-Bouteloua prairie. Journal of Range Management **25**: 246-250

Sauer, C.O. 1950. Grassland climax, fire, and man. Journal of Range Management **3(1)**: 16-21

Sims, P.L., J.S. Singh, and W.K. Lauenroth. 1978. The structure and function of ten western North American grasslands: I. Abiotic and vegetation characteristics. Journal of Ecology **66**: 251-285

Shorthouse, J.D. 2010. Ecoregions of Canada's prairie grasslands. Arthropods of Canadian Grasslands Ecology and Interactions in Grassland Habitats. Biological Survey of Canada, pp. 53–81

Storer, D.A., 1984. A simple high sample volume ashing procedure for determination of soil organic matter. Communications in Soil Science and Plant Analysis **15**: 7759-772

Sheoran, V., A.S. Sheoran and P. Poonia. 2010. Soil Reclamation of Abandoned Mine Land by Revegetation: A Review **3**: Iss.2

Soulodre, E.J.M. 2001. Restoration ecology of cattle grazing on mixed prairie wellsites: A hierarchical approach. MSc Thesis. University of Alberta 151 pp

Soest, P.J., and B.A. 1991. Methods for dietary fiber. neutral detergent fiber and non-starch polysaccharides in relation to animal nutrition. Journal of Dairy Science 74: 3583-3597

Strohmayer, P. 1999. Soil stockpiling for reclamation and restoration activities after mining and construction. Journal of Intentional mining, Reclamation and Environment **4**: 1-4

Tannas, S. C. 2011. Mechanisms regulating *Poa pratensis* L. and *Festuca campestris* Rybd. within the Foothills Fescue grasslands of southern Alberta. Ph. D. dissertation. University of Alberta

Thurow, T.L., S.D. Warren and D.H. Carlson. 1996. Tracked vehicle traffic effects on the hydrologic characteristics of central Texas rangeland. American Society of Agricultural and Biological Engineers **36(6)**:1645-1650

Tyser, R., and C. Worley. 1992. Alien flora in grasslands adjacent to road and trail corridors in Glacier National Park, Montana. Journal of Conservation Biology **6**: 253-261

Unger, P.W., and T.C. Kaspar. 1994. Soil compaction and root-growth - a review. Journal of Agron **86**:759-766

Unger, P.W., and T.C. Kaspar. 1994. Soil compaction and root growth: A review. Agronomy Journal **86**: 759-766

Voisin, A. 1960. Better Grassland Sward: Ecology, Botany, Management, Crosby Lockwood, London pp 341

Voorhees, W.B., D.A. Farrell, and W.E. Larson. 1975. Soil strength and aeration effects on root elongation. Soil Science Society of America Journal **39(5)**: .948-953

Van Soest, P., J.B. Robertson, and B.A. Lewis.1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. Journal of Dairy Science **74**: 3583–3597

Willms, W.D., and P.G. Jefferson. 1993. Production characteristics of the mixed prairie: constraints and potential. Journal of Canadian Animal Science **73**: 765-778

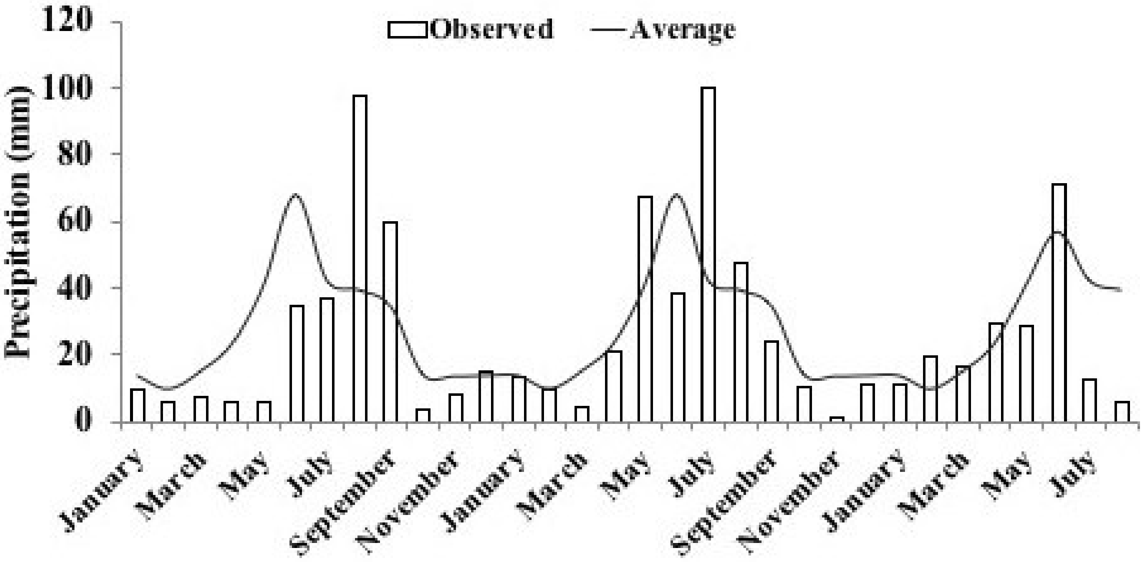
Wilson, S.D., 2002. Handbook of Ecological Restoration. Cambrige University Press, Cambridge, UK 443-465 pp

Wilson. S.D., 1988. The effects of military tank traffic on prairie: a management model. Environmental Management **12**: 397-403

Willms, W.D., and Quinton, D.A. 1995**.** Grazing effects on germinable seeds on the fescue prairie. Journal of Range Management **48**(5):423-430

Zink, T.A., M.F. Allen, B. Heindl-Tenhunen, and E.B. Allen. 1995. The effect of a disturbance corridor on an ecological reserve. Journal of Restoration Ecology **3(4)**: 304-310

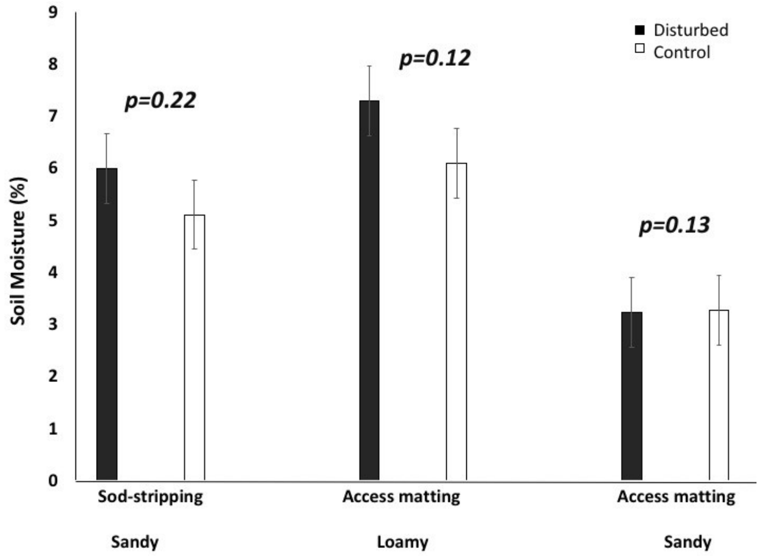
Appendices



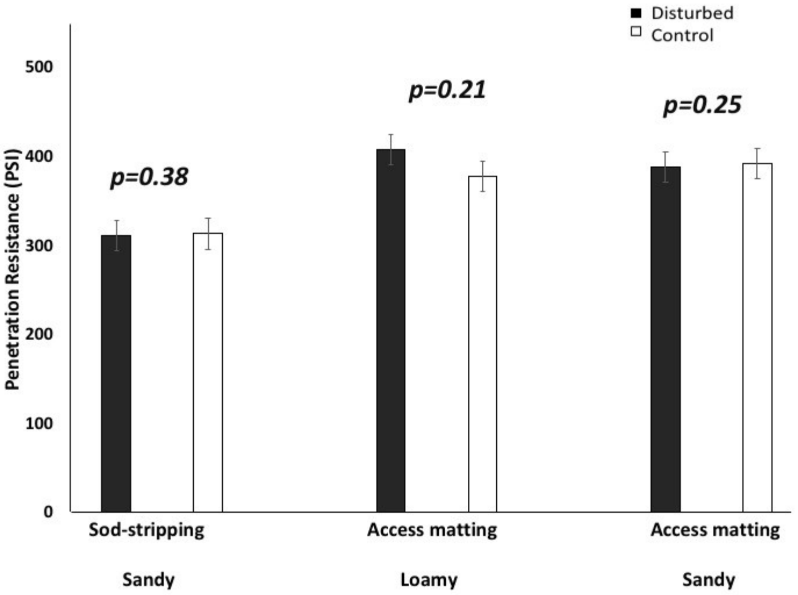
Appendix 1. Average long-term (30 year) precipitation (mm) and actual monthly precipitation received at the Mattheis Research Rangeland from January 2015 through August 2017.

Appendix 2. Results of the overall (a) soil moisture and (b) soil penetration resistance in July 2015. Soil moisture and penetration resistance did not change between disturbed and control areas in 2015. However, soil moisture did differ between 2015 and 2016.

A)



B)



Appendix 3. Results of the overall ANOVA tests of soil moisture and soil penetration resistance. Soil moisture and penetration resistance did not change between disturbed and control areas in 2015. However, soil moisture did differ between 2015 and 2016.

Source	Sod-striping Sandy			Access matting Loamy			Access matting Sandy		
	F	df	*P*	F	df	*P*	F	df	*P*
------------------------------- *Soil Moisture Responses* ----------------------------									
Treatment (T)	1.65	1,4	0.23	2.11	1,5	0.18	2.17	1,3	0.15
Year (Y)	**47.8**	**1,8**	**<.0001**	**65.3**	**1,10**	**0.0001**	**65.3**	**1,6**	**0.0001**
T x Y	1.43	1,8	0.25	1.45	1,10	0.25	1.40	2,6	0.25
------------------------- *Soil Penetration Resistance Responses* -------------									
Treatment(T)	0.05	1,4	0.80	0.33	1,5	0.64	0.01	1,3	0.94
Year (Y)	0.06	1,8	0.81	1.17	1,10	0.38	**5.74**	**1,6**	**0.07**
T x Y	0.16	1,8	0.70	0.76	1,10	0.46	0.11	1,6	0.76

[1] Values represent the numerator and denominator degrees freedom, respectively.

Appendix 4. Summary of mean (±SE) total soil moisture and penetration resistance (PR) following different transmission tower construction methods, over the two years following construction (2015 and 2016), as sampled in July of each year.

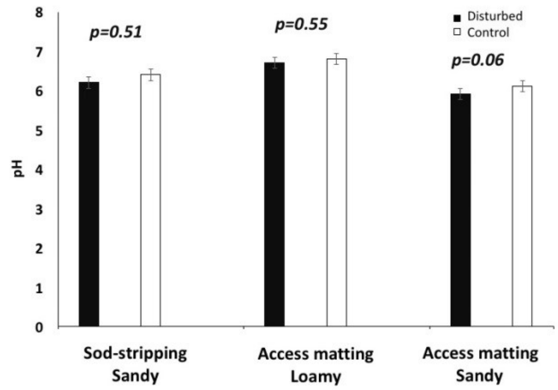
Response Treatment: Ecosite:		Sod-stripping Sandy		Access matting Loamy		Access matting Sandy	
		μ ± SE		μ ± SE		μ ± SE	
		Disturbed	Control	Disturbed	Control	Disturbed	Control
Moisture (%)	2015	5.8	4.7	7.2	6.5	3.3	3.2
	2016	4.8	5.5	7.0	7.6	5.5	5.7
		(±30.2)		(±30.3)		(±30.3)	
	Both Yrs	5.3 a	5.1 b	7.1 a	7.0 b	4.4 a	4.4 b
		(±30.2)		(±30.2)		(±30.3)	
PR (PSI)	2015	320.2	318.0	370.0	360.0	365.5	370.0
	2016	305.0	285.0	354.1	268.9	328.5	330.0
		(±0.08)		(±0.05)		(±19.8)	
	Both Yrs	312.6	301.5	362.5	314.4	347.0 a	350.0 b
		(±0.06)		(±0.1)		(±0.08)	

---

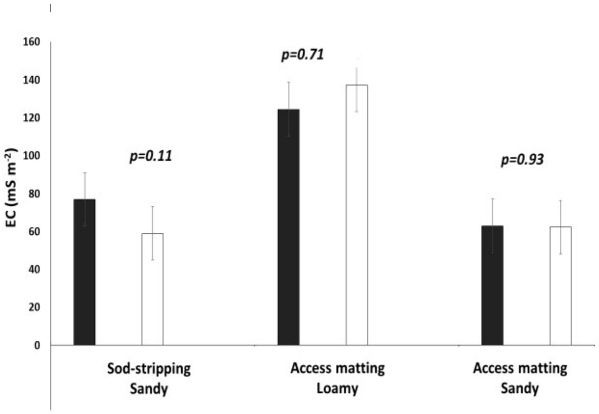
[1] Means within a treatment and response variable with different letters differ, P≤0.07.

Appendix 5. Summary of the soil chemistry characteristics that did not differ between the disturbed and control treatments in each of the three different tower construction method × ecosite combinations.

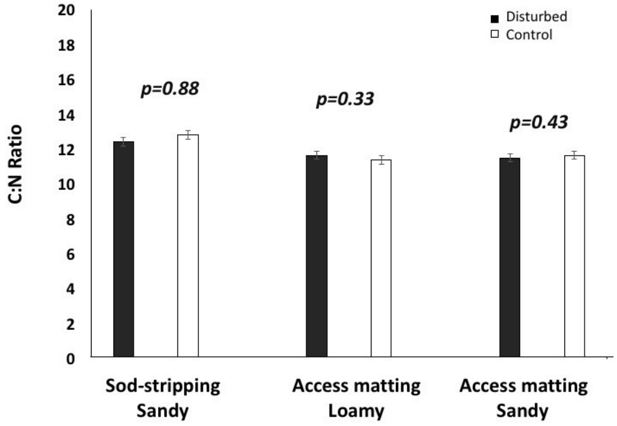
A)



B)



C)



Appendix 6. Mix of grass species and their seeding rate used during hydroseeding within all sod-stripping plots and select access matting towers (1218 and 1222) during late May of 2015. The total seeding rate was 15 kg ha^{-1}.

Grass Species	Common name	Composition (by mass)
Hesperostipa comata	Needle- and-thread	40 %
Koeleria macrantha	June grass	15 %
Bouteloua gracilis	Blue grama	15 %
Pascopyrum smithii	Western wheatgrass	10 %
Calamovilfa longifolia	Sand grass	20 %