Mitigating effects of access mats on construction traffic in Mixedgrass Prairie of Alberta

by

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Abstract

Grasslands ecosystems are increasingly subject to anthropogenic alterations, including conversion to cropland or tame pasture, and dissection by urban infrastructure. Linear disturbances, like roads, oil and gas pipelines, and electrical transmission lines, can fragment these ecosystems, directly alter underlying soils, and serve as vectors for plant invasions. A novel construction method, adapted from oil and gas extraction in the northern boreal forest, uses technology to redistribute equipment weight during construction in native grassland in an effort to decrease the footprint created from industrial development. The technology is comprised of an interlocking matrix of three-ply wooden mats, called access mats, used to create temporary road and work areas.

This study was conducted on the University of Alberta's Mattheis Research Ranch to examine the impact of various access mat placement treatments on native grassland of the Dry Mixedgrass prairie in SE Alberta, and reflected ongoing construction activities of ATCO's Eastern Alberta Transmission Line, which was located nearby. Treatments were conducted in which the timing and duration of mat placement were varied from spring to fall, and from 6 to 24 weeks, on each of two ecosites (loam and loamy-sand), and monitored for up to 3 years of recovery. Main areas of focus were soil physical attributes, such as soil bulk density, penetration resistance, and water infiltration, along with nutrient supply rates, as well as vegetation responses such as biomass and nutrient components.

Results of the field trials indicated traffic without mats (TWOM) increased soil penetration resistance (PR), while traffic with mats (TWM) initially had lower PR when mats were removed and soil moisture contents (SMC) two to three times the Control; however, SMC and PR within the TWM returned to Control levels six weeks after mat removal. Grass biomass was reduced under mats in place for 12 weeks or more compared to Controls in the first and second year ($p = 0.0007$) of recovery after treatment application. Introduced and ruderal forb biomass increased during first year of recovery ($p < 0.0001$). Biomass responses were more apparent on loamy-sand soils than loam soils. Light levels of traffic in this study did not create impacts that differed from the Controls for either grasses or introduced forbs under TWOM. Soil nutrient availability increased under TWM the year of treatment application relative to Controls; more specifically, nitrogen was ten times higher, sulfur double, iron four times higher, and manganese five times higher than those measured in the Control. Available soil nutrients quickly dissipated and led to levels similar to those of the Control by the following spring. Soil available nutrients under TWOM saw slight or no increase compared to Controls.

Under the conditions of this study soil physical properties and vegetation were maintained close to those of the Controls under TWM when mats were in place for no longer than 6 weeks, while simultaneously mitigating the effects of wheeled industrial traffic. Results indicate that soil and vegetation recovery are influenced by the dominant soil texture as well as the season and duration of access mat use. Mats moderated soil compaction at the cost of vegetation biomass in placements longer than six weeks. Mats would be recommended to extend work time frame and possibly increase levels of traffic with consideration for the plant community underneath, and removal before plant death or with a revegetation strategy for recovery in place.

Dedication

To Arlene Klonteig:

My other mom, my friend, my mentor,

my constant support, and my gentle critic.

You taught me how to be strong

I owe you so much.

I miss you still.

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List of Abbreviations

6	6 weeks of treatment application
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ADF	Acid detergent fiber
AEP	Alberta Environment and Parks
Al	Aluminum
ANOVA	Analysis of variance
B	Boron
BD	Bulk density
BMP	Best management practices
C	Celsius
Ca	Calcium
cm	Centimeter
CP	Crude protein
CPC/CPY	Crude protein concentration, crude protein yield
CTAB	Cetyltrimethylammonium bromide
E	Early
Eco	Ecosite
EC	Electrical conductivity
EG&S	Ecological goods and services
DMGP	Dry Mixedgrass prairie
F	F statistic
Fe	Iron
g	Gram

List of abbreviations (Cont'd)

ha	Hectare
IR	Infiltration rate
K	Potassium
km	Kilometer
kPA	Kilopascal
kVA	Kilovolt ampere
L	Late
log	Logarithm
m	Meter
Mg	Magnesium
ml	Milliliter
mm	Millimeter
Mn	Manganese
N	Nitrogen
NH_4	Ammonium
NO_3	Nitrate
om	Organic matter
P	Phosphorus
P	Probability value
pH	Potential of hydrogen
PR	Penetration resistance
PRS®	Plant root simulator
RCBD	Randomized complete block design
RRI	Rangeland Research Institute

List of abbreviations (Cont'd)

S	Sulfur
SE	Standard error
SEM	Standard error of the mean
SL	Season-long
SMC	Soil moisture content
SOM	Soil organic matter
ST	Sampling time
Trt	Treatment
TWOM	Traffic without mat
TWM	Traffic with mat
µm	Micrometer
µS	Microsiemens
Yr	Year
Zn	Zinc

Chapter 1: Impact of Vehicle Traffic on Prairies and its Mitigation Using Mats

1.1 Introduction

Native temperate grasslands, including the Dry Mixedgrass prairie (DMGP) of Alberta, are among the least protected habitats globally (Samson and Knopf 1996). Anthropogenic changes have reduced the area of DMGP to 43% of their original 4.8 million hectares (Adams et al. 2013). Areas of grasslands still under native plant cover provide some of the highest levels of ecological goods and services (EG&S) when maintained at late seral or climax stages of the potential natural community (Adams et al. 2013). While early stage plant communities, comprised of annual and ruderal plants, are naturally present in the landscape, in general they should not predominate to optimize provisions of EG&S (Adams et al. 2013). Increased levels of anthropogenic edge decrease grassland intactness (AEP 2016a), and physical disturbance to vegetation and soil alter EG&Ss (Anderson et al. 2007).

Disturbances like modern infrastructure construction occur in many landscapes and often involve industrial vehicles traveling across ecosystems, including native grasslands. Construction methods that reduce impacts from vehicles include working on frozen ground, which is considered least damaging or working on dry ground (AEP 2016a). Both have fewer negative impacts compared to working on wet ground. Alternatively, mitigation methods can be used, such as wooden access mats, to create a temporary durable surface and buffer between industrial vehicles and the ground surface. This thesis studied industrial traffic imposed directly on grasslands compared to traffic occurring over wooden access mats, and quantifies the effects of these two activities on prairie soil and vegetation.

From 2013 to 2014 the Eastern Alberta Transmission Line, a 500 kVA direct current distribution line, was built from the *Heartland* NE of Edmonton to SE Alberta, which included crossing 9 km of native grassland on the University of Alberta's Mattheis Research Ranch. Transportation corridors between towers were established with wooden access mats to create a temporary access road. These mats were placed on grassland for as little as six weeks and up to 24 months, and were driven over by pick-up trucks, loaders, and heavy cranes. Ground after the temporary access roads were removed was often comprised of bare vegetation and exposed soils. Expecting mats to maintain soil structure and protect prairie vegetation, these observations raised questions about the optimal strategy to deploy mats, their impacts, and subsequent soil /vegetation recovery in order to properly mitigate traffic impacts within these valuable ecosystems.

Planning for large infrastructure projects, like this transmission line, involves much consideration including routes, equipment, man-hours, and ways to reduce impacts and minimize disturbances while operating safely and sustainably (ATCO 2014). Many factors impact construction timelines, such as work hours, equipment and labor costs, terrain, soil conditions, and work stoppages, such as those caused by nesting migratory birds and spring thaw (personal communications with ATCO staff). Temporary mat roads prolong the timeframe during which soft or wet soils can be traversed, but can increase dangers associated with operating large and heavy equipment over soft soils, such as equipment tipping. Howard et al. (2008) found that mobile cranes operated over wooden mats account for 84% of crane related construction fatalities. With these factors to consider, the Eastern Alberta Transmission Line route was designed with mat technology, to find a balance and minimize ecological impacts and maximize safety.

Effects of traffic, wheeled and tracked vehicles, on grasslands have been relatively well studied. Soil has been shown to be damaged by compaction and ruts, with larger effects on finer textured soils, in wetter soil conditions, and when vehicles turn (Althoff and Thien 2005, Raper and Kirby 2006, Retta et al. 2013). Traffic impairs soil hydrologic functions (Hakansson et al. 1987), leads to accelerated erosion and admixing of soil horizons (Althoff et al. 2007), and deeper subsoil compaction can occur with increased loads (Voorhees et al. 1986 and Wortmann and Jasa 2003). Traffic also causes plant communities to change in favor of annual and invasive species rather than perennial native species. Vegetation responses are likely to increase with traffic intensity (Althoff et al. 2009, Dickson et al. 2008, Liddle and Grieg-Smith 1975, Milchunas et al. 2000, Wilson 1988). The damage by traffic to soils and vegetation has been known to persist for two to four years (Althoff et al. 2010, Palazzo et al. 2005, Thurow et al. 1996).

Good planning and effective strategies are keys to the recovery of soil and vegetation from disturbance, with identified times and situations where increased efforts are needed to aid recovery. Natural recovery, leaving areas to recover through natural processes, may return a disturbed area to pre-disturbance conditions, but there is debate as to the extent to which traffic-induced compaction is alleviated in natural systems through freeze/thaw processes, wet/dry cycles, and soil microbiota (Wortmann and Jasa 2003). Wilson (1988) found that 400% more traffic could be applied on the same plant community if traffic application was delayed until times of low soil moisture content, typically after July 1, compared to traffic application in May through June. Voorhees (1978) reported that penetration resistance increased by as much as 400% due to traffic induced compaction, while bulk density only increased 20% or less. A follow up study (Voorhees 1983) found that 20-50% of penetration resistance was reduced by natural weathering but concluded that bulk density remained elevated, with no improvement to soil structure either.

Vehicles pivoting or turning can create as much damage as multiple passes of traffic traversing in a straight line (Anderson et al. 2007); however, traffic induced compaction on wet subsoil may be negated by two consecutive dry years, leaving vegetation biomass unaffected (Voorhees et al. 1989). Wortmann and Jasa (2003) suggest the following strategies to reduce compaction damage from traffic: avoid soil with water contents between saturation and field capacity, minimize load weight, increase surface area contact, reduce disturbance of soil, maintain or build soil organic matter, and control the number of traffic passes. In theory, using mats reduces the weight of vehicle traffic by spreading the load over an increased surface area, which reduces localized pressure and reduces soil disturbance by creating a physical barrier between soil and traffic (Gartrell et al. 2009, Howard and Stroble 2008, USDA 1996). Mats fit three of Wortmann and Jasa's (2003) six suggestions to reduce traffic-caused compaction, but caution that excessive traffic passes (500+) can break mats allowing ruts to form anyway (Rushing and Howard 2011). Mats are increasingly becoming a common strategy to limit rut damage and reduce surface soil disturbance from construction, allowing construction time to be extended beyond dry or frozen ground conditions. Mats are a recommended practice for temporary access to avoid surface soil disturbance (AEP 2016a) from industrial disturbance on public rangeland in Alberta within the broader strategies for grassland conservation which highlight avoidance, reduction of area and impact extent, and development of practical restoration methods (AEP 2016b). However, little research on the effectiveness of mats has been conducted in DMGP, or other ecosystems in western Canada for that matter, including the comparative impact of their placement solely in the growing season, or on sensitive soils such as stabilized sand dunes.

Studies of mat efficacy for soil and vegetation conservation are limited, with most studies on mats testing mat durability (Anderton and Gartrell 2005 and Rushing and Howard 2011) or ground pressure (Doyle et al. 2014) of mats installed over leveled subsoil (Howard and Stroble 2008) rather than on *in situ* applications of mats over actively growing late seral vegetation. Studies by Dollhopf et al. (2007), McWilliams (2008), McWilliams et al. (2007), and Mitchem et al. (2009) were done using field experiments in Wyoming, on sagebrush steppe and Mixedgrass Prairie within a semi-arid, cold desert climate. While Kestler et al. (1996) examined mat use in Alberta on a powerline constructed in similar climatic conditions to the current study, that investigation had added complications of steep terrain and chinooks events that rapidly thawed frozen soils. Findings of the latter were that mats allowed travel, including turns on thawing soil (Kestler et al. 1996), while maintaining the plant community (Kestler et al. 1996 and Mitchem et al. 2009) and preserving soil bulk density under mats (Mitchem et al. 2009). Studies by Kestler et al. (1996) and the project that Dollhopf et al. (2007), McWilliams (2008), McWilliams et al. (2007), and Mitchem et al. (2009) conducted all examined construction and traffic on frozen ground for all or part of the time that mats were in place. The resulting overlap of seasons with the dormant season may have reduced the significance of results by masking seasonal effects of mat placement.

While conducting research for my thesis, it became evident that there were no peer-reviewed and published studies reporting on the effects of mats put down exclusively on actively growing vegetation, including in the northern temperate grasslands of western Canada. Mats placed during the growing season essentially block solar radiation from reaching vegetation, forcing plant growth to occur using stored carbohydrates for energy instead of energy produced during photosynthesis. In the short term, this etiolated growth favors grazing tolerant species (Lardner et al. 2003), and in the long-term this blocked photosynthesis can lead to plant death. When recovering from defoliation, stored energy in the form of carbohydrates is used to regrow photosynthetic material, such as leaves and stems (Bokhari 1977). Boschma et al. (2013) found continued severe defoliation can result in plant death. Hence, mats placed on actively growing plants may crush plants in a manner similar to severe defoliation, and if mats are left in place long enough then impacts to severe defoliation such as those documented by Boschma et al. (2013) may occur, including plant death.

As there have been few peer reviewed studies on the effects of mats compared to traffic on soils and vegetation, there is a knowledge gap in this area of applied ecology. Study is needed on the effects of mats placed on different soil types and plant communities, including during various seasons of growth, with varying deployment durations and traffic levels, and to determine effective weight limits that still maintain soil characteristics and vegetation resilience. Mats are being increasingly used in the mitigation of industrial impacts on agro-ecosystems, on a variety of landscapes, and for longer time periods. Coordination of labor and equipment for large scale projects testing these technologies is a substantial task; with progress for proactive thought and implementation of conservation methods. Studies like this one are useful to learn, adapt and understand which ecosystems benefit most from mat application, and on how mats should be used to optimally mitigate impacts to grassland vegetation and soils.

My overall research goal was to assess the efficacy of wooden access mats for protecting DMGP soils and vegetation from industrial traffic and maintain soil properties, aboveground vegetative diversity, and biomass. Specific study objectives were to:

1) Quantify and compare the impacts of direct industrial traffic on DMGP soils and vegetation within loamy and loamy-sand ecosites, as well as the ability of access mats to mitigate these impacts;
2) Identify the relative impacts of contrasting seasons and duration of direct traffic activity and traffic imposed over matting during the growing season, for a recovery period of up to three growing seasons.

In order to address these objectives I ran a two year field study that placed access mats and industrial traffic on DMGP. In Chapter 2, I examine treatment effects on basic soil physical properties, including penetration resistance, soil moisture content, bulk density, water infiltration rate, and soil nutrient supply in the form of plant available macro and micronutrients. In Chapter 3, I examine effects of access mats and traffic on vegetation, specifically forage and root biomass, forage quality via acid detergent fiber and crude protein analysis. Chapter 4 synthesizes these results and recommends best management practices.

Results of this study are expected to enhance our understanding of how access mats impact grassland ecosystems, and frame when, where, and how mat use can best reduce industrial traffic impacts on native grassland, assist strategic development plans, and refine best management practices for industrial construction.

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Chapter 2: Access Mats Mitigate Impacts of Industrial Traffic on Soil Physical Properties

2.1 Introduction

Native grasslands are in need of conservation as they are one of the most altered and least protected habitats globally (Samson and Knopf 1996). Grassland soils provide a variety of ecological goods and services such as carbon storage, water purification, and support for plant growth (Sayre et al. 2012). During modern construction of industrial infrastructure on Western Canada's prairies, vehicles often travel directly on native grasslands, resulting in compacted and rutted soils (Althoff and Thien 2005, Anderson et al. 2007, Braunack 1986, Kestler et al. 1996, and Raper 2005), which become susceptible to wind and water erosion (Althoff and Thien 2005, Althoff et al. 2010, Desserud et al. 2010, and Raper 2005). Disturbances to grassland soil increase the release of soluble forms of nutrients (Whitehead 2000), and compact soils thereby decreasing the storage and supply of water and nutrients (USDA 2001). Nutrients are also released from roots and litter into the soil after plant death decomposition (Dickinson 1974). As plants variably benefit from nutrient flushes via decomposed plant material (Dickinson 1974 and Whitehead 2000), if perennial plant propagules are absent, early colonizing and invasive species can quickly germinate and deplete the flush of nutrients(Anderson et al. 2007). In some cases compaction can cause nutrient deficiencies in plants and negatively impact forage yield, and in select cases, lead to plant death (Unger and Kaspar 1994).Moreover, existing native vegetation is likely to be crushed or ripped up with repeated passes of industrial vehicles over short time periods, limiting opportunities for perennial vegetation regrowth and recovery, particularly on compacted soils (Althoff et al. 2009, Liddle 1974, Milchunas et al. 2000, and Thurow et al. 1996). Alternative management practices are needed for landowners, industry, and government to limit damage from industrial development activities to native grasslands during construction and ensure ecosystem conservation. Wooden access mats used as temporary construction platforms and roadways have been proposed as a strategy to mitigate changes in soil conditions related to heavy equipment traffic during construction (AEP 2016), but few studies have examined their efficacy (Dollhopf et al. 2007 and Mitchem et al. 2009).

Sandy or wet soils are especially sensitive to traffic and resulting compaction (Rushing and Tingle 2009) and the use of mats to mitigate soil compaction during industrial construction practices on native grassland is a relatively new and increasing trend. When vehicle travel on native grasslands cannot be avoided, mats are used to redistribute vehicle weight, provide a durable and safe work platform for large equipment, and reduce localized compaction on soil, thereby preventing alteration of important soil physical metrics and facilitate conservation of these areas. In order to enhance our understanding of mats ability to prevent soil compaction and maintain physical structure, we conducted a two-year study comparing the effects of industrial traffic with and without mats on Dry Mixedgrass Prairie (DMGP) soils. This study will further frame when, where, and how mats may be used to reduce industrial traffic impacts on native grassland, and thereby refine best management practices for industrial activity on grasslands.

Our overall goal was to assess mat efficacy to protect DMGP soils from industrial traffic and prevent the alteration of soil physical and chemical properties. Specific study objectives were to:

1) Compare effects of industrial traffic with and without mats on DMGP soil physical and chemical properties within loamy and loamy-sand ecosites,
2) Test whether varying season or duration of traffic and associated mat placement altered effects on DMGP soils.

2.2 Materials and Methods

2.2.1 Site Description

Four study sites were established in April of 2015 within the Brooks Plain of the Dry Mixedgrass Natural Subregion in SE Alberta. The area has a mean annual precipitation of 354 mm and average daily temperature of 4.2°C (Downing and Pettapiece 2006). From 2013 to 2014 a 500 kVA direct current power line, known as the Eastern Alberta Transmission Line, was constructed by ATCO (Alberta Transmission Company) to transfer power from the *Heartland* NE of Edmonton, Alberta to SE Alberta, Canada. Approximately 9 km of this line crossed the 5,000 ha University of Alberta Mattheis Research Ranch. The line runs parallel to Highway 36 that bisects the ranch, north to south. Surrounding landscapes immediately around this powerline were evaluated and provided an ideal location to represent soil conditions and soil disturbance occurring under powerline construction. Both loam and loamy-sand textured sites were chosen to evaluate how soils with different soil textures were impacted by mats during construction. Site locations were chosen based on internal uniformity in soil texture, topography, and plant community composition to facilitate direct comparison of treatments.

Site 1 (50°52'29.59"N; 111°55'40.14"W) and site 2 (50°52'19.21"N; 111°54'37.45"W) were located on well-drained loamy-sand textured soil (77% sand, 15% silt, and 8% clay for site 1, and 76% sand, 18% silt, and 6% clay for site 2; Brown Chernozems) on the central portion of the Mattheis Ranch within an area of stabilized sand dunes (Figure 2–1). These soils had pH = 5.75 (± 0.04), EC = 69.5 (± 3.9) µS/cm, and organic matter content = 2.6 (± 0.2 %). Plant communities at these sites were dominated by *Calamovilfa longifolia* (Hook.) Scribn., with *Hesperostipa comata* (Trin. and Rup.) and *Bouteloua gracilis* (Willd ex Kunth) Lag. Ex Griffiths as sub-dominants. Site 3 (50°54'30.98"N; 111°53'37.85"W) was located on a well-drained loamy textured soil (37 % sand, 49 % silt, and 14 % clay; Brown Chernozem) in the NE portion of the Mattheis ranch (Figure 2–1). The plant community was dominated by *Bouteloua gracilis* and *Koeleria macrantha* (Ledeb.) Schult. with *Hesperostipa comata* and *Pascopyrum smithii* (Rydb.) Á. Löve as sub-dominants. Site 4 (50°54'5.69"N; 111°52'58.55"W) was located on an imperfectly drained loamy textured soil (36 % sand, 50 % silt, and 14 % clay, Brown Chernozemic) also in the NE portion of the Mattheis ranch (Figure 2–1). The overlying plant community was dominated by *Koeleria macrantha* and *Bouteloua gracilis*, with *Hesperostipa comata* and *Pascopyrum smithii* as sub-dominants. Sites 3 and 4 had greater levels of organic matter relative to loamy-sand sites [pH = 5.91 (± 0.04), EC = 103.0 (± 3.9) µS/cm, organic matter content = 3.8 (± 0.4) %]. Soil texture is reported as a single value from sampled averaged within each site,

2.2.2 Experimental Design and Treatments

A randomized complete block design was implemented at each of the four sites, with four blocks at each site, each of which contained 11 different treatments (N = 44 plots per site). Treatments were established to evaluate the effects of subjecting grassland to industrial traffic without mats (TWOM) compared to industrial vehicle traffic with mats (TWM) at different times of year for varying durations of mat deployment. Each site was approximately 50 × 100 m in size, and within each site, blocks were set up as four rows, paired on either side of a central travel lane in a chevron pattern (Figure 2–2). Plots were 3 × 8 m in size, the approximate size of each mat and allowed for a loader to travel over and clear the mat, with a minimum of 2 m buffer between each plot. Within each block, in addition to a non-treated Control, 10 treatments were set up to compare seasonality [Early (E), Late (L), or Season Long (SL)] and deployment duration (6 and 12 weeks for E and L, and 24 weeks for SL), in combination with both TWOM and TWM. Early treatments started in 2015 on 30 April and ended either on 10 June (after 6 weeks) or on 22 July (after 12 weeks). Late treatments started in 2015 on 22 July and ended on 3 September (6 weeks) or 15 October (12 weeks). Season long treatments started in 2015 on 30 April and ended on 15 October (24 weeks); Table 2–1 summarized the treatments conducted during 2015.

Mats were 2.4 × 4.2 m in size, and were comprised of three layers of interlocking wooden boards, usually spruce. Mats were selected for their uniformity at the start of the study (i.e. to ensure no boards were missing or damaged), and each weighed approximately 700 kg. Treatments with matting had mats installed and removed by a loader on the appropriate dates. Mat plots were driven over by a loader (either Komatsu Wheel Loader WA200-5 or Caterpillar Wheel Loader 930K) eight times on both the first and last day of the specified treatment period to provide for work conditions comparable to industry practices. Both loaders have similar weights (approximately 10 – 13 tonne), and had wheel widths of 50 cm. Loaders were not carrying any additional mats when applying traffic treatments, and traveled with one set of wheels centered over the plot middle (either with or without a mat). Thus, approximately half the loader weight was placed on the plot, which simulated traffic under actual field conditions, as mat roads are typically at least two mats wide (i.e. 4.8 m wide) to ensure a wide enough work area to allow heavy equipment traffic to pass. In summary, treatments consisted of 176 plots total, with comparison of non-treated Control plots to plots exposed to wheeled traffic, both with and without underlying mats, which occurred across five different combinations of time and duration.

2.2.3 Soil Sampling and Measurement

The main rooting zone in grasslands is the upper 15 cm of the soil profile (Cahill 2003, Chang et al. 2016, Coupland and Johnson 1965, Dormaar and Willms 1993, and Dormaar et al.

1994), and is more likely than deeper depths to show effects of surface disturbance, such as compaction (Liddle and Moore 1973). As a result, the majority of soil sampling was concentrated in this upper 15 cm soil zone to evaluate the response of grasslands to direct traffic compared to the traffic mitigation ability of mats.

2.2.3.1. Soil Physical Characterization

Penetration resistance (PR), measured in 2015, began for all 176 plots on April 30 prior to treatment application, and was then measured at six-week intervals, from June 11 until October 15, as treatments were completed. In 2016, all 176 plots were measured five times on April 26, June 06, June 18, July 05, and July 27. For both years PR was taken as the maximum resistance achieved to reach a depth of 15 cm. To overcome any variability of readings within each plot, 10 PR measurements were taken at random locations within a plot. Measurements of PR in 2015 were taken with a soil compaction tester (Dickey John, IL,USA) with a 1.27 cm^2 tip, and in 2016 with an HS-4210 digital static cone penetrometer (DSCP) (Humboldt Mfg. Co., IL, USA) with a 1.5 cm^2 tip. Readings of PR during 2015 could only be taken to a maximum of 4136.85 kPa (600 PSI) using the Dicky John instrument. The DSCP was used in 2016 to increase the accuracy of readings. Readings from the DSCP were converted to reflect the soil compaction tester by a linear regression created from readings taken by both probes measuring soil with the same moisture content on the same soil on the same day (Appendices 5 through 8). Justification for combining penetrometer data is based on results from Gao et al. (2012) who found that PR was not particularly sensitive to cone diameter.

Soil moisture content (SMC) was measured only within the Control and TWM plots at six week intervals from June 11 until October 15, 2015, and at four times in 2016: on May 4, June 6, July 5 and July 27. TWOM plots were not sampled due to a high level of soil compaction from wheeled traffic, which consistently bent and damaged the soil moisture meter metal prongs, resulting in inaccurate readings. Across each sampled plot, a total of six moisture measurements were taken from random locations with a ML3 ThetaProbe soil moisture sensor (Delta-T Devices, Burwell, UK) with a sample volume of ca. 42.4 cm^3 (3 cm diameter × 6 cm deep cylinder), or a Field Scout Digital Moisture Sensor TDR 300 (Turf-Tec International, FL, USA), with a sample volume ca. 53.0 cm^3 (3 cm diameter × 7.5 cm deep cylinder). The Field Scout was used after the ThetaProbe broke. As the ThetaProbe had fewer measurements they were corrected, using slope calculations from a linear regression from both probes sampled within the same soil at the same time, to convert the ThetaProbe readings to those of the Field Scout soil moisture levels (Appendices 1 through 4).

Soil bulk density (BD) was measured in the Control, E12 TWM, and E12 TWOM plots on July 29, 2015. Bulk density was measured within all plots on July 14, 2016 following the removal of all mats the previous fall. For 2015 BD measurements, two soil cores (3.175 cm wide × 7.5 cm deep) were collected from a localized area (30 cm diameter) free of previous sampling damage from each plot and combined, with a total volume of 118.76 cm^3. In 2016 two soil cores (4.7 cm wide × 7 cm deep) were collected from a localized area (30 cm diameter) free of previous sampling damage from each plot and kept separate, each core with a volume of 121.45 cm^3. Soils were crumbled apart, roots and rocks larger than 2 mm were removed with a sieve, and soil was dried in a 105°C oven until it reached a stable mass. Bulk density was calculated as the mass of oven-dried soil divided by the known core volume, minus the volume of rocks and roots (Blake and Hartge 1986). Duplicate readings from 2016 within a plot were averaged prior to analysis.

Water infiltration rate (IR) was measured on the Control, E12 TWM, and E12 TWOM plots on August 4, 2015, and again within all plots on July 29, 2016. An infiltration ring (203.2 mm diameter) was inserted into the lower right corner of each plot in 2015, and in the upper left corner in 2016; rings were at least 15 cm from edges, and inserted at least 127 mm deep into the soil with as little soil disturbance as possible. Based on the USDA (2001) standardized method, 824 ml of water was poured into the ring (representing 1 inch of rainfall) and the time to achieve infiltration, defined as the total absence of ponded water on the soil surface, was recorded in minutes and seconds. Vegetation and litter were left in place during testing to assess *in-situ* water IR.

2.2.3.2. Soil Chemical Characterization

In 2015 measures of pH and electrical conductivity (EC) were taken from the Control, E12 TWM, and E12 TWOM plots. From each plot four soil cores (3.175 cm diameter × 15 cm deep) were collected from a localized area (30 cm diameter) free of previous sampling damage. These cores were combined, air dried to stable mass, roots removed and then passed through a 2 mm sieve. A 2:1 mixture of 80 g distilled water and 40 g dry soil was then created and shaken for 30 minutes, after which soil pH were assessed using an Accumet® Basic AB150 Benchtop pH/mv meter (Hach, Loveland, CO, USA. Fisher Scientific). After settling, the soil solution was filtered through filter paper (Fisherbrand™, grade Q8, particle retention 20 to 25µmm), and resulting filtrate assessed for soil EC using an Milwaukee Mw80 Smart pH EC meter (Hach, Loveland, CO, USA. Fisher Scientific). The probe was calibrated with known EC standards.

Soil organic matter (SOM) was measured in 2015 for the Control, E12 TWM, and E12 TWOM plots. The same soil cores described above were used to measure SOM using loss on ignition in a muffle furnace method. A subsample of 10 g of soil was added to an oven-proof crucible and dried at 110°C for over eight hours, then ashed at 550°C in a muffle furnace for 4 hours, and reweighed when temperature returned to 110°C. Soil organic matter was determined as the percent mass loss relative to the initial sample (Storer 1984). Soil pH, EC, and SOM showed no effect of treatment in 2015 and were not expected to change over the course of the monitoring period. As such, these metrics were not reassessed in 2016.

2.2.3.3. Soil Nutrient Characterization

Soil nutrient supply rates were assessed with Plant Root Simulator (PRS®) probes (Western Ag Innovations Inc., Saskatoon, SK, Canada) installed 10 cm into the mineral topsoil, where most soil nutrients are released, and microbes and roots are most active (Chang et al. 2016). Probes were installed into corner locations, at least 15 cm from the edges of Control, E12 TWM, and E12 TWOM plots on 24 and 25 July, 2015, and removed on 17 October, 2015.

Due to naturally low soil nutrient levels in DMGP soils, probes were installed for longer (3–4 months) than typically recommended (2–4 weeks) by Western Ag Innovations Inc. to ensure sufficient precipitation events for nutrient mineralization and accumulation; no nutrient levels exceeded probe saturation levels. One year later in 2016, probes were installed into the Control, E12 TWM, and E12 TWOM plots, as well as the L12 TWM, and SL24 TWM plots on 24 April, and removed on 29 August. All probes, after removal and thorough cleaning with deionized water, were sent to Western Ag Innovations Inc. (Saskatoon, SK, Canada) for analysis. Nutrient supply results are expressed in kg per ha for the length of study period installation, with probes installed for 12 weeks in 2015 and 18 weeks in 2016.

2.2.4 Data Analysis

Soil physical and chemical data were assessed with an analysis of variance (ANOVA) in SAS 9.4 (Carlsbad, NC, USA) using a generalized linear mixed model (PROC GLIMMIX) and soil nutrient supply data were assessed with analysis of variance (ANOVA) in SAS 9.4 (Carlsbad, NC, USA) with mixed models (PROC MIXED). Normality was tested with a Shapiro-Wilks test, and a studentized test of residuals was used to confirm the absence of outliers. If not normally distributed, data were log10 or square root transformed to achieve normality. Log transforms were applied to the PR data from September 2 and October 16 of 2015, and all of 2016, as well as the IR data from 2016, all SMC, and on the following soil nutrients: total nitrogen (N: NO_3 + NH_4), nitrate (NO_3), ammonium (NH_4), iron (Fe), manganese (Mn), and sulfur (S) for 2015 and 2016. A square root transform was applied to the soil nutrient supply of phosphorus (P) for 2015 and 2016. While the soil nutrients ammonium and boron (B) were initially evaluated, they were often below detectable limits, with the majority of nitrogen comprised of nitrate (~93%), and as such will not be reported further. All other soil nutrients met assumptions for parametric analysis and did not require transformation.

For the analysis of all variables treatments were treated as fixed effects, comprised of unique combinations of traffic treatment (TWM or TWOM), season of application (E, L or SL) and the duration (weeks: 6, 12, 24) of disturbance. Additionally, sampling time was treated as a repeated measure (either within a year, or between years). Sites 1 and 2 were analyzed as two replicates within the same ecosite, as both were located on loamy-sand soil and had similar vegetation. Sites 3 and 4 were analyzed as two replicates within the same ecosite as both were on loamy soils, again with similar vegetation. Duplicate sites within ecosite type were random effects, as were the four replicate blocks within each site. Significance of all main effects and their interactions was set at $p < 0.05$, unless otherwise stated. Individual treatment least-square means within significant data sets were subsequently compared using a post-hoc Tukey's test. All treatments were compared against the Control in order to parse out whether and how the disturbance treatments altered soil properties. Interactive effects of ecosites by treatment were considered. Additionally, pairwise comparisons were made of the TWOM and TWM treatments within each season by duration regime to assess the mitigative effect of matting on direct wheeled traffic. All comparisons were assessed with significance at $p < 0.05$.

Penetration resistance was analyzed in three ways and soil moisture content two ways, because differences in the time and duration of mat placement resulted in some treatment plots (e.g., SL treatments) being covered with mats at the beginning, and throughout part or most of the first year of the trial. Field plots were sampled after mat removal (as that occurred), resulting in an unbalanced design over the sampling periods. To account for the unbalanced design, PR results are presented in three ways: 1) in Table 2–2(a) only those sample dates for 2015 and 2016 where all 176 treatment plots were sampled was analyzed, 2) in Table 2–2(b) all sample periods for 2015 and 2016 were analyzed regardless of the number of treatment plots, and 3) in Table 2–2(c) sample dates from 2015 that were excluded from Table 2–2(a) were analyzed separately due to the different number of accessible treatment plots for each sample date. Analysis from Table 2–2(b) was used to create Figures 2–3 to 2–6, which for ease of reading, are presented separately, grouped by treatment type and soil texture. To account for the unbalanced design, SMC results are presented in two ways: 1) in Table 2–3(a) only those sample dates for 2015 and 2016 where all 176 treatment plots were sampled was analyzed, 2) in Table 2–3(b) all sample periods for 2015 and 2016 were analyzed regardless of the number of treatment plots. Analysis from Table 2–3(b) was used to create Figures 2–8 to 2–10, which for ease of reading, are presented separately by soil texture.

2.3 Results

2.3.2 Soil Physical and Chemical Responses

Soil penetration resistance consistently varied in response to the interaction of ecosite, traffic treatment and sampling date (Table 2–2). Within loamy soils, TWOM treatments (i.e., direct wheeled traffic) generally had greater PR than the Controls from July to October of the initial year of treatment application, treatments started early (E6, E12, and SL2) had longer lasting effects that were still apparent in the spring and late summer of the following year (Figure 2–3). Late treatments (L6 and L12) displaying this same greater PR only in the second spring sampling in 2016, all treatments tended to return to Control levels in mid-summer (Figure 2–3). Penetration resistance on loamy-sand soils demonstrated several key responses. First, the TWOM treatments once again led to greater PR than the Control throughout the first treatment year, and while this response appeared to dissipate by mid-June of 2016, it subsequently reappeared throughout July of that year (Figure 2–4). Second, early wheeled traffic led to much greater PR than the late treatments, and this response persisted until at least early June of 2016 (Figure 2–4). Third, while PR did not differ in response to the duration of wheeled traffic treatment in the late season, between the early treatments, wheeled traffic led to greater PR (despite being the same number of passes) when performed over a longer period of time (12 weeks) as compared to being limited to a short window.

In contrast to the pattern for the TWOM treatments, soil PR on loam soils was consistently lower relative to the Controls within the TWM plots, as measured immediately after mats were removed (Figure 2–5). However, within each of these same TWM treatments, PR then increased after mat removal such that PR values were similar to those found in the Controls by the next sampling period (Figure 2–5); the exception to this trend was in the L12TWM and SL24TWM treatments, which had low PR values into the following spring, only to subsequently rise to levels similar of the Control (Figure 2–5). Reductions in soil PR also occurred within loamy-sand soils due to the TWM treatments relative to the Controls, but were generally smaller than those in loamy soils (Figure 2–6). Soil PR values once again increased in loamy-sand soils following mat removal (Figure 2–6). At no time did PR values in the TWM plots increase to levels above that of the Controls, regardless of soil type (Figures 2–5, 2–6).

Final comparison of soil PR one year after treatment application on loam soils indicated that all treatments, with the exception of the E12 TWOM treatment, had returned to levels similar to the Controls and their matted counterparts (Figure 2–7). In contrast, on loamy-sand soils all TWOM treatments remained greater than both the Controls and the paired TWM treatments, with no differences among the TWM treatments and the Controls (Figure 2–7).

Soil moisture contents were not available for the direct traffic treatments due to the impracticality of sampling these compact soils. On TWM plots, both in loamy (Figure 2–8) and loamy-sand soils (Figure 2–9), observed SMC values were elevated due to the placement of mats, as measured immediately after the removal of mats. However, in all cases, SMC returned to levels comparable to that of the Controls within one or two sampling periods (Table 2–3 and Figure 2–8). Of note is that on both soil types, the L12 TWM and SL24TWM treatments led to modestly elevated soil moisture readings in May of 2016, only to disappear thereafter. Comparison of SMC within the Control plots to the TWM plots one full year after treatment application for both the loam and loamy-sand soils indicated that all treatments had returned to levels similar to that of the Controls (Figure 2–10). Sampling periods with high PR generally coincided with low SMC, while those with low PR coincided with high SMC across all treatments for both soil types (Figure 2–3 through 2–6 for PR; and 2–8 and 2–9 for SMC).

Bulk density measures on loamy-sand soils were greater than those from loamy soils, but treatments generally had no effect on soil bulk density, with no changes evident between years (Table 2–4).

Water infiltration rate was impacted by the ecosite and also by disturbance treatments, both in 2015 and 2016 (Table 2–5). In 2015 loamy ecosites had IR of 136.4 mm hr^{-1} while loamy-sand ecosites were 180.2 mm hr^{-1} with a standard error of 8.6 mm hr^{-1} ($p = 0.0694$, Table 2–5). In 2016 loamy ecosites had IR of 102.1 mm hr^{-1}, while loamy-sand ecosites were 222.3 mm hr^{-1} with a standard error of 34.4 mm hr^{-1} ($p = 0.0656$, Table 2–5). In 2015, the E12 TWOM had a reduced IR compared to the Control and paired E12 TWM, the latter of which were similar in IR. In 2016 all TWOM treatments tested for IR were lower compared to the Control, with the SL24 and E6 treatments having the lowest IRs among TWOM treatments. In contrast, the E6, L6 and L12 treatments from the TWM had similar water IRs to the Controls, while those of the SL24 and E12 were intermediate in IR (Table 2–5). Notably, pairwise comparisons indicated that all TWOM treatments had reduced IRs compared to the TWM treatments (Table 2–5).

Soil pH and OM did not respond to the disturbance treatments, nor did they differ between the ecosites examined (Table 2–6). Soil EC was greater within loamy soils than the loamy-sand soils (Table 2–6).

2.3.2 Soil Nutrient Responses

Total nitrogen (N) is comprised of nitrate (NO_3^-) and ammonium (NH_4^+), with NO_3^- making up approximately 95% of total available soil N. Other macronutrients assessed using PRS® probes were phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg), while micronutrients included iron (Fe), manganese (Mn), zinc (Zn), boron (B), and aluminum (Al). Estimates of available NH_4, K, Ca, Mg, B, and Al in 2015, and NH_4, P, Mg, ZN and B in 2016, were non-significant in relation to the various treatments (Tables 3–12, 3–13).

Total N supply, largely of NO_3^-, was impacted by disturbance treatment ($p < 0.0001$) in both sampling years (Table 3–12). Supply of N in soils associated with the E12 TWM treatment in 2015 was by far the greatest, with the E12 TWOM at intermediate levels, and the Control supplying the least N (Figures 3–3 and 3–4). One year later, the SL24 TWM treatment had the greatest N supply, followed by the L12 TWM treatment. Minor differences were apparent between the E12 TWM and each of the E12 TWOM and Control (Figures 3–3 and 3–4).

Soil available phosphorous (P) responded to the treatments in 2015, but not 2016 (Table 3–12). During the first year of assessment, levels of P in the E12 TWM treatment were greater ($p < 0.0001$) than in the E12 TWOM and Control, which in turn, were equal (mean P supply = 23.9, 11.2, and 7.1 µg 10 cm $^{-2}$ 12 weeks^{-1} for the 12 week installation period, respectively, SE = ±3.5). Potassium supply rates also differed in relation to treatments, but only in 2016 ($p = 0.04$; Table 3–12) and not the year prior. Closer examination of the treatments during 2016 suggested no differences were evident ($p > 0.05$; mean K supply: Control = 155.5, E12 TWOM = 117.0, E12 TWM = 157.4, L12 TWM = 159.9, and SL24 TWM = 118.3 µg 10 cm $^{-2}$ 18 weeks^{-1} for the18 week installation period, with SEM = ±22.2). Sulfur supply was influenced by the interaction of ecosite × treatment in 2015, and directly by treatment in 2016 (Table 3–12). In 2015, the E12 TWM treatment had a greater S supply ($p < 0.0001$) compared to the E12 TWOM and Control, while no differences in S supply were apparent on loamy-sand soils (Figure 3–5). In 2016, the SL24 TWM treatment had a greater S supply than all other treatments ($p < 0.01$), while the L12 TWM, E12 TWM, and E12 TWOM treatments were at mid-levels, and the Control had the lowest S supply (Figure 3–6). Calcium supply was significantly affected by treatment, but only in 2016 ($F_{4, 68}$ = 2.58, p = 0.04), at which time it was greater (p < 0.05) in the E12 TWOM treatment than the SL24 TWM, L12 TWM, E12 TWM and Control treatments (mean Ca supply = 2108.3, 1976.6, 1972.7, 1859.4, and 1888.0 µg 10 cm $^{-2}$ 18 weeks^{-1}for the 18 week installation period, respectively, SE = ±60.4). Supply rates of magnesium did not differ among the disturbance treatments (Table 3–12).

Iron supply was significantly different among the main treatment levels in 2015, and varied with the treatment × ecosite interaction in 2016 (Table 3–13). Iron supply was greater (p = 0.0001) in the E12 TWM treatment than the E12 TWOM and Controls during the first year (mean Fe supply = 8.2, 2.4, and 1.6 µg 10 cm $^{-2}$ 12 weeks^{-1}for the installation period, respectively, with SE = ±1.5). In 2016 on loam soils, the SL24 TWM treatment had a greater Fe supply (p < 0.0001) than all other treatments, which in turn, consistently remained low (Figure 3–7). No differences in Fe supply were evident in loamy-sand soils during 2016. Manganese supply varied with treatments in both sampling years (Table 3–13). Manganese supply rates in 2015 were greater within the E12 TWM treatment (p < 0.0001) compared to the E12 TWOM and Controls, with the latter having the lowest Mn supply. During 2016, the SL24 TWM was greater (p < 0.0001) in Mn supply than all other treatments, with smaller differences among the remaining treatments (Figure 3–8). Zinc supply responded to treatment in 2015 (p = 0.04; Table 3–13) but not the following year. During 2015, Zn supply was greater for the E12 TWM treatment (p < 0.05) than both the E12 TWOM and Control (mean Zn supply = 1.4, 0.9, and 0.9 µg 10 cm $^{-2}$ 12 weeks^{-1}for the installation period, respectively, SE = ±0.2). Finally, Aluminum supply rate was altered by the main disturbance treatments in 2016 (p < 0.001; Table 3–13), during which Al supply was greater (p < 0.001) under the E12 TWOM than the SL24 TWM, L12 TWM, E12 TWM, and Control treatments, all of which were in turn, similar (mean Al supply =

13.6, 10.0, 9.5, 9.5, and 9.1 µg 10 cm $^{-2}$ 18 weeks^{-1} for the 18 week installation period, respectively, SE = ±0.7).

On loam soils, variation in aboveground biomass was not associated ($F_{1, 22} = 0.58$, $p = 0.456$) with total N supply for the Control, E12 TWOM or E12 TWM treatments (Figure 3–9). In contrast, on loamy-sand soils, above-ground biomass was positively associated ($F_{1,22} = 13.73$, $p = 0.0012$) with total N supply, with the greatest biomass response to added N evident within the E12 TWM treatments as compared to the Control and E12 TWOM (Figure 3–10). Similarly, total crude protein yield was not associated ($F_{1, 22} = 1.86$, $p = 0.1866$) with total N supply on loam soils (Figure 3–11). On loamy-sand soils however, total crude protein yield was positively related to total N supply ($F_{1, 22} = 15.79$, $p = 0.0006$), particularly the E12 TWM treatments (Figure 3–12). On both loam and loamy-sand soils, the proportion of live biomass made of introduced forbs was positively related to N supply rates ($F_{1,22} = 9.40$, $p = 0.0057$; $F_{1,22} = 55.05$, $p < 0.0001$, respectively), with this pattern again more evident in the E12 TWM treatment than the Control and E12 TWOM (Figures 3–13, 3–14).

2.4 Discussion

Bulk density was not affected by either the traffic treatments, with and without matting, while PR was maintained under TWM but increased markedly under the TWOM treatments. These increases persisted into the second growing season, and were more apparent in loamy-sand soils compared to those with more balanced loamy soil textures. On one hand, these results are encouraging in that the bulk densities observed were not exceeded by any treatments in this study; namely 1.70 g cm^{-1} in loam soils and 1.75 g cm^{-1} in loamy-sand soils (McWilliams et al. 2007). Grantham et al. (2001) found that physical changes such as soil compaction and exposure of bare soil are quick to occur during construction with vehicles travelling directly on grasslands, with damage often occurring within the first pass of a vehicle and critical thresholds often exceeded by as little as four passes of equipment. It should be noted that our levels of traffic were relatively light (i.e., 8 passes over 6 to 24 weeks) compared to what would likely occur under normal construction activities of high voltage powerlines, and thus we are unable to rule out the possibility that compaction may occur with further increases in the frequency of traffic or increases in the size of equipment.

Despite the lack of changes in soil BD, soil PR was increased by traffic occurring directly on the prairie compared to the TWOM treatments, suggesting at least some benefit to maintaining surface soil physical properties by matting when exposed to heavy equipment. This finding is also consistent with the observation for grassland areas exposed to wheeled traffic to exhibit marked depressions on ground surface (by about 3 cm). Given this, clarification is necessary to reconcile the lack of differences in BD despite the observed changes in PR. While PR measures represent the maximum physical resistance of the soil to mechanical probing to a depth of 15 cm, bulk density measures were taken to 7.5 cm depth. Thus, it is possible that soil compaction in wheeled ruts following traffic occurred only at the very top of the mineral soil (e.g., top 2 cm), but not below this depth, which would lead to high PR readings, but limit any changes in overall BD to a depth of 7.5 cm. This result would also explain why it was very difficult to assess SMC within the direct traffic plots, as the insertion of probes on the TDR unit was nearly impossible at the soil surface, even to the point of precluding sampling of those treatments.

Results of the PR readings suggest that access mats likely remained effective as a compaction mitigation strategy during construction, presumably by redistributing the weight of heavy equipment across a larger surface area and thereby providing superior protection of the surface of mineral soils (Gartrell et al. 2009 and Mitchem et al. 2009). The use of mats in this study appeared to allow vehicle travel to occur while preventing compression of the very top layer of soil. It remains unknown how a compacted surface layer on the soil may alter other aspects of grassland function, such as the presence of microphytic crusts, the entry of seeds from desirable grassland species, or the emergence of these same plants from the soil seed bank.

While there was clear evidence of recovery in PR values by the end of 2016 in relation to the matted traffic treatments, persistent negative effects of direct traffic remained evident into the second year, especially on loamy-sand soils (e.g., soils with greater sand content). Hakansson et al. (1987) found that clay increases soils' ability to compact while Jabro et al. (2014) suggested the expansion of clay in wet/dry and freeze/thaw cycles may reduce compaction. This expansion would account for why loam soils, with greater amounts of OM and clay, may have exhibited more rapid recovery of PR values. In contrast, the abundance of sand grains in loamy-sand soils inherently decreases PR (Braunack 1986) while compaction causes new alignment of sand grains (Balachowski and Kurek 2014) following exposure to direct wheeled traffic, would thereby extend the period of time over which the increase in PR persisted. Several studies (Jabro et al. 2014, Raper 2005, Raper and Kirby 2006, Voorhees 1983, and Voorhees et al. 1986) have found that increased PR and BD after traffic application was maintained for several years, but lessened to varying degrees by natural forces (physical freeze/thaw and wet/dry cycles, as well as biological activity) within the first few years, similar to results seen in the loam soils of this study.

Water infiltration rates were affected by the TWOM treatments during the first year and in both TWOM as well as select TWM treatments of the second year of recovery. Localized compaction of TWOM treatments likely altered soil particle spatial arrangement, decreased pore space and their connectivity (Defossez and Richard 2002), increased PR, and ultimately led to the reduced IRs, an effect that persisted into the second year of monitoring. Moreover, IRs remained at less than 50% of the Control during the second year. This effect closely align with observed increase in PR, and suggests that direct wheeled traffic markedly impeded hydrologic function, which is an important impact considering the inherently water limited nature of the Mixedgrass Prairie and the need to optimize water uptake and conservation for plant growth (Willms and Jefferson 1993).

In contrast, the presence of access mats did not alter IR despite the occurrence of traffic the first year. However, one year later IRs declined in select treatments of the TWM (SL24 and E12), within which large macro pores may have been disrupted or lost in the topsoil (Braunack 1986 and Liddle 1974), even despite the absence of an increase in PR and BD (Raper 2005). Any loss of macro pores may explain the reduced IR of select TWM treatments seen in the second year, as permeability is most strongly affected by large pores (Mahmoodlu et al. 2015) and IR is most affected by near soil surface conditions and reductions in continuous large pores (USDA 2001). Matting may also have altered the presence of litter, initially increased the year after treatment application under early 12 week mat placements and then decreased the subsequent year for both early 6 and 12 week placement (chapter 3), and surface microphytic crusts, both of which are important in helping maintain soil aggregation and soil hydrologic function, including water infiltration. It remains unclear as to why only 2 of the 5 matting treatments declined in IR during the second year, although the negative impact of the SL24 may be expected given it would have the greatest likelihood of negatively impacting hydrologic characteristics such as crusts and litter.

In this study, observed IR responses were not dependent on ecosite/soil conditions, even though sandier soils were found to have increased PR. In general, larger grains of sand are more likely to shift and realign, thereby impeding water movement through the rooting zone (Unger and Kaspar 1994). Soil texture is an important factor regulating infiltration (USDA 2001), and areas with greater soil clay content, similar to the loamy study sites tested here, may have been expected to have lower intrinsic IRs due to their reduced pore size. In any case, soil texture is an important determinant of IR, subsequent water availability, and associated grassland productivity and composition (Epstein et al. 1997 and Bork and Irving 2015).

Measurements of SMC were ultimately greater within the TWM treatments immediately after mat removal, but returned quickly to levels similar to the Controls. Mats likely created a physical impediment to solar radiation and winds, thereby reducing evaporation of water, which would help conserve water within the soil below. Similarly, in the absence of actively growing vegetation, water depletion via transpiration would have been at very low levels (or absent), further conserving water. Given the increase in SMC within several matting treatments relative to the Controls (e.g., see Figures 2–8, 2–9), it also appears that precipitation was able to contribute to ongoing soil moisture recharge even while mats were in place. Relatively prompt depletion of this increased SM within 1-1.5 months after mats were removed would represent the combined effects of evaporation; particularly with a reduced soil crust and litter cover (see Chapter 3), as well as the re-establishment of transpiration due to vegetation regrowth initiated from either the bud bank and/or soil seed bank. It remains unclear how SMC was affected by the traffic only treatments, as the presence of a compacted layer at the soil surface (and responsible for the increase in PR) prevented the sampling of SMC using TDR probes. Soil moisture may decrease as soil water holding capacity is affected by decreased pore volume in compacted soils, even in the absence of changes in measured BD. In general, decreases in PR are known to coincide with reductions in SMC (Hamza and Anderson 2005), and appears to be consistent with the pattern detected in this study, although SMC was not correlated with PR.

Both of the traffic treatments evaluated (TWOM and TWM) failed to alter soil pH, EC or soil OM. This is perhaps not surprising given that these aspects of the mineral soil are more likely to respond to the alteration of inputs or removal of soil, which did not occur in this investigation. Instead, changes to the soils associated with these treatments were limited to soil physical properties, and associated changes in hydrologic function (i.e. IR).

An initial release of soil nutrients was evident in 2015 immediately after the spring treatment application, with the early 12 week mat placement exhibiting significantly more available nutrients than paired direct traffic application. The pattern of high nutrient release under mats is supported by Whitehead (2000), who found grassland soil disturbance from grazing increased the release of soluble forms of nutrients and that grassland nutrients are almost entirely derived from nutrients recycled from the death and decomposition of plant material. Taking into account that mats maintained soil moisture levels, the moist environment under the mats would accelerate decomposition of surface litter, producing the elevated nutrient levels seen. Intermediate amounts of available nutrients in TWOM soils may have been due to the direct traffic which compressed the above ground plant material and litter to the soil surface as traffic was applied, creating a litter layer in contact with the soil surface. This litter layer would add nutrients, but without the moist environment under the mat decomposition would be less extreme, and this would account for the intermediate increase in nutrients without a subsequent loss of root biomass. Interestingly, the Control plots consistently had the lowest levels of soil nutrient supply rates as plants were not impacted by any treatment therein, and the community and associated soil were likely at a state of equilibrium that maximized nutrient use, with the arid environment limiting decomposition (Dormaar and Willms 1993).

In 2016, along with the three treatments analyzed in 2015, (Control, E12 TWOM and E12 TWM) two more treatments (L12 TWM and SL24 TWM) were included for analysis. These additions, which included a later season of placement and the season-long treatment, helped to identify further changes in nutrient supply due to variation in the length and season of placement. Mat treatments in place for the full growing season clearly had elevated nutrient levels into 2016, while mat treatments from the late season application were slightly elevated. In contrast, mat treatments from the initial spring treatment were now similar to those from the Control. This occurred as available nutrients were quickly consumed or leached while nutrients released later in the year were maintained overwinter and as longer duration mat treatments increased the time of decomposition. Nutrients are limited in the DMGP, second only to water; plants able to quickly use nutrients have the advantage to compete for resources and reproduce.

Nutrient cycling from plant death and decay (Moise and Henry 2014 and Whitehead 2000) are the main supply of nutrients in these ecosites. Although both ecosites experienced loss of litter and grass biomass, loamy-sand ecosites had greater change in the plant community (see Chapter 3) in the form of loss of grass and litter biomass with increased introduced forb biomass on mat treatments. While nutrient releases were generally larger on loam soil compared to loamy-sand soils, this may be due to the nutrient holding capacity of the high clay-loam soil compared to the sandier soil (Whitehead 2000). Slightly more acidic loamy-sand soils are likely the reason for more available zinc (Froehlich 2011) therein compared to the loam soils. Higher levels of Mn, total N, NO_3^-, and Mg on loam soils compared to loamy-sand soils is likely due to higher clay and SOM content of loam soils, which holds more nutrients (Bork and Irving 2015).

2.5 Conclusion

Direct traffic from heavy equipment resulted in high levels of soil compaction, as demonstrated by elevated penetration resistance, and reduced hydrological function, as evidenced by lower water infiltration. Moreover, these impacts were more evident and lasted longer on loamy-sand soils than loamy soils in this Mixedgrass Prairie environment. It remains unclear as to how long the negative impacts of direct traffic may last, and long-term studies to assess soil properties following industrial traffic are required, including the role of freeze/thaw cycles in restoring soil properties.

In contrast, grassland soils exposed to heavy traffic overtop of access mats, regardless of season or duration, did not experience negative effects on soil physical properties, demonstrated by maintained penetration resistance, indicating mat use is an important strategy to help conserve prairie soils. Hydrologic properties were impaired on select matted area, indicating some loss of hydrologic function under mats place on spring soils for long durations, 12 weeks or more. Matted areas did exhibit short-term increases in soil moisture as well as increases in nutrient availability. Increased moisture could make these areas more susceptible to compaction should traffic drive on them while un-protected, and industry should therefore try to minimize traffic after mat removal. Further studies are required to determine if a threshold exists where access mats are unable to mitigated increased vehicle weight. Increased traffic frequency over access mats also requires further study to determine if number of passes impairs soil physical and hydrological properties.

Nutrient increases after matting, particularly from longer periods of time, and may affect vegetation recovery, including favoring the establishment of weedy species (Chapter 3). It also is unclear how mat placement on grassland longer than 24 weeks may impact soils, particularly with greater associated impacts to vegetation. Overall, results of this study highlight the potential for access mats to minimize impacts to soil physical and hydrologic properties, although their use will also need to be balanced off against associated impacts to vegetation and nutrient cycling.

2.6 References

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Table 2–1. Treatment application timeline and abbreviation details.

Treatment	Season	Weeks	Start	End	Visual Timeline
Control	Season Long	24	30-Apr	15-Oct	**Control**
E6 TWM	Early	6	30-Apr	10-Jun	**Early 6 Mat**
E6 TWOM	Early	6	30-Apr	10-Jun	**Early 6 Traffic**
E12 TWM	Early	12	30-Apr	22-Jul	**Early 12 Mat**
E12 TWOM	Early	12	30-Apr	22-Jul	**Early 12 Traffic**
L6 TWM	Late	6	22-Jul	3-Sep	**Late 6 Mat**
L6 TWOM	Late	6	22-Jul	3-Sep	**Late 6 Traffic**
L12 TWM	Late	12	22-Jul	15-Oct	**Late 12 Mat**
L12 TWOM	Late	12	22-Jul	15-Oct	**Late 12 Traffic**
SL24 TWM	Season Long	24	30-Apr	15-Oct	**Season Long 24 mat**
SL24 TWOM	Season Long	24	30-Apr	15-Oct	**Season Long 24 Traffic**

Table shows treatment breakdown consisting of: abbreviated treatment name, application season and duration in weeks, application date for 2015, and timeline visual representation. Traffic with mats (TWM) traffic imposed on mats placed directly on the grassland, traffic without mats (TWOM) traffic imposed directly on the grassland. Control = non-treated native grassland; E6 TWM = traffic imposed on mats placed early in the growing season (April 30 to June 10) for 6 weeks; E6 TWOM = traffic imposed directly on grassland early in the growing season (April 30 to June 10) over 6 weeks and measured on-track; E12 TWM = traffic imposed on mats placed early in the growing season (April 30 to July 22) for 12 weeks; E12 TWOM = traffic imposed directly on grassland early in the growing season (April 30 to July 22) over 12 weeks and measured on track; L6 TWM = traffic imposed on mats placed late in the growing season (July 22 to Sept 3) for 6 weeks; L6 TWOM = traffic imposed directly on grassland late in the growing season (July 22 to Sept 3) over 6 weeks and measured on-track; L12 TWM = traffic imposed on mats placed late in the growing season (July 22 to Oct 15) for 12 weeks; L12 TWOM = traffic imposed directly on grassland late in the growing season (July 22 to Oct 15) over 12 weeks and measured on-track; SL24 TWM = traffic imposed on mats placed throughout the growing season (April 30 to Oct 15) for 24 weeks; SL24 TWOM = traffic imposed directly on grassland throughout the growing season (April 30 to Oct 15) over 24 weeks and measured on-track.

Table 2–2. ANOVA summary of penetration resistance.

	(a) Full Treatments		(b) All Samples	
	F-stat†	**p-value**	**F-stat†**	**p-value**
Ecosite (Eco)	$1.90_{1,2}$	0.302	$3.99_{1,1274}$	0.0459
Treatment (Trt)	$51.63_{10,152}$	**< 0.0001**	$138.93_{10,1274}$	**< 0.0001**
Eco × Trt	$1.67_{10,616}$	0.0833	$5.26_{10,1274}$	**<0.0001**
Sampling Date (SD)	$365.63_{4,616}$	**< 0.0001**	-	**-**
Eco × SD	$60.48_{4,616}$	**< 0.0001**	-	-
Trt × SD	$5.84_{40,616}$	**< 0.0001**	$14.72_{72,1274}$	**< 0.0001**
Eco × Trt × SD	$2.03_{40,616}$	**< 0.0001**	$8.13_{81,1274}$	**< 0.0001**

(c) Separate Dates	June 11, 2015		July 22, 2015		September 2, 2015		October 16, 2015	
	F-stat‡	**p-value**	**F-stat‡**	**p-value**	**F-stat§**	**p-value**	**F-stat§**	**p-value**
Ecosite (Eco)	$2.55_{1,2}$	0.2516	$58.36_{1,2}$	**0.0167**	$0.08_{1,2}$	0.8067	$5.73_{1,2}$	0.1391
Treatment (Trt)	$201.6_{2,40}$	**< 0.0001**	$119.55_{4,68}$	**< 0.0001**	$67.5_{6,96}$	**<.0001**	$92.43_{10,152}$	**< 0.0001**
Eco × Trt	$4.16_{2,40}$	**0.0228**	$11.42_{4,68}$	**< 0.0001**	$3.72_{6,96}$	**0.0023**	$5.08_{10,152}$	**< 0.0001**

† F–stat subscript indicates the numerator and denominator degrees freedom, respectively.

‡ Transformations did not normalize data, original data were analyzed.

§ Data were log transformed for analysis.

Summary of the ANOVA responses of PR (mPa) in relation to ecosite type, disturbance treatment, date of sampling, and the interaction, within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2015 and 2016 growing season one and two years after treatment application. (a) Full Treatments: PR data is based on dates when all treatments were sampled (April 30 and October 16 in 2015, and April 26, June 06, June 18, July 05, and July 27 in 2016); (b) All Samples: PR data are based on every sample taken from any treatment, although due to values missed from the staggered treatment the analysis of sampling date and the interaction of ecosite × sampling date are not available; (c) Select dates from 2015 show active recovery during the growing season.

Table 2–3. ANOVA summary of soil moisture content.

	ANOVA			
	(a) Full Treatments		(b) All Samples	
	F-stat†	**p-value**	**F-stat†**	**p-value**
Ecosite (Eco)	$112.21_{1,502}$	**< 0.0001**	$182.10_{1,627}$	**< 0.0001**
Treatment (Trt)	$18.22_{5,502}$	**< 0.0001**	$43.45_{5,627}$	**< 0.0001**
Eco × Trt	$3.26_{5,502}$	**0.0066**	$8.66_{5,627}$	**< 0.0001**
Sampling Date (SD)	$133.68_{4,502}$	**< 0.0001**	$217.97_{7,627}$	**< 0.0001**
Trt × SD	$11.25_{20,502}$	**< 0.0001**	$32.13_{26,627}$	**< 0.0001**
Eco × Trt × SD	$2.3_{24,502}$	**0.0005**	$10.79_{33,627}$	**< 0.0001**

† F–stat subscript indicates the numerator and denominator degrees freedom, respectively.

Summary of the ANOVA responses of SMC (%) in relation to ecosite type, disturbance treatment, date of sampling, and the interaction, within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2015 and 2016 growing season one and two years after treatment application. (a) Full Treatments: SMC data is based on dates when all treatments were sampled (October 15 in 2015, and May 04, June 06, June 18, July 05, and July 27 in 2016); (b) All Samples: SMC data are based on every sample taken from any treatment, although due to values missed from the staggered treatment the analysis of sampling date and the interaction of ecosite × sampling date are not available.

Table 2–4. ANOVA summary and ecosites effects of soil bulk density (BD) in the top 7.5 cm of soil.

	ANOVA					
	---2015---			---2016---		
	F-stat†		**p-value**	**F-stat**		**p-value**
Ecosite (Eco)	$29.00_{1,2}$		**0.0328**	$20.09_{1,2}$		**0.0463**
Treatment (Trt)	$2.02_{2,40}$		0.1462	$0.56_{10,64}$		0.8415
Eco × Trt	$0.30_{2,40}$		0.7421	$0.85_{10,260}$		0.5791
			μ‡			
Ecosite	Loam	Loamy-Sand		Loam	Loamy-Sand	
	g cm^{-3}	g cm^{-3}		g cm^{-3}	g cm^{-3}	
	0.706 b	0.947 a	**0.0328**	0.818 b	1.117 a	**0.0463**

† F–stat subscript indicates the numerator and denominator degrees freedom, respectively.

‡ Within each year column, means (n = 8) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05); SEM in 2015 (± 0.0317 g cm^{-3}) and in 2016 (± 0.0472 g cm^{-3}).

Summary of ANOVA responses of soil BD (g cm^{-3}) (n = 8) among ecosites, selected disturbance treatments, and their interaction, within the DMGP at the Mattheis Research Ranch, as sampled in the year of treatment application and one year into recovery, on July 29 of 2015, and July 14 2016, respectively.

Table 2–5. ANOVA summary and treatment effect of water infiltration rate (IR).

	ANOVA			
	--------------------2015--------------------		--------------------2016--------------------	
	F-stat†	**p-value**	**F-stat‡**	**p-value**
Ecosite (Eco)	$12.93_{1,2}$	0.0694	$13.76_{1,2}$	0.0656
Treatment (Trt)	$13.17_{2,40}$	**< 0.0001**	$18.20_{10,152}$	**< 0.0001**
Eco × Trt	$0.31_{2,40}$	0.733	$1.04_{10,152}$	0.4097

	μ§					
Treatment	TWOM	TWM		TWOM	TWM	
	mm hour^{-1}			mm hour^{-1}		
Control	178.9 a			254.4 a		
SL24	–	–	–	78.1 d	176.9 b	**< 0.0001**
E12	114.1 b	182.0 a	**< 0.0001**¶	118.8 c	157.3 b	**0.0102**
E6	–	–	–	73.2 d	246.1 ab	**< 0.0001**
L12	–	–	–	112.3 c	237.7 ab	**< 0.0001**
L6	–	–	–	110.5 c	218.8 ab	**< 0.0001**

† F–stat subscript indicates the numerator and denominator degrees freedom, respectively.

‡ Data were log transformed to achieve normality.

§ Within each year column, means (n = 16) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05); SEM in 2015 (± 10.6 mm hour-1) and in 2016 (± 32.4 mm hour-1).

¶ Pairwise comparisons of TWOM and TWM treatments within a year.

Summary of the ANOVA response for soil infiltration rate (mm hour^{-1}) (n = 16) in relation to ecosite, disturbance treatments, and their interaction, within the DMGP at the Mattheis Research Ranch, as measured on August 4, 2015 and July 29, 2016, during the year of treatment and one year after treatment, respectively. Year was not assessed as a repeated measure. See Table 2-1 for treatment definitions.

Table 2–6. ANOVA summary and ecosite effects of soil condition.

	ANOVA					
	Soil pH		EC (µS cm^{-1})		Organic Matter (%)	
	F-stat†	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$0.85_{1,2}$	0.4532	$20.79_{1,2}$	**0.0449**	$3.42_{1,2}$	0.2058
Treatment (Trt)	$1.00_{2,40}$	0.3765	$1.36_{2,40}$	0.2690	$0.14_{2,40}$	0.8706
Eco x Trt	$0.24_{2,40}$	0.7895	$0.32_{2,40}$	0.7249	$0.12_{2,40}$	0.8871

	µ		
Ecosite	Loam	Loamy-Sand	
	µs cm^{-1}	µs cm^{-1}	
	107.0 a	68.7 b	**0.0449**
SE	± 3.9		

† F–stat subscript indicates the numerator and denominator degrees freedom, respectively.

Summary of the ANOVA responses of soil conditions (n = 8) among ecosites, select disturbance treatments (Control, E12TWM, and E12TWOM), and their interaction, within the DMGP at the Mattheis Research Ranch, as sampled during soil sampling on July 29 of 2015. See Table 2–1 for treatment definitions.

Table 2–7. ANOVA summary of soil macronutrient.

	ANOVA					
	Ecosite		Treatment		Ecosite × Treatment	
Response	**F-stat†**	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
		------------------------ 2015 Treatments (n = 3 trts tested) --------------------				
Total-N‡	$0.18_{1,2}$	0.711	$77.3_{2,39}$	**< 0.0001**	$1.77_{2,39}$	0.148
NO3-N‡	$0.12_{1,2}$	0.764	$80.1_{2,39}$	**< 0.0001**	$2.31_{2,39}$	0.112
NH4-N‡	$0.67_{1,2}$	0.498	$0.80_{2,9.1}$	0.479	$1.30_{2,9.1}$	0.319
P§	$0.01_{1,2}$	0.920	$19.2_{2,39}$	**< 0.0001**	$2.65_{2,39}$	0.084
K	$9.05_{1,2}$	0.095	$2.21_{2,39}$	0.310	$1.05_{2,39}$	0.361
S‡	$1.08_{1,2}$	0.408	$12.2_{2,39}$	**< 0.0001**	$4.48_{2,39}$	**0.018**
Ca	$0.13_{1,2}$	0.750	$0.29_{2,39}$	0.747	$0.54_{2,39}$	0.585
Mg	$3.09_{1,2}$	0.219	$0.51_{2,39}$	0.603	$0.35_{2,39}$	0.710
		------------------------ 2016 Treatments (n = 5 trts tested) --------------------				
Total-N‡	$5.38_{1,2}$	0.146	$60.2_{4,68}$	**< 0.0001**	$1.91_{4,68}$	0.119
NO3-N‡	$2.55_{1,2.32}$	0.234	$35.6_{4,55.2}$	**< 0.0001**	$0.37_{4,55.2}$	0.826
NH4-N‡	$0.37_{1,2}$	0.550	$0.18_{4,19}$	0.945	$0.69_{4,19}$	0.605
P§	$0.03_{1,2}$	0.884	$0.02_{4,68}$	0.999	$1.63_{4,68}$	0.176
K	$1.29_{1,2}$	0.373	$2.66_{4,68}$	**0.040**	$2.08_{4,68}$	0.092
S‡	$0.26_{1,2}$	0.663	$3.83_{4,68}$	**0.0072**	$0.40_{4,68}$	0.807
Ca	$1.66_{1,2}$	0.326	$2.58_{4,68}$	**0.0447**	$0.12_{4,68}$	0.976
Mg	$5.83_{1,2}$	0.137	$0.55_{4,68}$	0.698	$0.73_{4,68}$	0.576

† F-stat subscripts indicate the numerator and denominator degrees freedom, respectively.

‡ Data were log transformed for analysis.

§ Data were square root transformed for analysis.

Summary of the ANOVA response of various plant available soil macronutrients, in relation to ecosite type, disturbance treatment, and their interactions, within the DMGP at the Mattheis Research Ranch, as sampled with PRS® probes in the 2015 and 2016 growing seasons year of and one year after treatment, respectively.

Table 2–8. ANOVA summary of soil micronutrient.

	ANOVA					
	Ecosite		Treatment		Ecosite × Treatment	
Response	**F-stat†**	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
		------------------------ 2015 Treatments (n = 3 trts tested) --------------------				
Fe‡	$1.24_{1,2}$	0.380	$11.38_{2,39}$	**0.0001**	$0.58_{2,39}$	0.564
Mn‡	$4.32_{1,2}$	0.171	$17.87_{2,39}$	**< 0.0001**	$2.02_{2,39}$	0.146
Zn	$0.03_{1,2}$	0.881	$3.46_{2,39}$	**0.0414**	$1.29_{2,39}$	0.286
B	$0.14_{1,2}$	0.740	$0.39_{2,20}$	0.682	$1.16_{2,20}$	0.334
Al	$0.02_{1,2}$	0.910	$0.15_{2,39}$	0.858	$0.27_{2,39}$	0.764
		------------------------ 2016 Treatments (n = 5 trts tested) --------------------				
Fe‡	$0.27_{1,2}$	0.656	$14.09_{4,68}$	**< 0.0001**	$4.80_{4,68}$	**0.0018**
Mn‡	$0.79_{1,2}$	0.467	$8.80_{4,68}$	**< 0.0001**	$1.06_{4,68}$	0.384
Zn	$2.88_{1,2}$	0.232	$1.47_{4,68}$	0.220	$1.03_{4,68}$	0.398
B	$0.43_{1,2}$	0.577	$2.54_{4,38}$	0.0555	$1.51_{4,38}$	0..217
Al	$0.32_{1,2}$	0.628	$6.46_{4,68}$	**0.0002**	$1.24_{4,68}$	0.300

† F-stat subscripts indicate the numerator and denominator degrees freedom, respectively.

‡ Data were log transformed for analysis.

Summary of the ANOVA response of various plant available soil micronutrients, in relation to ecosite type, disturbance treatment, and their interactions, within the DMGP at the Mattheis Research Ranch, as sampled with PRS® probes in the 2015 and 2016 growing seasons year of and one year after treatment, respectively.

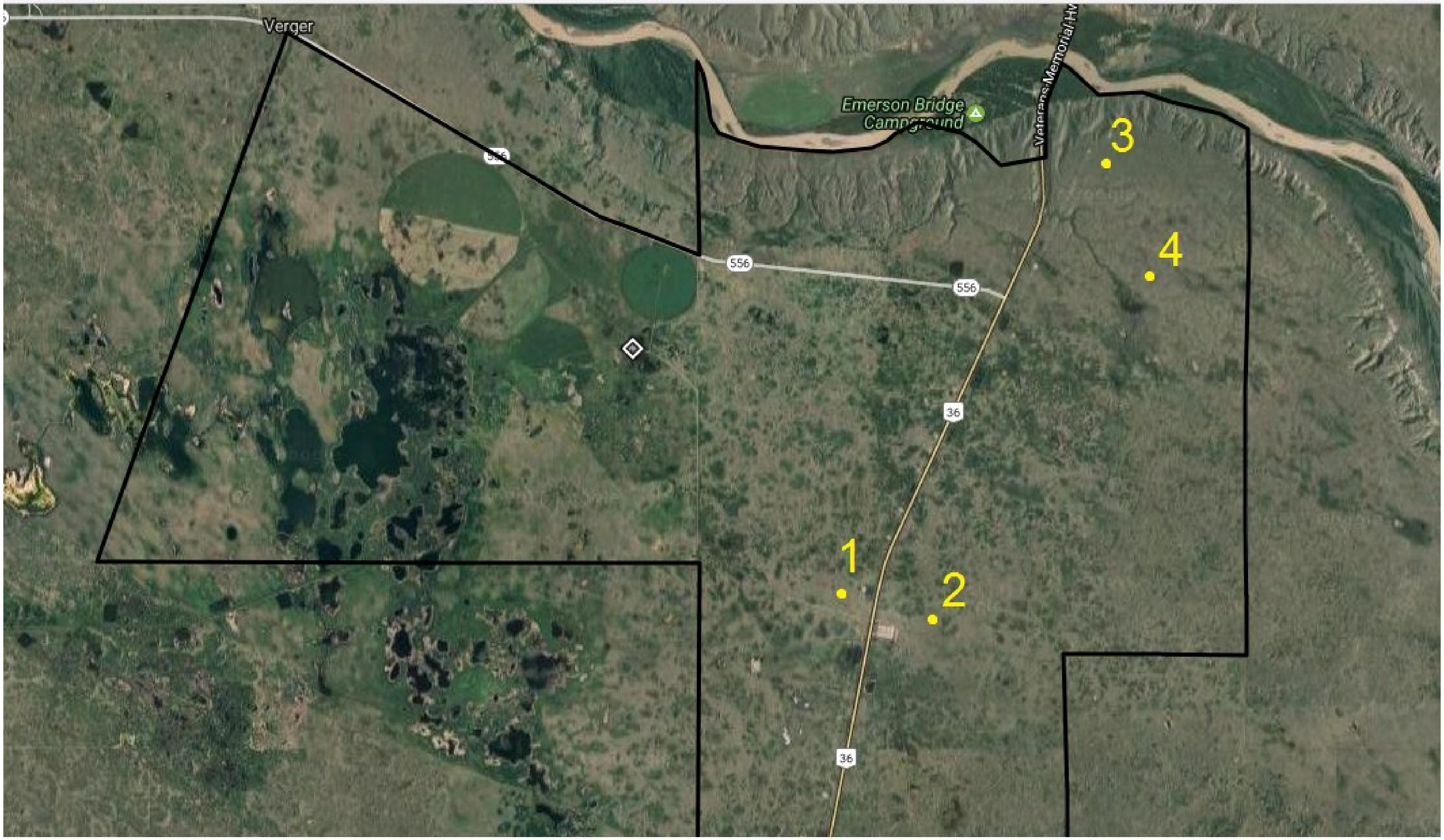

Figure 2–1. Outline of University of Alberta Mattheis Research Ranch.

Mattheis Research Ranch (black boundary) is part of the Rangeland Research Institute. Study sites are labeled in yellow (sites 1 and 2 are on loamy-sand soils, and 3 and 4 are on loam soils).

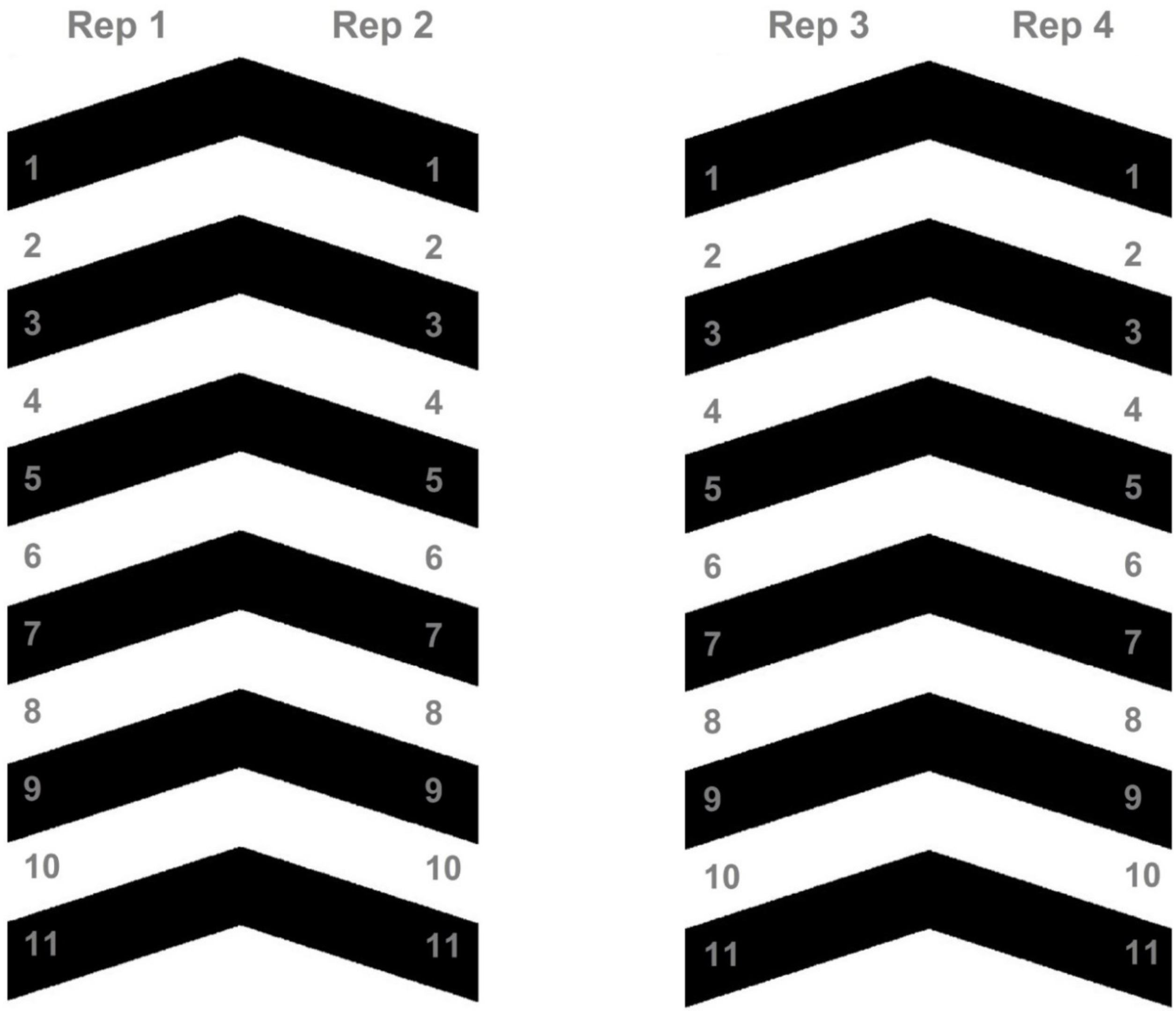

Figure 2–2. Representative site diagram.

Site diagram (one of 4 sites) with replicate blocks of 11 plots in two paired rows on either side of travel lane, treatments randomly assigned to plots.

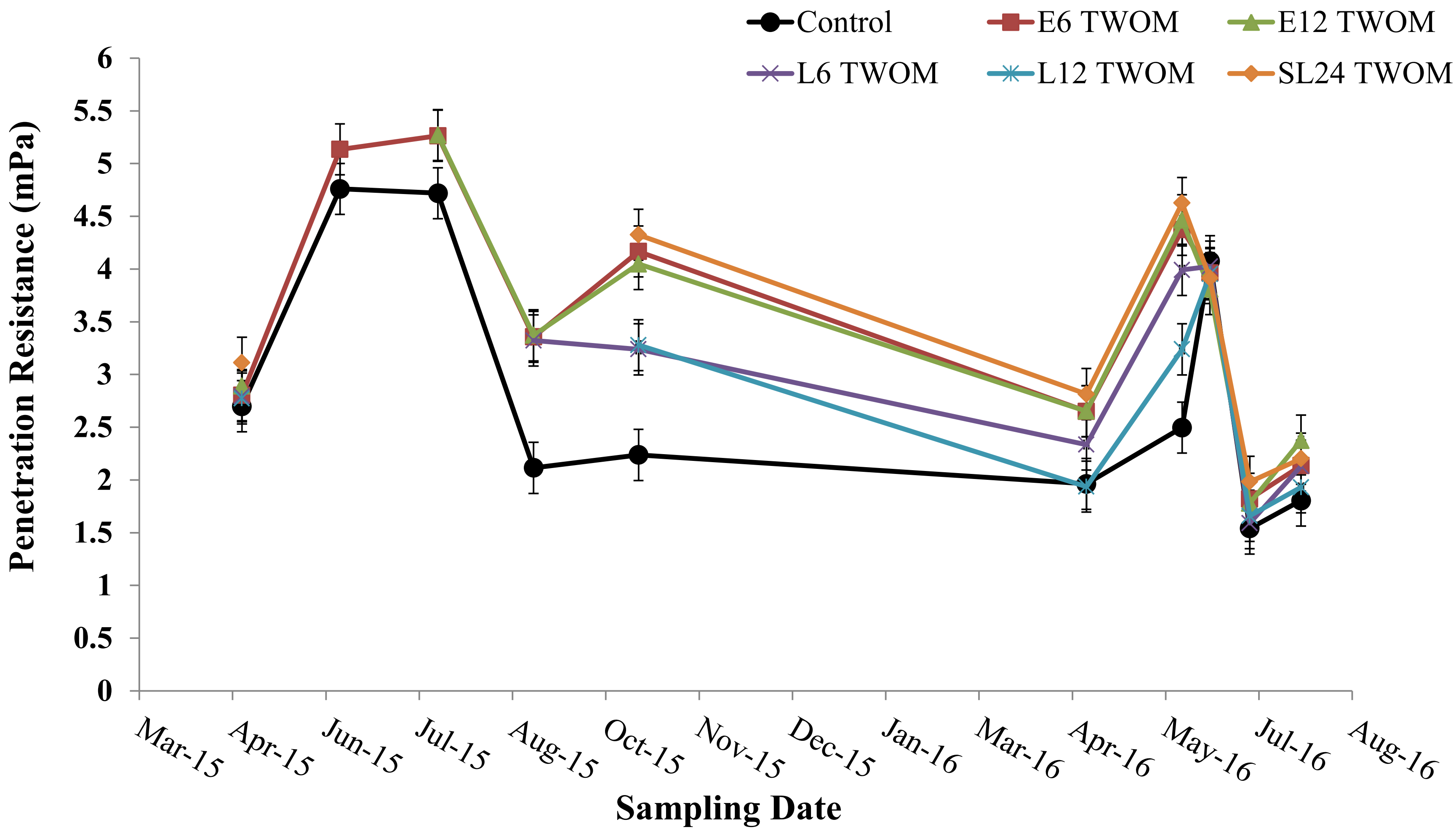

Figure 2–3. Penetration resistance (PR) of Control and traffic without mats (TWOM) treatments on loam soils.

TWOM was consistently higher than the Control; treatments applied early (E6, E12, SL24) had greater PR (mPa) levels (n = 8) than treatments applied late, except during periods of low soil moisture content (late June 2016) when all PR levels were high. Sample times are: in 2015April 30; June 11; July 23; September 2; October 17; in 2016 April 26; June 06; June 18; July 05; July 27 ($F_{81, 1274}$ = 8.13, $p < 0.0001$) with SEM (±0.242 mPa). See Table 2–1 for treatment definitions.

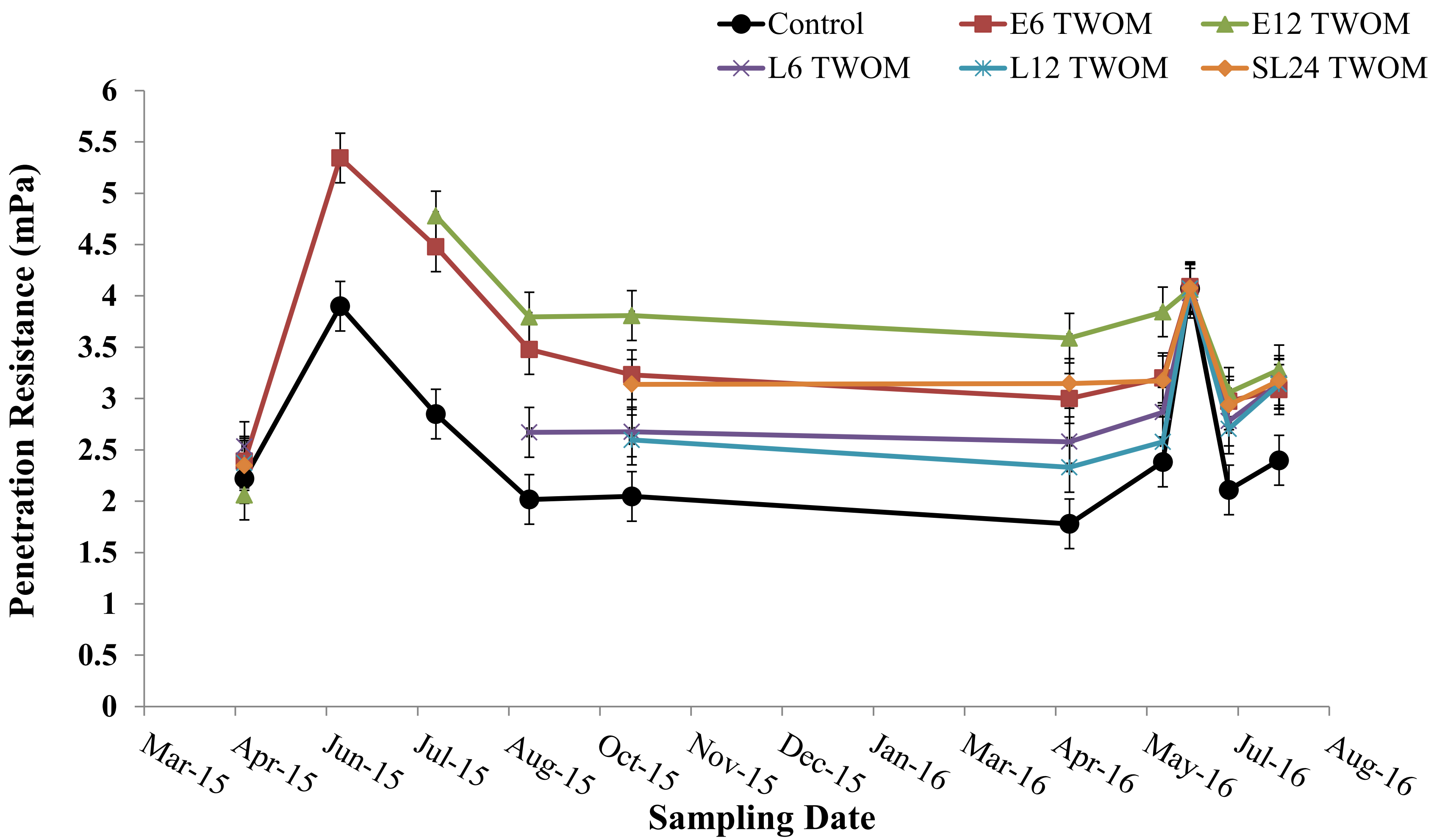

Figure 2–4. Penetration resistance (PR) of Control and traffic without mats (TWOM) treatments on loamy-sand soils.

TWOM was consistently higher than the Control; treatments applied early (E6, E12, SL24) had greater PR (mPa) levels (n = 8) than treatments applied late, except during periods of low soil moisture content (late June 2016) when all PR levels were high. Sample times are: in 2015April 30; June 11; July 23; September 2; October 17; in 2016 April 26; June 06; June 18; July 05; July 27 ($F_{81, 1274}$ = 8.13, $p < 0.0001$) with SEM (± 0.242 mPa). See Table 2–1 for treatment definitions.

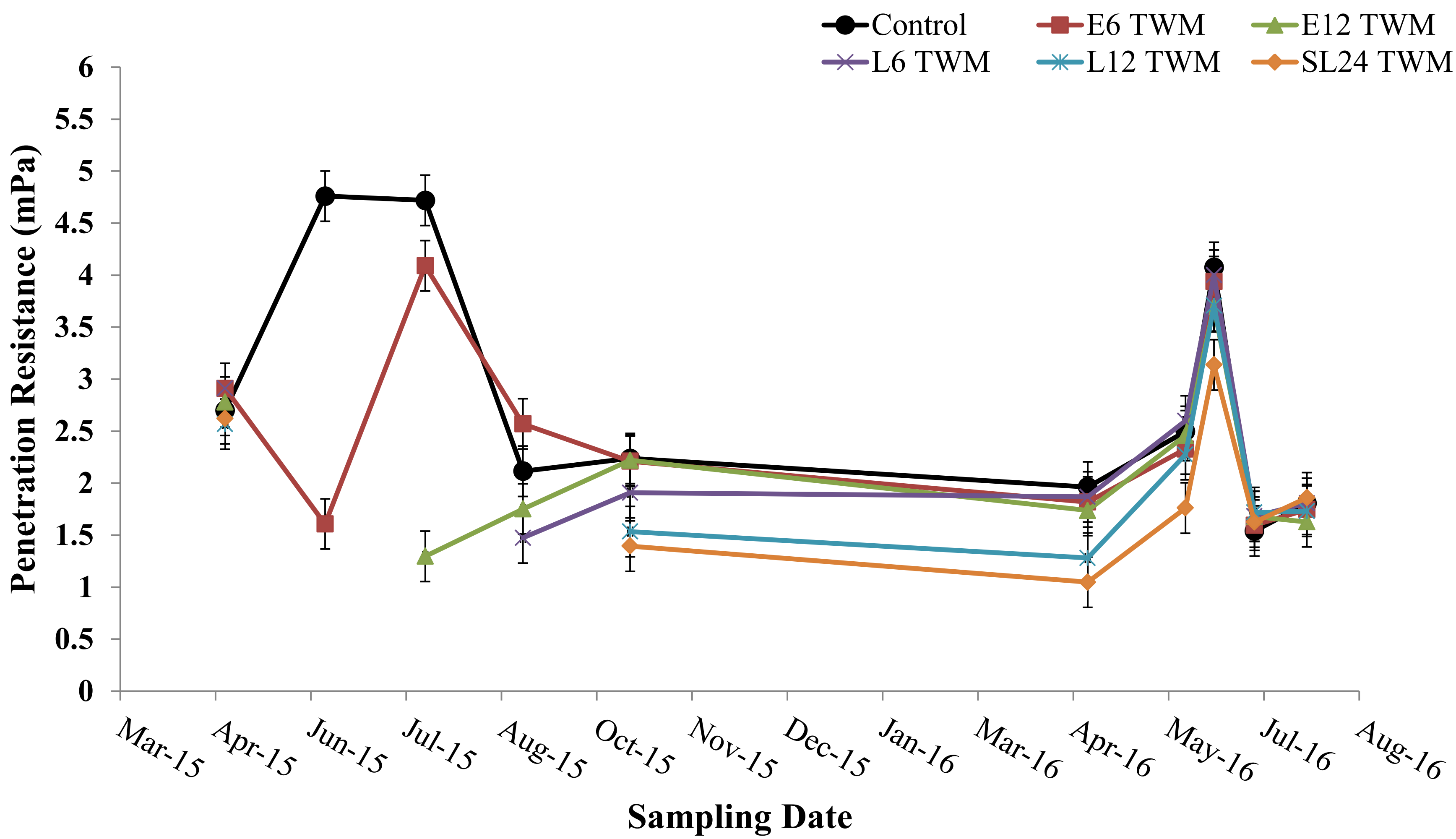

Figure 2–5. Penetration resistance (PR) of Control and traffic with mats (TWM) treatments on loam soils.

TWM was initially lower than the Control when mat removed upon treatment completion for all treatments regardless of season or duration; PR (mPa) (n = 8) increased to approach or equal Control with time. Sample times are: in 2015April 30; June 11; July 23; September 2; October 17; in 2016 April 26; June 06; June 18; July 05; July 27 ($F_{81, 1274} = 8.13$, $p < 0.0001$) with SEM (± 0.242 mPa). See Table 2–1 for treatment definitions.

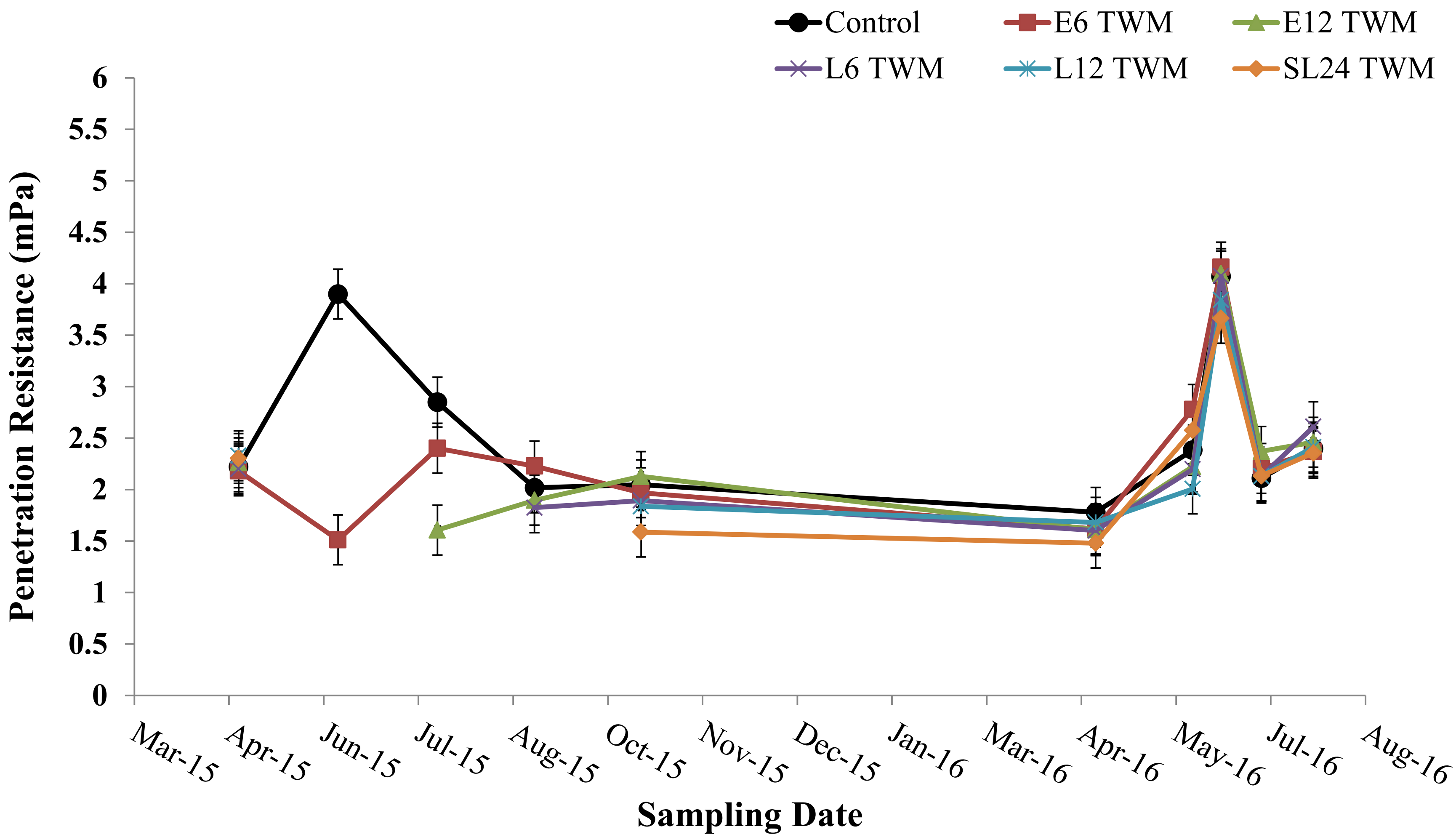

Figure 2–6. Penetration resistance (PR) of Control and traffic with mats (TWM) treatments on loamy-sand soils.

TWM was initially lower than the Control when mat removed upon treatment completion for all treatments regardless of season or duration; PR (mPa) (n = 8) increased to equal Control with time. Sample times are: in 2015April 30; June 11; July 23; September 2; October 17; in 2016 April 26; June 06; June 18; July 05; July 27 ($F_{81,\,1274} = 8.13$, $p < 0.0001$) with SEM (± 0.242 mPa). See Table 2–1 for treatment definitions.

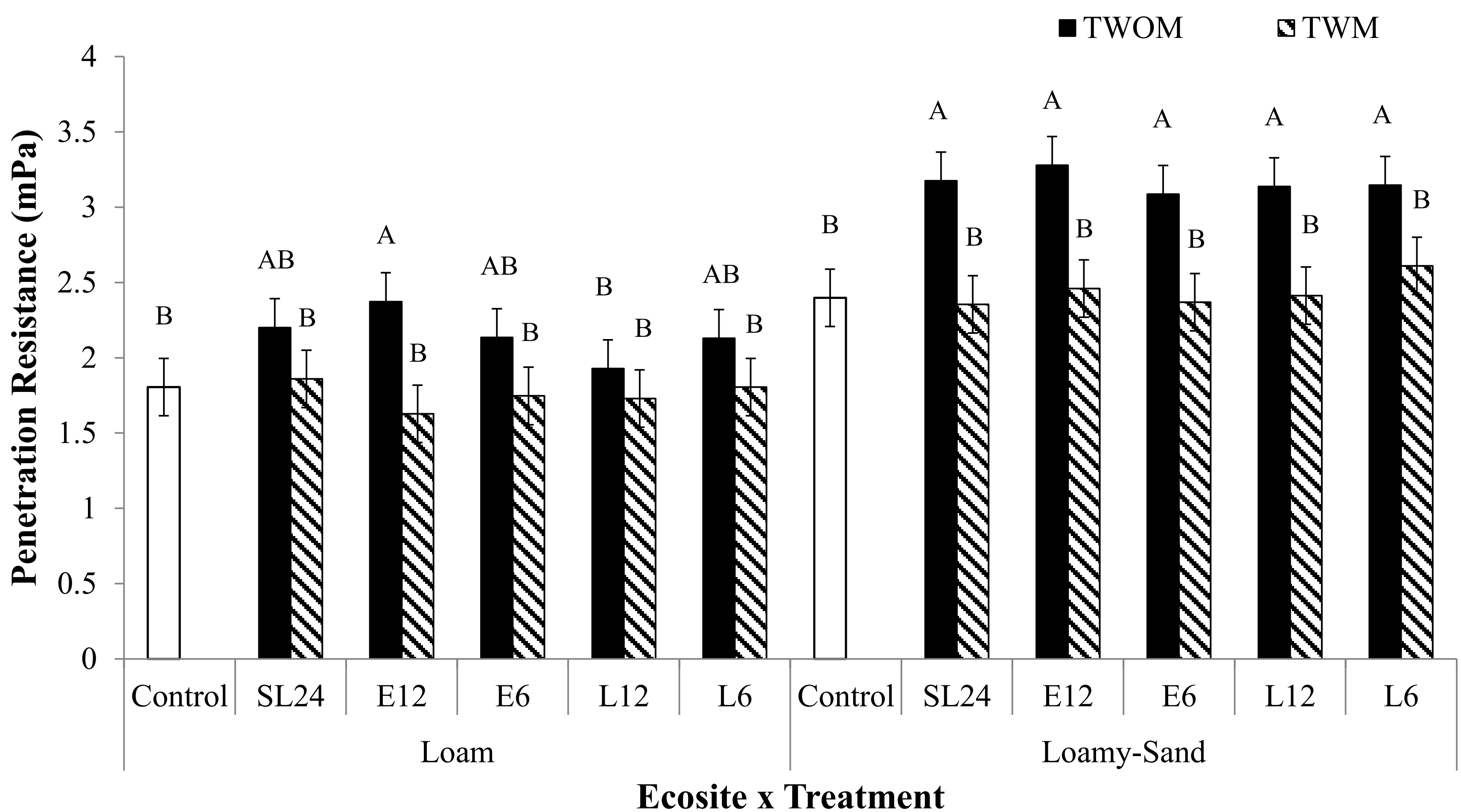

Figure 2–7. Comparisons of penetration resistance (PR) one year after treatment applications.

Residual impacts of various traffic treatments after one year recovery showing comparisons of PR (mPa) (n = 16) in the DMGP, measurements for July 27, 2016 ($F_{66,\ 1064} = 8.39$, $p < 0.0001$) with SEM (± 0.1904 mPa). PR was lower on loam soils than on loamy-sand soils, TWOM treatments were consistently higher than the paired TWM and the Control for each soil type. Within an ecosite, column means (n = 16) with the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05); SEM ±0.1904 mPa. See Table 2–1 for treatment definitions.

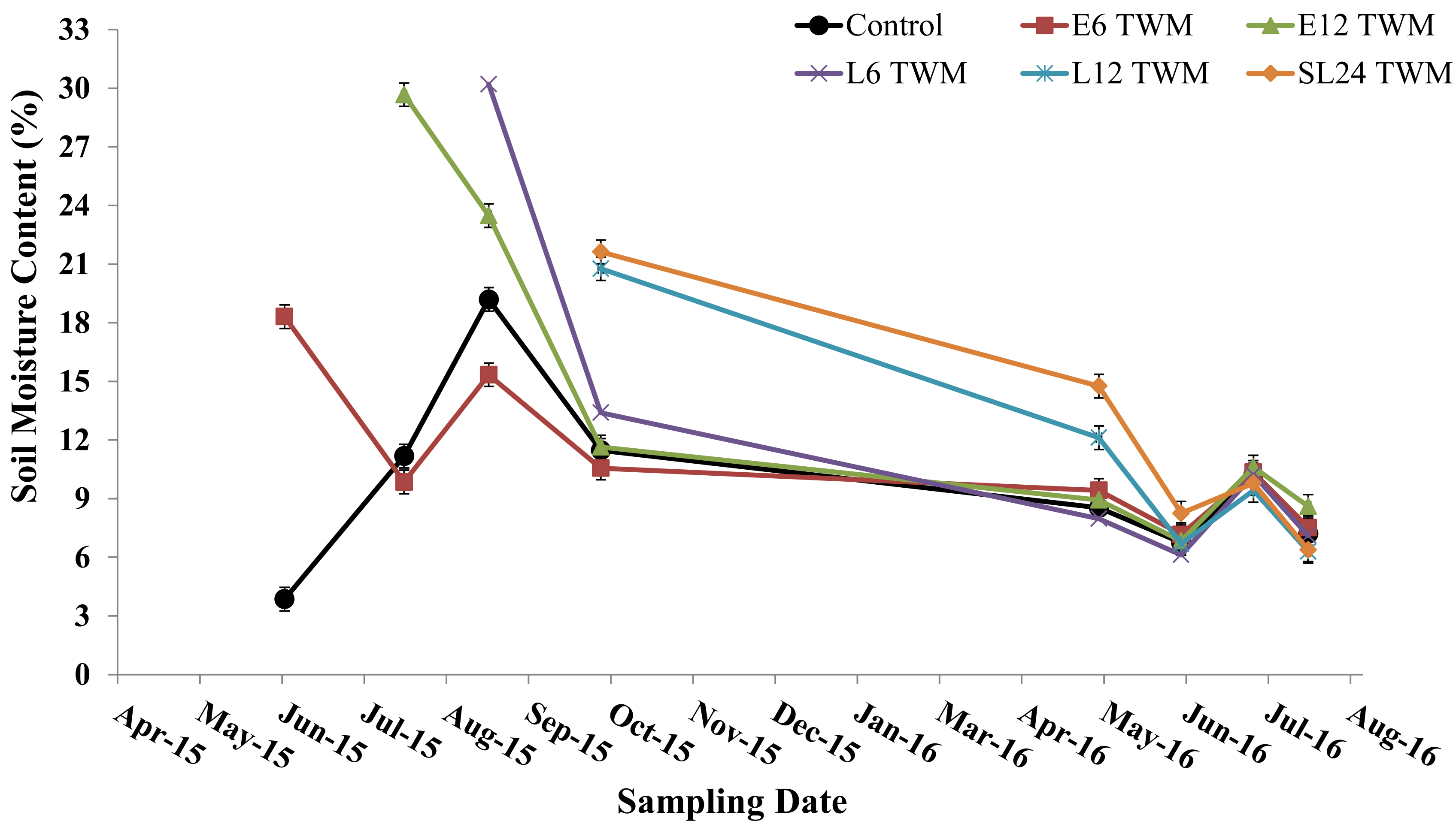

Figure 2–8. Soil moisture content (SMC) (%) of Control and traffic with mat (TWM) treatments on loam soils.

SMC (n = 8) was initially greater than Control for all TWM treatments, regardless of season or duration, when mats removed at end of treatment; with time SMC progressed towards Control levels; and by June of first year recovery SMC for all TWM and Control were equal. Sample times are: in 2015 June 12; July 30; September 2; October 17; and in 2016 May 4; June 06; July 05; July 27 ($F_{33, 627}$ = 10.79, $p < 0.0001$) with SEM (± 0.6025 %). See Table 2–1 for treatment definitions.

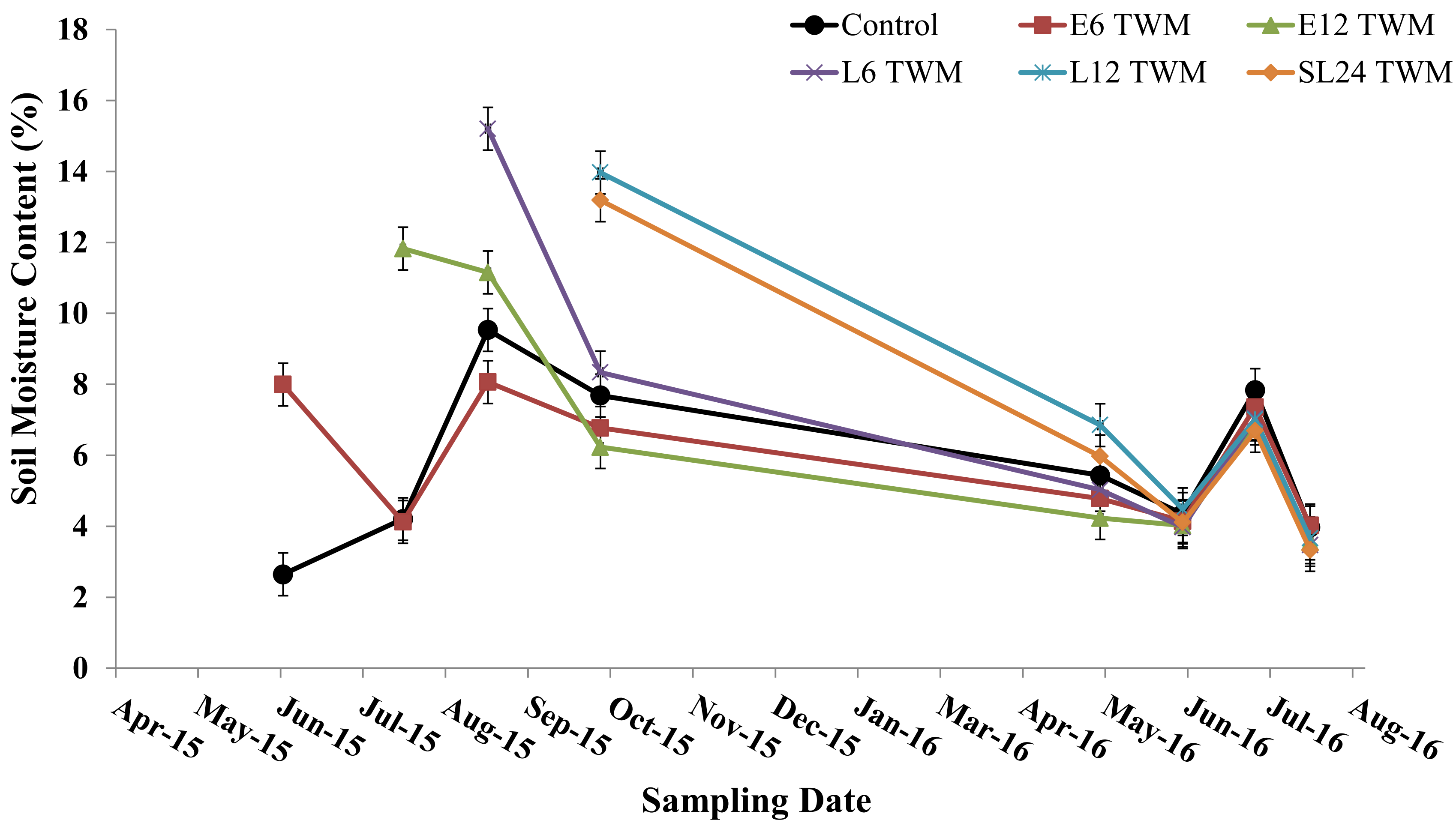

Figure 2–9. Soil moisture content (SMC) (%) of Control and traffic with mat (TWM) treatments on loamy-sand soils.

SMC (n = 8) was initially greater than Control for all TWM treatments, regardless of season or duration, when mats removed at end of treatment; with time the SMC progressed towards Control levels; and by June of first year recovery SMC for all TWM and Control were equal. Sample times are: in 2015 June 12; July 30; September 2; October 17; and in 2016 May 4; June 06; July 05; July 27 ($F_{33, 627} = 10.79$, $p < 0.0001$) with SEM (± 0.6025 %). See Table 2–1 for treatment definitions.

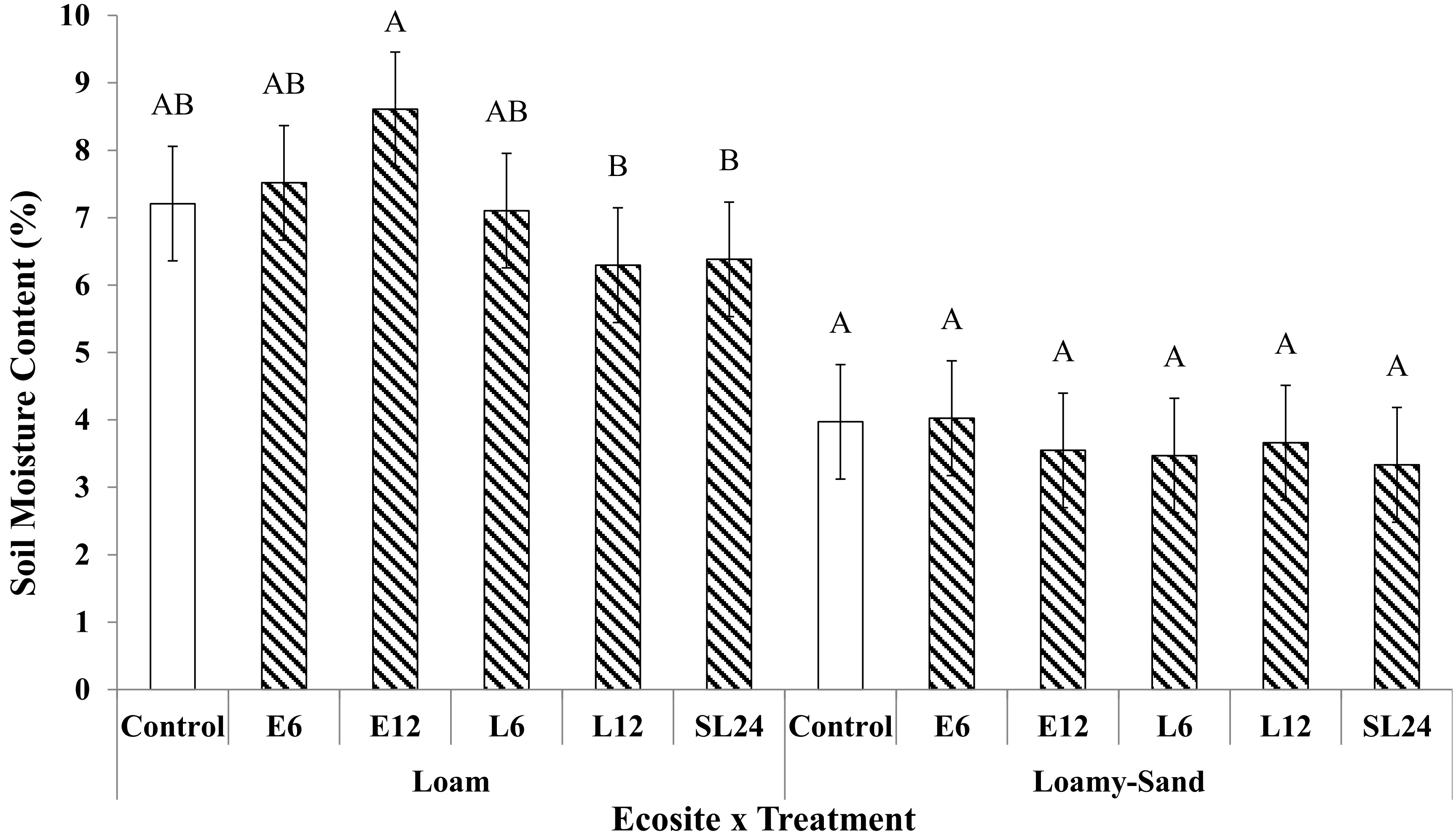

Figure 2–10. Comparison of soil moisture content (%) by ecosite for Control and traffic with mat (TWM) treatments one year after application.

Loam soil had higher SMC (n = 16) than loamy-sand soils when measured at the end of sampling in 2016. All treatments were equal to the Control by the end of 2016 ($F_{24, 502} = 2.3$, $p = 0.0005$) with SEM (± 0.850 %). See Table 2–1 for treatment definitions.

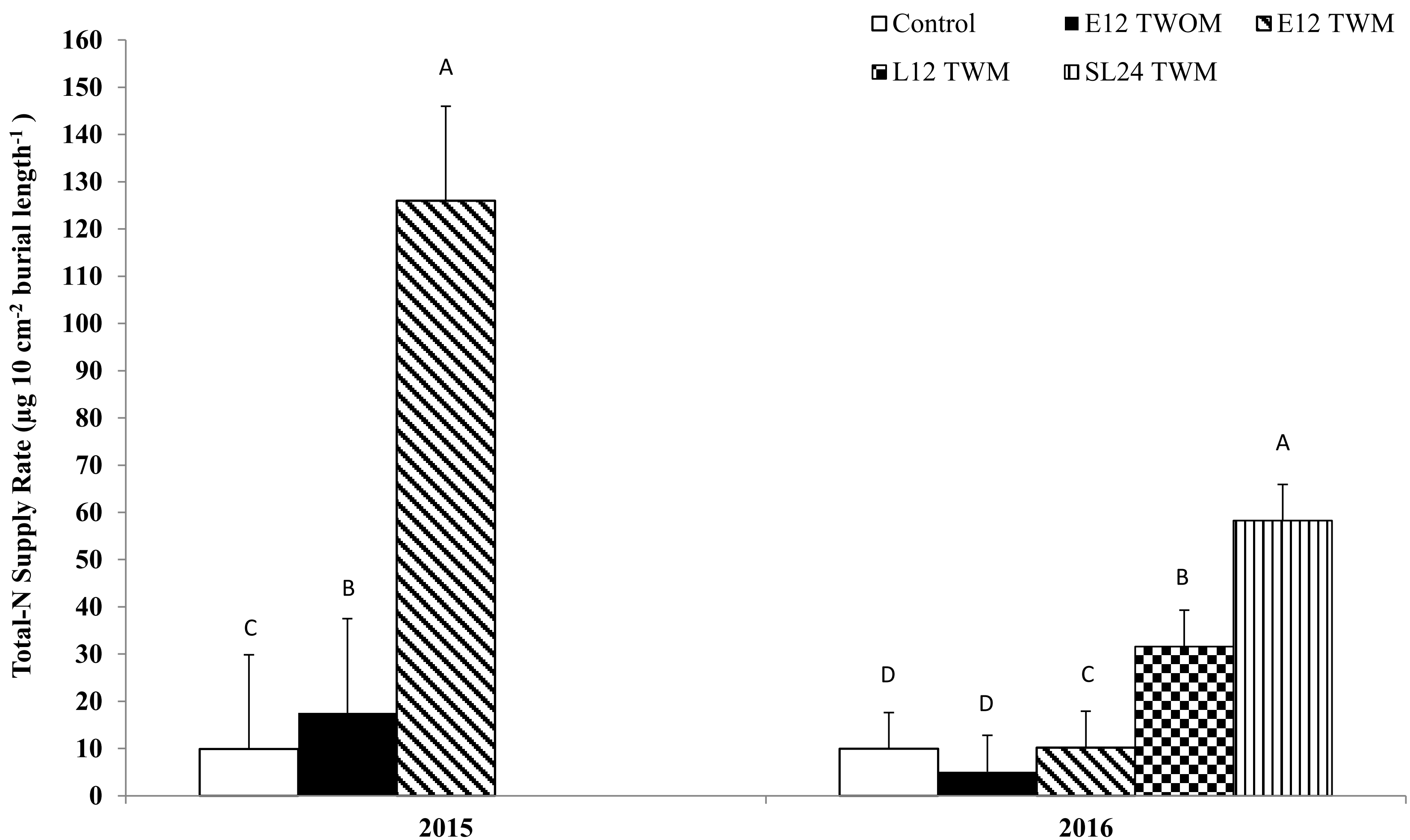

Figure 2–11. Comparisons of total nitrogen in select treatments in 2015 and 2016.

Mean (n = 16) comparative supply of available total nitrogen (NO_3^- and NH_4^+ combined) (µg 10 cm^{-2} burial $length^{-1}$) among various traffic treatments, shown separately for 2015 and 2016 with SEM (± 20.9 and ± 7.7 µg 10 cm^{-2} burial $length^{-1}$ respectively), as indicated by PRS® probes installed during each growing season. Within a year, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment definitions.

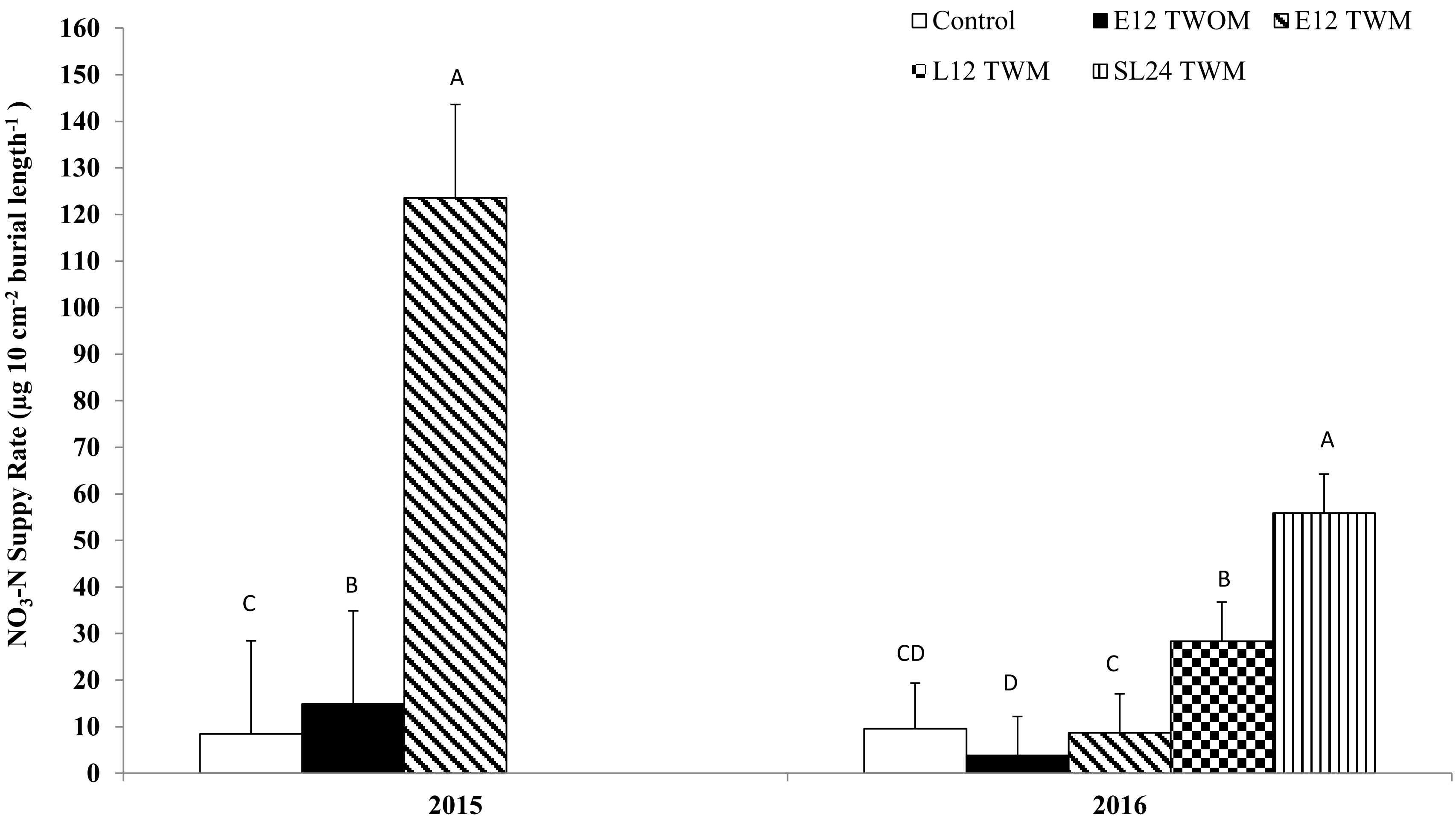

Figure 2–12. Comparison of nitrate supply within select treatments during 2015 and 2016.

Mean ($n = 16$) comparative supply rates of available NO_3^- (µg 10 cm^{-2} burial $length^{-1}$) among various traffic treatments, shown separately for 2015 and 2016 with SEM (± 20.4 and ± 9.6 µg 10 cm^{-2} burial $length^{-1}$ respectively), as indicated by PRS® probes installed during each growing season. Within a year, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment definitions.

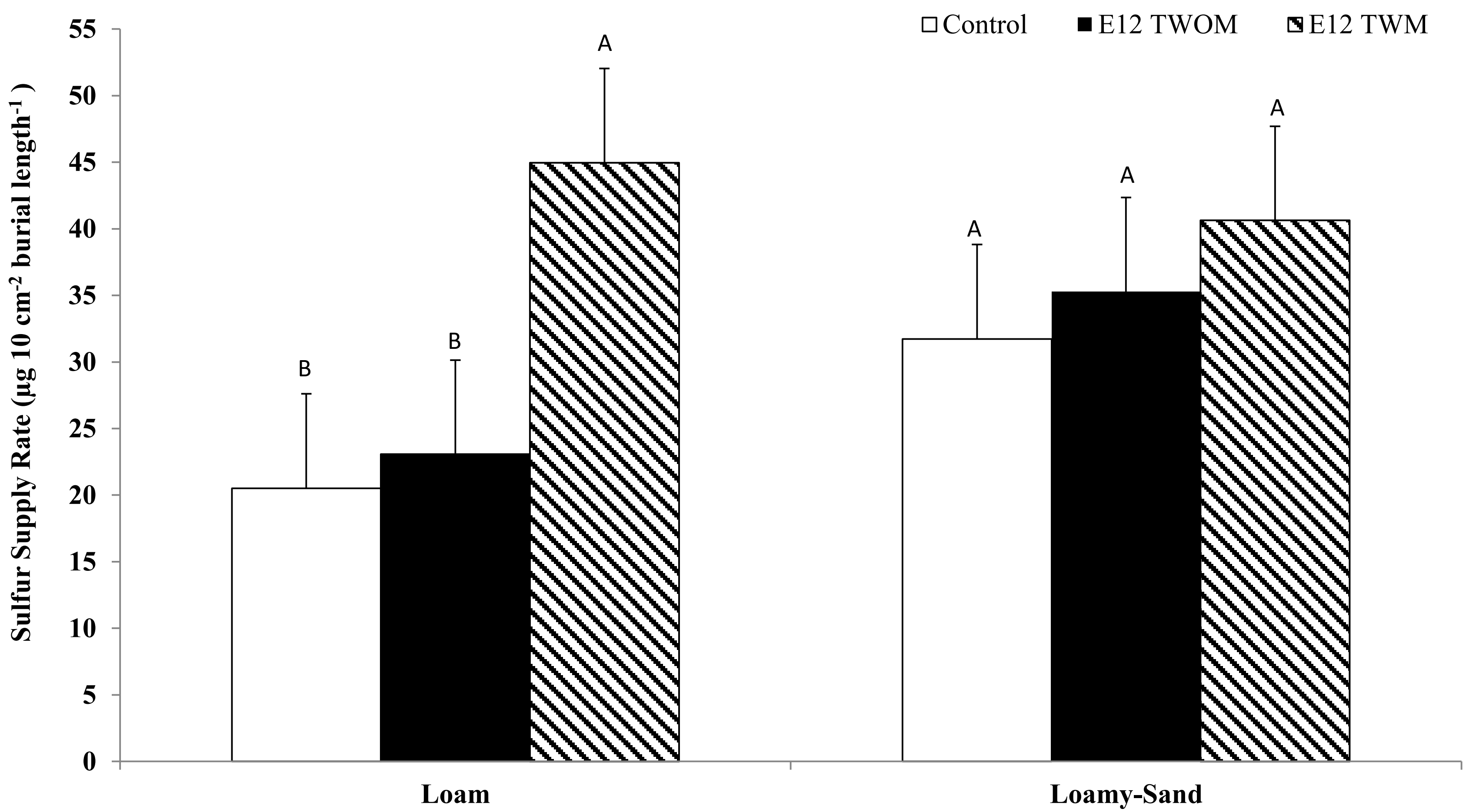

Figure 2–13. Comparison of sulfur (µg 10 cm^{-2} 12 $weeks^{-1}$) in 2015 in select treatments by ecosite.

Mean (n = 8) comparative supply rates of available sulfur (µg 10 cm^{-2} 12 $weeks^{-1}$) among various traffic treatments as measured in 2015 and shown by contrasting ecosites, as indicated by PRS® probes installed during the 2015 growing season with SEM (± 7.1 µg 10 cm^{-2} 12 $weeks^{-1}$). Within an ecosite, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial length of 12 weeks in 2015. See Table 3–1 for treatment definitions.

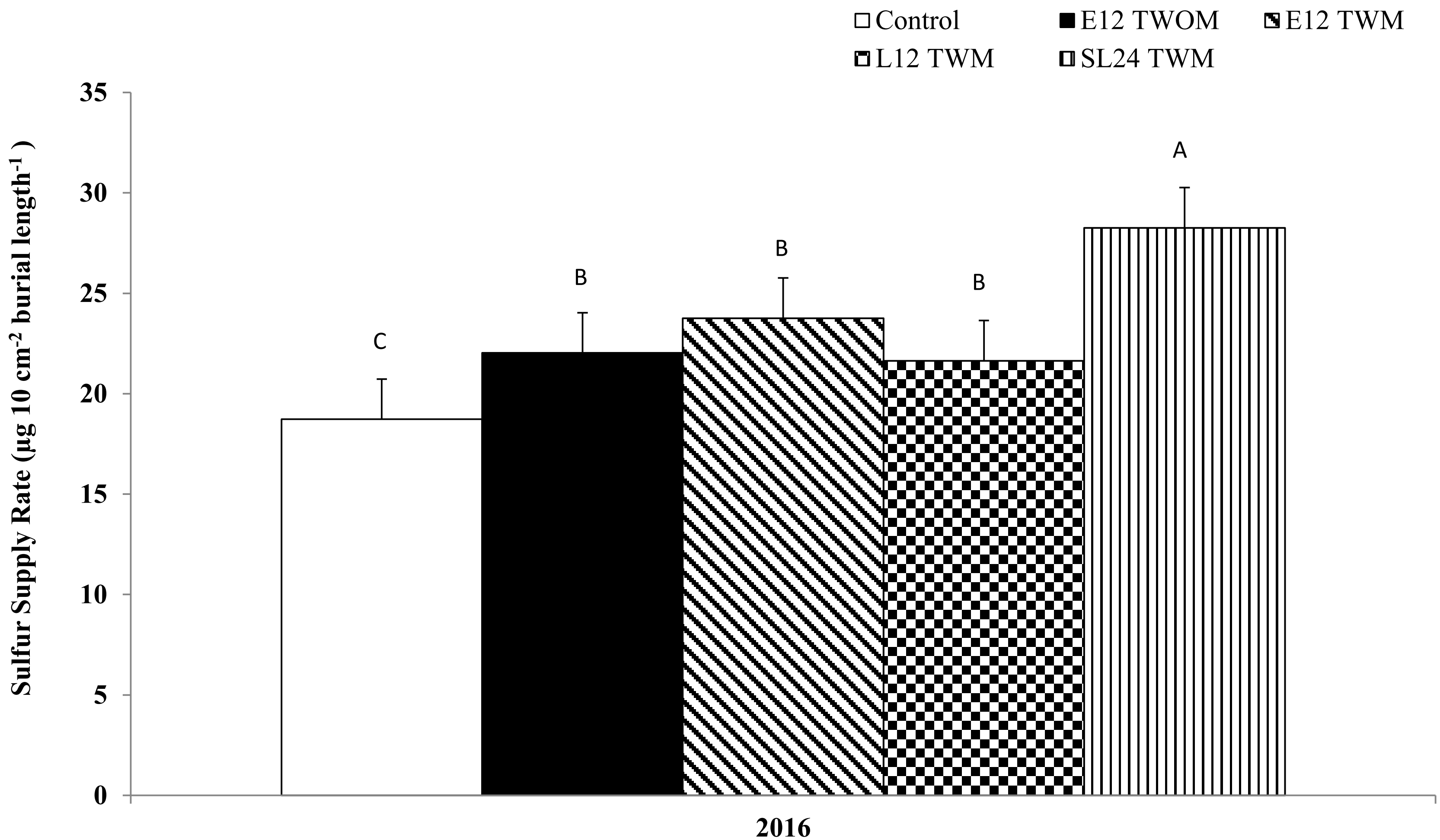

Figure 2–14. Comparison of sulfur (µg 10 cm^{-2} 18 $weeks^{-1}$) in 2016 in select treatments.

Mean (n = 16) comparative supply rates of available sulfur (µg 10 cm^{-2} 18 $weeks^{-1}$) among various traffic treatments as measured in 2016, as indicated by PRS® probes installed during the 2016 growing season with SEM (± 2.0 µg 10 cm^{-2} 18 $weeks^{-1}$). Within an ecosite, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial lengths of 18 weeks in 2016. See Table 3–1 for treatment definitions.

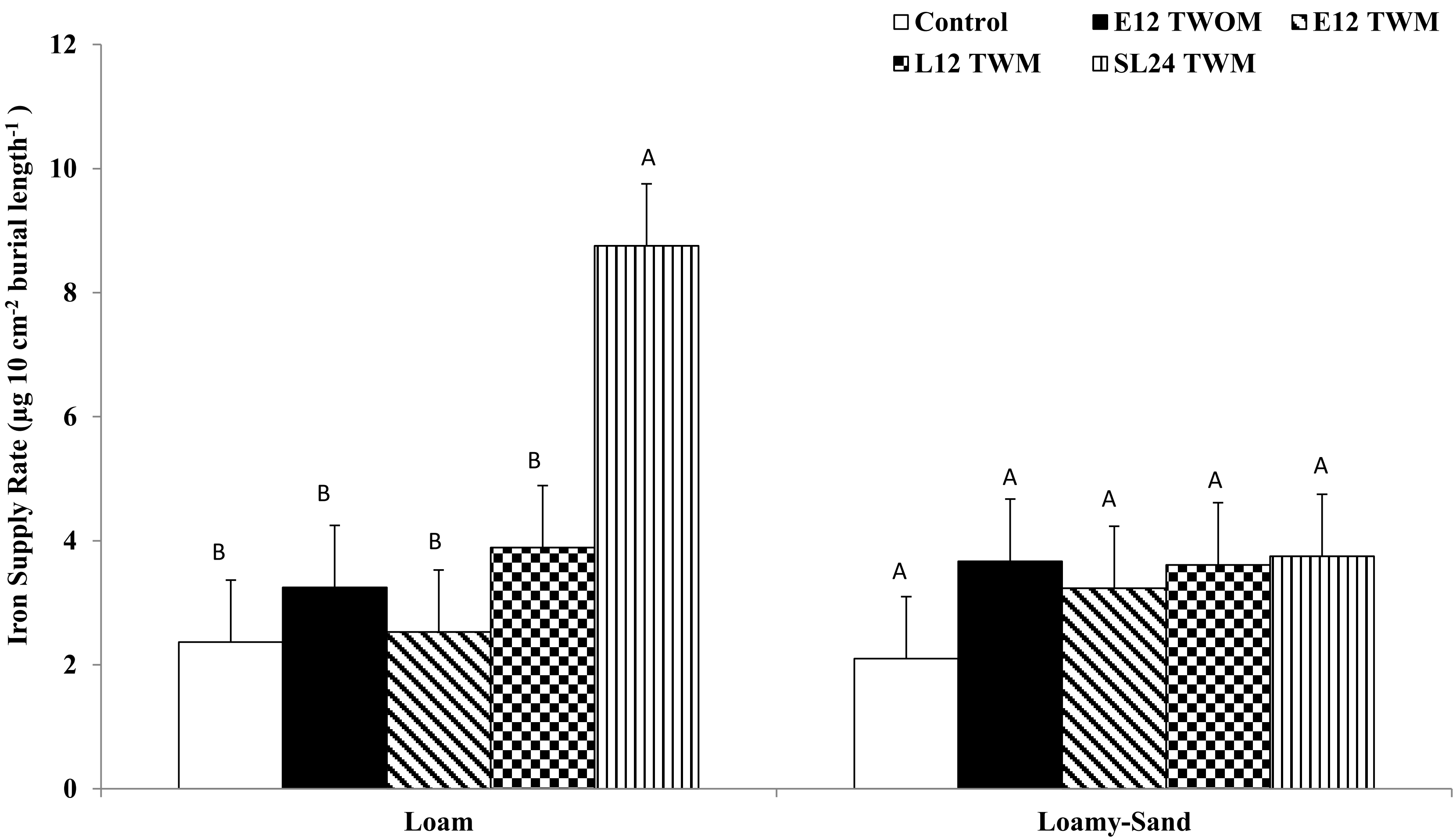

Figure 2–15. Comparison of iron (µg 10 cm^{-2} 18 $weeks^{-1}$) in 2016 in select treatments by ecosite.

Mean (n = 8) comparative supply rates of available iron (µg 10 cm^{-2} 18 $weeks^{-1}$), shown separately by ecosite, among various traffic treatments, as indicated by PRS® probes installed during the 2016 growing season with SEM (± 1.0 µg 10 cm^{-2} 18 $weeks^{-1}$). Within an ecosite, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial lengths of 18 weeks in 2016. See Table 3–1 for treatment definitions.

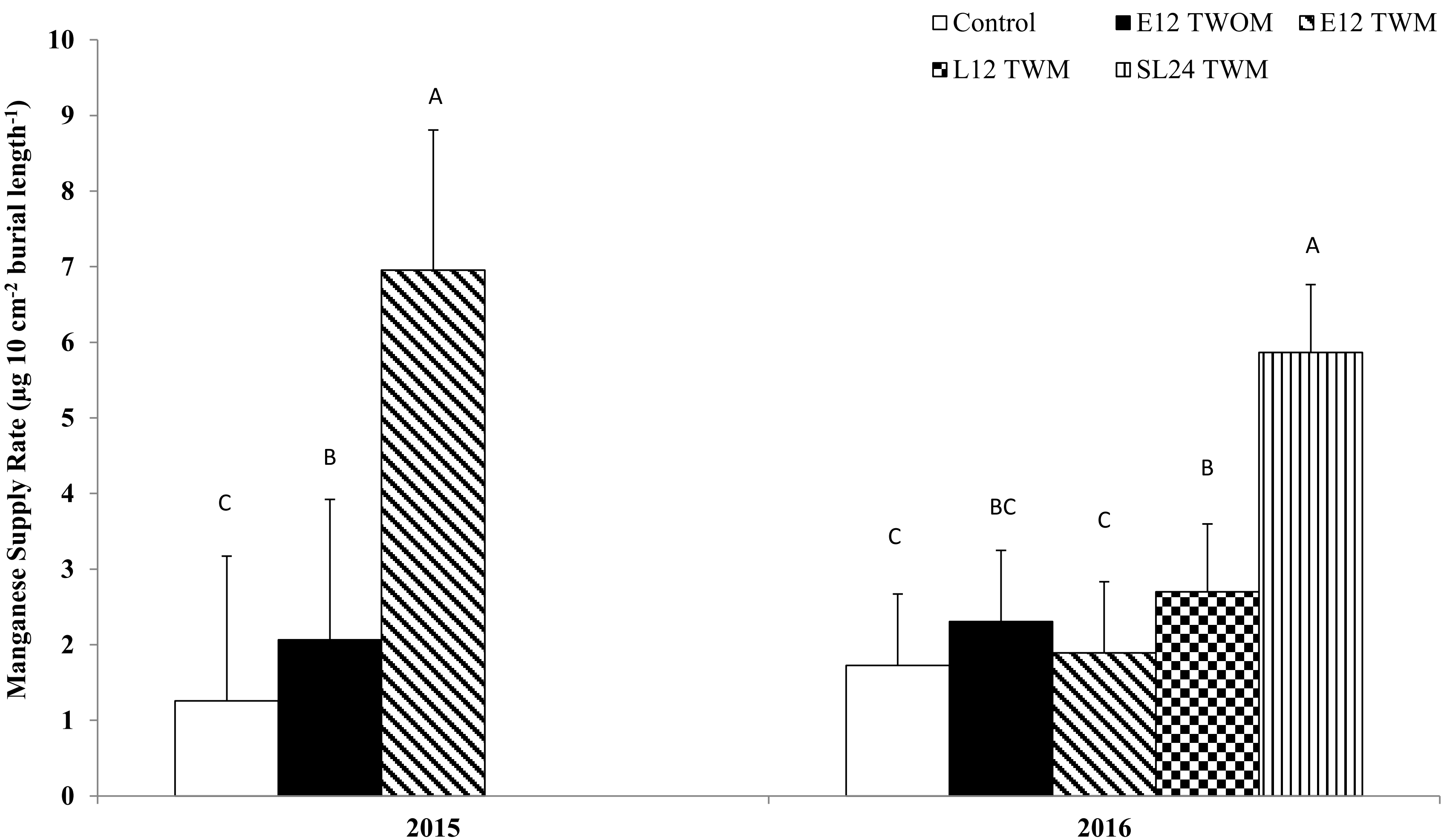

Figure 2–16. Comparison of manganese (µg 10 cm^{-2} burial $length^{-1}$) in selected treatments in 2015 and 2016.

Mean (n = 16) comparative supply rates of available manganese (µg 10 cm^{-2} burial $length^{-1}$), among various traffic treatments in each 2015 and 2016, as indicated by PRS® probes installed during each growing season, with SEM (± 1.9 and ± 0.9 µg 10 cm^{-2} burial $length^{-1}$, respectively). Within a year, treatments with different letters differ ($p < 0.05$). PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment definitions.

Chapter 3: Effects of Access Mats and Industrial Traffic on Vegetation

3.1 Introduction

Grasslands, comprised of native perennial grasses and forbs, evolved under disturbances such as drought, wildfire, and grazing, into ecosystems that fully occupy the rooting zone of the soil. However, modern industrial activities can be detrimental to these systems and in particular vehicle traffic can cause lasting impacts on vegetation. The use of access mats to mitigate these effects has been widely adopted by industry, but few studies have examined their benefits or refined their recommended application and use.

During industrial infrastructure construction on grasslands, direct damage from vehicle traffic can crush or tear vegetation (Althoff et al. 2007, Kestler et al. 1996, Palazzo et al. 2005, Retta et al. 2013), and facilitate the entry and therefore invasion of invasive plant species (Althoff et al. 2007). One pass can be sufficient to crush vegetation (Grantham et al. 2001) while multiple passes and wheel turns can further increase damage (Anderson et al. 2007, Ayers 1994, Grantham et al. 2001, Retta et al. 2013). Construction on dry or frozen soil generally reduces damage to vegetation and soil (AEP 2016a, Althoff and Thien 2005, Braunack 1986, Desserud et al. 2010, Dickson et al. 2008, Gao et al. 2012, Hamza and Anderson 2005, Raper 2005, Tarawally et al. 2004, Thurow et al. 1996, Voorhees et al. 1986), and is therefore recommended as a best management practice. However, large construction projects often require prolonged timelines to complete, with construction on less than ideal conditions depending on the season of occurrence. Creative application of technologies from other sectors of the industry has therefore led to the use of access mats as temporary roads and platforms during construction on grasslands in order to extend the window for construction to occur.

Where construction must occur during the growing season, wooden access mats are recommended as an alternative to equipment travel on bare ground (AEP 2016b). Mats may extend the timeframe available for construction, protect the environment (AEP 2016a, AEP 2016b, Gramineae 2013, Howard and Stroble 2008, Rushing and Howard 2011), provide a safe (i.e., firm and stable) work area for active construction (Howard and Stroble 2008), and allow for increased traffic passes (Howard and Stroble 2008, Rushing and Howard 2011, Rushing and Tingle 2009, Schweitzer 1996). Most previous studies conducted on mats have focused on the performance and durability of mats (Anderton and Gartrell 2005, Doyle et al. 2014, Gartrell et al. 2009), with one study, which produced multiple reports, focused on the recovery of vegetation after construction (Dollhopf et al. 2007, McWilliams 2008 (thesis), McWilliams et al. 2007, Mitchem et al. 2009) and all other studies had mats placed completely or partly in the dormant season. Industrial activities during the growing season may increase the negative effects on vegetation (Liddle 1974).

Grasslands provide important habitat and forage for domestic livestock and wild ungulates. Industrial construction on grasslands can impact forage quantity and quality (Unger and Kaspar 1994), crush vegetation (Althoff and Thien 2005), and compact soil (Anderson et al. 2007) which increases soil bulk density and penetration resistance, and in in turn impacts plant root growth (Unger and Kaspar 1994). Mats may prevent soil compaction and rut formation (see Chapter 2). Mats may alter the main environmental factors controlling plant growth: light, temperature, soil water, nutrients and gas exchange (Woolhouse 1983). The impacts to above ground biomass will vary with the duration of mat placement (Dollhopf et al. 2007). The length of time a plant species can withstand mat coverage, which intercepts solar radiation and prevents plants from producing photosynthates, depends on stored carbohydrates reserves (Biligetu and

Coulman 2011) and associated species tolerance to such stress, as well as the period of regrowth before being subjected to additional stresses. Traits such as quick regrowth, linked to the amount of non-structural carbohydrate stores (Lardner et al. 2003), will likely affect how quickly plants recover from mat deployments. Long duration mat deployment may create conditions similar to that caused by grazing animals, where above ground plant biomass is removed, which results in increased surface and subsoil temperatures, as well as increased wind speed at the soil surface, all of which increase evaporative conditions (Adams et al. 2013). Traffic induced soil compaction also alter the ability of vegetation to access water and nutrients, and facilitate gas exchange (Gao et al. 2012, Hamza and Anderson 2005, Liddle 1974). Isolated, crushed, or broken roots will die and decompose. Ultimately, damage to plants and associated decomposition differ based on root type (Coffin and Lauenroth 1990) and location depth (Chang et al. 2016, Dormaar and Willms 1993).

Season of mat deployment may also impact plant survival of underlying vegetation. Dormant plants in winter or late summer (i.e. after the primary growth period) may be less affected by mat placement as active growth has stopped. Conversely, mats placed on actively growing vegetation may coincide with critical periods of low carbohydrate reserves (usually spring green-up) although this will vary with vegetation type and the exact phonological development of the species (i.e., C_3 compared to C_4 grasses), or crush elevated meristematic tissues. The latter increases damage to plants, and under etiolated (i.e., light extinction) conditions, causes plants to deplete stored carbohydrates. Tolerance to stresses imposed by mat deployment, such as reduced water infiltration and impeded interception of solar radiation, will vary by species and specific plant traits like relative growth rate (Gianoli and Salgado-Luarte n.d.). Tolerance to shade has been positively associated with a long leaf life-span, and negatively to high photosynthetic capacity and leaf biomass in woody plants of the northern hemisphere (Hallik et al. 2009); as such, plants with these traits may suffer more damage when subject to matting. In contrast, the tolerance of grassland species to an extended absence of light is not well known.

Traffic imposed disturbance can reduce total plant cover and create shifts in plant community composition (Althoff et al. 2009). If whole-scale community changes occur under mats, such as if plants in established communities die off under mats, then revegetation may not be able to occur from remaining vegetative bud banks of the pre-existing community (i.e. via the plant crown or root buds) (Aguilera and Lauenroth 1993). In this case, revegetation would then need to occur from the remaining persistent seed bank and/or above-ground seed entry (Desserud et al. 2010), or rhizomatous/creeping root encroachment from adjacent intact communities (Althoff et al. 2009). Overall, this process is often associated with widespread vegetation changes from a community dominated by desirable late-seral species, to one comprised of early colonizers, invasive or weedy species. The latter in turn, may have lower forage value and pose a risk of further spread into adjacent native grasslands (Adams et al. 2013). Seedbanks of native grasslands often contain seeds of non-native species (Willms and Quinton 1995) which often dominate following soil disturbances (Desserud et al. 2010), and therefore carry a risk of heightened community change under severe disturbance of current vegetation (e.g., under matting) (AEP 2016a, Althoff et al. 2009, Desserud et al. 2010, Milchunas et al. 2000, Wilson 1988).

Our overall research goal was to assess wooden access mat use efficacy to mitigate the direct effects of heavy industrial traffic on DMGP vegetation, and thereby prevent undesirable alterations to vegetation, including forage biomass and quality, as well as impacts to plant available soil nutrients. Specific study objectives were to:

1) Quantify the magnitude and duration of impacts of industrial traffic occurring with and without access mats on DMGP vegetation within loamy and loamy-sand ecosites, and
2) Assess whether these effects vary in magnitude and duration with the season and duration of mat placement.

Results of this study are expected to enhance our understanding of industrial traffic impacts on arid native grasslands, as well as establish whether, when, where, and how access mats may be used to reduce the impacts of heavy industrial traffic, thereby assisting in the refinement of BMPs for industrial construction activity.

3.2 Materials and Methods

3.2.1 Site Description

The Eastern Alberta Transmission Line, a 500 kVA direct current power line, was constructed from 2013 to 2014 by ATCO (Alberta Transmission Company) to transfer power from the *Heartland* industrial area NE of Edmonton to remote regions 400 km away in SE Alberta. Approximately 9 km of this line crossed the University of Alberta's 4,900 ha Mattheis Research Ranch located in the Brooks Plain of the Dry Mixedgrass Natural Subregion in SE Alberta. This area receives 354 mm of mean annual precipitation and has a daily temperature of 4.2°C (Downing and Pettapiece 2006). Landscapes within the same ecosites impacted by the powerline were evaluated and four study sites were established in April of 2015. These sites provided ideal representative locations to assess, in a highly controlled manner, how disturbances from industrial traffic alter the plant community and associated biomass in this environment. Sites were chosen to evaluate effects on the most divergent soil textures on the ranch that were impacted by mats during construction, and included both loamy and loamy-sand soils. Sites were chosen based on low internal variability of soil texture, topography, and plant community composition.

Located on stabilized sand dunes in the center of the research ranch, site 1 (50°52’29.59”N; 111°55’40.14”W) and site 2 (50°52’19.21”N; 111°54’37.45”W) had well-drained loamy-sand textured Brown Chernozemic soils (Figure 3–1). These soils had for site 1 pH = 5.9 (± 0.06), EC = 70.7 (± 5.0) µS/cm, and organic matter content = 2.7 (± 0.1) % and for site 2 pH = 5.8 (± 0.06), EC = 68.3 (± 4.7) µS/cm, and organic matter content = 2.6 (± 0.1) %. *Calamovilfa longifolia* (Hook.) Scribn. dominated these plant communities, with *Hesperostipa comata* (Trin. And Rup.) and *Bouteloua gracilis* (Willd ex Kunth) Lag. Ex Griffiths as sub-dominants. Blocked by ecosite soil types for analysis, sites 1 and 2 had similar vegetation and soils, being comprised of 77 % sand, 15 % silt, and 8 % clay for site 1 and 76 % sand, 18 % silt, and 6 % clay for site 2.

Located in the NE corner of the research ranch, site 3 (50°54’30.98”N; 111°53’37.85”W) had a well-drained loamy textured Brown Chernozemic soil (Figure 3–1), and site 4 (50°54’5.69”N; 111°52’58.55”W) was on an imperfectly drained loamy textured Brown Chernozemic soil (Figure 3–1). These soils had for site 3 pH = 6.0 (± 0.05), EC = 97.0 (± 5.5) µS/cm, and organic matter content = 4.3 (± 0.1) % and for site 4 pH = 5.9 (± 0.04), EC = 109.1 (± 6.6) µS/cm, and organic matter content = 3.2 (± 0.1) %. Site 3 had *Bouteloua gracilis* and *Koeleria macrantha* (Ledeb.) Schult. as dominant vegetation, with *Hesperostipa comata* and *Pascopyrum smithii* (Rydb.) Á. Löve as sub-dominants. In site 4, *Koeleria macrantha* and

Bouteloua gracilis were dominant, with *Hesperostipa comata* and *Pascopyrum smithii* as sub-dominants. Blocked by ecosite type for analysis, sites 3 and 4 had similar vegetation, with soils comprised of 37 % sand, 49 % silt, and 14 % clay for site 3 and 36 % sand, 50 % silt, and 14 % clay for site 4.

3.2.2 Experimental Design and Treatments

On each of the four sites, each of which measured approximately 50 × 100 m in size, a randomized complete block (RCBD) design was implemented in a chevron pattern (see Figure 3–2). Four blocks were set up within each site, as two rows paired on either side of a central travel lane. Each block contained 11 unique treatments for a total of 44 plots per site (Figure 3–2), and 176 plots overall. Plots were 3 × 8 m in size, the approximate size of an access mat and allowed for a loader to travel over and clear the mat, with a 2 m buffer between adjacent plots. To fully evaluate industrial traffic effects, paired treatments were assessed on DMGP, with both heavy traffic imposed directly on the grassland without protection by mats (known as traffic without mats: TWOM), and traffic imposed with the underlying protection of access mats placed on the grassland surface (known as traffic with mats: TWM). Mats were 2.4 × 4.2 m in dimension, and made of three interlocking layers of wooden boards, usually spruce. Installation and removal of mats occurred using a wheeled loader at the start and end dates of each treatment. Mats weighed approximately 700 kg and were selected for uniformity at the study start with no missing or damaged boards.

Seasonality [Early (E), Late (L), or Season Long (SL)] and disturbance duration (weeks: 6, 12 or 24) were combined to create five treatment combinations, which when combined with TWM or TWOM, created 10 unique treatments in each block (Table 3–1). An additional Control (i.e. non-treated) plot was included within each block. Early treatments started in 2015 on 30

April and ended either on 10 June (after 6 weeks) or 22 July (after 12 weeks). Late season treatments started in 2015 on 22 July and ended on 3 September (after 6 weeks) or 15 October (after 12 weeks). Season long treatments for the entire growing season started in 2015 on 30 April and ended on 15 October (after 24 weeks); Table 3–1 summarized the treatments conducted during 2015.

For all but the non-treated Control plots, industrial traffic was applied similar to that occurring with actual field construction of the adjacent high voltage transmission line. This tested both direct traffic impacts on DMGP in TWOM plots, and facilitated comparison of grassland responses in TWOM to TWM plots. Treatment plots were driven over eight times on both the first and last day of each specific treatment period by a similarly weighted loader (either Komatsu Wheel Loader WA200-5, or Caterpillar Wheel Loader 930K, each weighing approximately 10 – 13 tonne) with a 50 cm wheel width. No additional weight was carried when applying traffic treatments. To simulate typical traffic conditions, the loader was driven with wheels from one side of the loader centered over the middle of the plot (with or without a mat), thereby applying approximately half the loader's weight to each plot. Mat roads are typically at least two mats wide (i.e. 4.8 m wide) to allow for vehicles to pass; thus, in our treatment plots the one side centered loader effectively simulated typical field conditions for heavy equipment traffic. Overall, 176 treatment plots facilitated comparisons of non-disturbed Control plots to wheeled industrial traffic, with and without mats, across five different combinations of treatments times and duration, on each of two ecosites (loam and loamy-sand).

3.2.3 Vegetation Assessment

Forage quantity and quality are key metrics to evaluate the grazing potential of grasslands, including in relation to ongoing land use. Forage quantity, measured as aboveground biomass, was determined and further split into functional groups (graminoids: grasses and grass-likes; native forbs; introduced forbs: introduced, annual, ruderal and weedy forbs; and litter). Forage quantity, measured at peak standing biomass, was assessed in all treatments plots, between August 1 – 12 in 2016, and July 11 – 20 in 2017. In each year, an aggregate area of one meter squared was sampled in each plot by clipping four 0.25 m^2 quadrats (50 cm × 50 cm) from areas within the plot that had as little soil disturbance as possible and no previous vegetation harvested.

Root biomass was also determined for each of the Control, E12 TWOM, and E12 TWM treatments in 2015, and for all treatments in 2016. Root biomass was determined via root gravimetric weight. In 2015, on July 29th, two soil cores (3.175 cm wide by 7.5 cm deep) were collected from a localized area (30 cm diameter) free of previous sampling from each plot and combined, with a total volume of 118.76 cm^3. In 2016, on July 14th, two soil cores (4.7 cm wide by 7 cm deep) were collected from a localized area (30 cm diameter) free of previous sampling influence from each plot and kept separate; each core volume was 121.45 cm^3. Soil cores were promptly dried and broken apart by hand, after which roots were removed, washed, dried, and weighed.

3.2.3.1 Forage Quality Characterization

Crude protein (CP) and digestibility were determined for the Control, E12 TWOM, and E12 TWM treatments, for each of the major vegetation biomass groups (graminoids, native forbs, and introduced forbs). After harvest and weighing, samples were ground to 0.1 mm using a Resch ball mill (SPEX Sample Metuchen, NJ, USA). Nitrogen concentration was determined from combustion of 5 mg pellets of material from each sample and high temperature conversion by a FLASH 2000 HT Elemental Analyzer for Isotope Ratio Mass Spectrometry (Thermo

Scientific, Waltham, Massachusetts) (Van Soest et al. 1991). Calibration was done daily with known standards of nitrogen and carbon content using orchard grass and tobacco leaves (Standards #502-055 and 502-082, respectively). Standards were included after every 10 sample and used to correct any drift in readings. Duplicate samples were run for each sample and results averaged prior to further analysis. Mineral nitrogen levels were multiplied by 6.25 to estimate crude protein concentrations (Newman et al. 2006). Finally, crude protein (biomass) yield (CPY) was calculated for each vegetation sample and plot by multiplying the biomass of each component by the proportional crude protein concentration (CP/100).

Digestibility of each vegetation sample was determined by acid detergent fiber (ADF) analysis using an A200 Fiber Analyzer (ANKOM Technology, Macedon, New York) (Ball et a. 2001). ADF is the value of relatively non-digestible fibrous portion of forage remaining after digestion with sulfuric acid; higher ADF forages represent lower digestible energy (Newman et al. 2006).To determine ADF, 0.5 g of dried ground sample was sealed in a F57 filter bag (25 micron porosity; ANKOM Technology, Macedon, New York) and digested with 8% sulfuric acid and cetyle trimethylammonium bromide (CTAB) for 60 minutes. Plant material remaining in the filter bag after digestion is predominately (non-digestible) cellulose and lignin, and used to determine, via gravimetric weight, non-digestible plant material. An empty sealed bag was included in each run to indicate the mass loss from bags and used for correction of each batch of samples.

Live vegetation biomass, total crude protein yield, and the proportion of live biomass comprised of introduced forbs, were independently regressed against total nitrogen supply (chapter 2) within the treatments for which the latter data were available, separately for each soil type.

3.2.4. Data Analysis

Vegetation biomass and forage quality data were assessed with analysis of variance (ANOVA) in SAS 9.4 (Carlsbad, NC, USA) with mixed models (PROC MIXED). Normality was tested by a Shapiro-Wilks test, and a studentized test used to assess normality of residuals and confirm equality of variances among treatments. If not normally distributed, data were transformed to achieve normality. A square root transform was applied to grass and litter biomass for 2016 and 2017. A log10 transform was done on introduced forb and native forb biomass for 2016 and 2017, introduced forb crude protein and crude protein yield. ADF values for grass, introduced forb and native forb; grass crude protein and crude protein yield, native forb and total crude protein yield met assumptions for parametric analysis and did not require transformation.

For the analysis of all variables, ecosite type (namely soil texture: loam or loamy-sand) was a random effect and the combination of disturbance treatments of traffic (TWM and TWOM), season of application (E, L or SL) and duration (weeks: 6, 12, 24) were considered fixed effect, with year treated as a repeated measure. Duplicate locations within ecosite type, and replicate blocks within a site ($n = 4$ per treatment) were random effects. All possible interactions were examined among ecosite, treatment, and year. Significance of all main effects and interactions was set at $p < 0.05$, unless stated otherwise.

Individual treatment least-square means within significant data sets were subsequently compared with a post-hoc Tukey's test. To simplify treatment comparisons given their complex structure, all traffic and matted treatments were initially compared against the Control to determine the effects of direct traffic and traffic taking place on mats, respectively. Next, additional pairwise comparisons were conducted between the pairs of TWM and TWOM treatments within each season × duration combination to assess whether mats mitigated or exacerbated the effect of wheeled industrial traffic, with significance noted at $p < 0.05$. All data presented are based on original means, with analysis conducted on transformed data where applicable, as such presented means occasionally do not show the significant results.

3.3 Results

3.3.1 Biomass Responses

A summary of the ANOVA results for the biomass response of grasses, litter, and both introduced and native forbs is shown in Table 3–2. Means presented in Tables 3–3 to 3–7 are untransformed means. Tukey's letters and pairwise comparisons are based on transformed means where applicable, as such presented results may appear non-significant while there is a significant difference of transformed means and comparisons.

Grass biomass had significant interactions of ecosite × treatment ($F_{10, 152} = 4.43$; $p < 0.0001$), ecosite × year ($F_{1, 154} = 6.94$; $p = 0.0093$), and treatment × year ($F_{10, 154} = 3.30$; $p = 0.0007$) (Table 3–2). For ecosite × treatment results, relative to the Control plots, grass biomass was unaffected by all the TWOM and TWM treatments on loamy ecosites, as well as the TWOM treatments on loamy-sand ecosites (Table 3–3). In contrast, the TWM treatments led to a reduction in grass biomass, but only within the E6 and SL24 treatments ($p < 0.0001$) on loamy-sand soils. Grass biomass declined by as much as 79% in the SL 24 treatment. Additionally, these declines in biomass occurred relative to both the Control and the paired TWOM comparison (Table 3–3); all other TWM treatments (E12, L12, and L6) were similar to the Control (Table 3–3). Ecosite × year interactions revealed that grass biomass was generally greater ($p < 0.0001$) in 2017 (1266.3 kg ha^{-1}) than 2016 (892.7 kg ha^{-1}) on loam soils, while remaining similar ($p = 0.313$) between 2016 (1235.3 kg ha^{-1}) and 2017 (1383.8 kg ha^{-1}) on loamy-sand ecosites (pooled SEM = ± 177.0). Treatment × year effects are shown in Table 3–4. During both 2016 and 2017, all TWOM treatments were similar to the Control (Table 3–4). In contrast, distinct negative effects of mats were evident on grass biomass during both years, particularly the SL24 treatment, where reductions of up to 61% occurred. In 2016, all treatments involving early season mat placement (E6, E12, and SL24) of the TWM had less grass biomass than the Control. In 2017 residual negative impacts of the SL24 TWM showed a continued reduction in grass biomass (-48%), with all other treatments (E6, E12, L6 and L12) now similar to the Control (Table 3–4). However, pairwise comparison of the TWOM and TWM treatments in 2016 indicated that matting within both the SL24 and E12 TWM treatments led to lower grass biomass compared to the SL24 and E12 TWOM ($p < 0.001$). In 2017, grass biomass remained lower due to matting compared to the direct wheeled traffic only within the SL24 treatment (Table 3–4).

For litter biomass, the three-way interaction of ecosite, treatment and year was significant ($F_{10, 154} = 2.24$; $p = 0.018$). Litter biomass on loam ecosites in both 2016 and 2017 did not exhibit any differences between the Controls and any of the TWOM and TWM treatments, nor were there differences between TWOM and TWM pairs (Table 3–5). On loamy-sand ecosites in 2016, while all TWOM treatments were similar to the Control, the E12 TWM treatment had more litter (by 83%) than the Control while all other TWM treatments remained similar to Control. On loamy-sand ecosites in 2017, all TWOM treatments were similar to Control, while the SL24 and E12 TWM had as much as 66% less litter mass compared to the Control (Table 3–5). Paired comparisons in 2016 indicated that only the E12 TWM treatment had more litter than the E12 TWOM, while all other pairs were similar; in 2017, the SL24 TWM treatment had less litter compared to the SL24 TWOM treatment, with no other differences (Table 3–5).

Introduced forb biomass also demonstrated a three-way interaction of ecosite, treatment and year ($F_{10, 154} = 6.22$; $p < 0.0001$). Within loam ecosites during 2016, introduced forb biomass in all TWOM treatments remained similar to the Control (Table 3–6). In contrast, the SL24 TWM treatment led to a 12-fold increase in the biomass of introduced forbs relative to the Control. Additionally, the E6 TWM treatment led to a four-fold increase in introduced forbs, with all other TWM treatments similar to the Control (Table 3–6). Paired comparisons showed that the SL24 and E6 TWM treatments led to greater biomass than their direct traffic counterparts (SL24 and E6 TWOM), while all other pairs were similar on loam ecosites in 2016 (Table 3–6). One year later on loam soils in 2017, introduced forb biomass remained similar across all 11 disturbance treatments (Table 3–6).

On loamy-sand soils in 2016, the SL24 disturbance was the only TWOM treatment producing greater introduced forb biomass (by 4.5–fold) relative to the Control (Table 3–6). Introduced forb biomass increased compared to the Control in response to all the early applied mat treatments (i.e., the E6, E12 and SL24 TWM treatments) by 4–19–fold, with the greatest increase taking place in the SL24 TWM, and the smallest in the E6 TWM. In contrast, the late applied treatments (L6 and L12 TWM) were similar to the Control (Table 3–6). Pairwise comparisons of the TWOM and TWM treatments in 2016 on loamy-sand soils again indicated the early applied TWM treatments (E6, E12, and SL24) had greater introduced forb biomass than their paired TWOM counterparts, while introduced forb biomass remained similar among the late applied treatments (L6 and L12). By 2017 within the loamy-sand ecosites no differences were evident in the biomass of introduced forbs among all treatments, including pairwise comparisons of the TWOM and TWM treatments (Table 3–6).

Native forb biomass was affected by a year × treatment interaction ($F_{10, 154} = 3.10$; $p = 0.001$). During 2016, most of the TWOM treatments were lower (all but the E12 TWOM) in native forb biomass relative to the Control. Within TWM treatments however, both the E6 and SL24 TWM were similar to the Control, with all other TWM treatments (E12, L6, and L12) lower in native forb biomass (Table 3–7). In pairwise comparison to the TWOM treatments, only the SL24 treatment differed, with matting leading to a 97% increase in native forb mass during 2016 (Table 3–7). In 2017 among all the direct wheeled traffic treatments, only the L6 TWOM regime led to a reduction in native forb biomass compared to the Control. Among the matted treatments, native forb biomass was 81% greater in the SL24 TWM treatment compared to the Control, while being 53% lower in the L6 TWM treatment relative to the Control; all remaining treatments (E6, E12, and L12) were similar to the Control (Table 3–7). Pairwise comparison in 2017 indicated only the SL24 TWM regime was greater than the SL24 TWOM (Table 3–7).

Root biomass was not impacted by any disturbance treatment during 2015 ($p \geq 0.21$), but was impacted by the main effect of treatment ($F_{10, 152} = 4.34$; $p < 0.0001$) in 2016 (Table 3–8). In 2016 both the E6 TWM and TWOM paired, as well as the L6 TWM, had increased root biomass compared to the Control, whereas the SL24 TWM had reduced root biomass (Table 3–8). Pairwise, except for SL24 TWM and TWOM, all treatments had equal root biomass (Table 3–8).

3.3.2. Herbage Quality

Crude protein concentration (CPC) of both grasses and introduced forbs were influenced by the interaction of ecosite × treatment (Table 3–9). While grass CPC did not differ among treatments within the loam ecosites, on loamy-sand ecosites the E12 TWM treatment produced higher levels of CPC in grasses compared to both the Control and E12 TWOM treatments, the latter of which were similar (Table 3–9). Introduced forb CPC again did not differ among treatments within the loam soils, but was lower in biomass harvested within the E12 TWM treatment than both the Control and E12 TWOM. Native forb CPC varied between ecosites but not the disturbance treatments (Table 3–9). Native forb CPC values were 10.1 and 9.0% for the loam and loamy-sand sites, respectively, with 0.6 % SE ($F_{1, 2} = 25.79$, $p < 0.0001$).

When observed CPC values were combined with biomass to derive crude protein yield (CPY), grass CPY did not differ in relation to any factor analyzed ($p \geq 0.16$; Table 3–10). Introduced forb CPY was influenced by the interaction of ecosite × treatment, with no differences on loam soils (Table 3–10). In contrast, on loamy-sand soils both traffic treatments altered introduced forb CPY relative to the Control, but in divergent ways. While direct traffic led to 50% less introduced forb CPY, matting led to a 4.4 fold increase in this metric (Table 3–10). Native forb CPY was impacted by the main effect of disturbance treatment (Table 3–10), although post-hoc tests did not provide much clarification: in general, native forb CPY tended to decline to a greater extent due to matting than traffic. This results in the combination of biomass and CPC, biomass declined under both disturbance treatments although CPC was not affected, as such the CPY reflects the change in biomass, as described above. Total CPY of vegetation, including the combination of grass, introduced and native forb CPY was affected by the interaction of ecosite × treatment (Table 3–10). Differences in total CPY were only evident in loamy-sand soils, wherein the E12 TWM treatment had greater CPY than both the Control and E12 TWOM (Tables 3–10).

Non-digestible grass fiber content, as determined by ADF concentrations, was significantly influenced by the interaction of ecosite × treatment (Table 3–11). While grass ADF did not differ among treatments on loam soils, on loamy-sand soils the E12 TWM led to lower ADF compared to the Control (Table 3–11). Within introduced forbs, ADF levels varied among treatments, being greater in the E12 TWM treatment compared to both the E12 TWOM and Control (Table 3–11). Native forb ADF analysis showed a significant interaction of ecosite × treatment; although the data for native forbs followed a pattern similar to that of grasses (Table 3–11), post-hoc tests suggested minimal differences.

3.4 Discussion

3.4.1 Biomass Responses

Direct wheeled traffic had limited impacts on biomass production, as the traffic was applied in limited amounts with plants able to recovery with full access the sunlight and any available water. Compare this to mats, where after traffic was applied the mats would still be in place blocking sunlight and rain, preventing recovery until the mat was removed. The soil compaction described in chapter 2 on the direct traffic treatments may have even acted as catchments for rain aiding in recovery in this moisture limited environment.

Mats in place for short time periods (6 and 12 weeks) did not impact grass biomass more than one year after treatment application. Grass biomass was also negatively impacted to a greater extent during the first year of recovery on loamy-sand soils and within the early applied disturbance treatments. In contrast, two years after treatment application the only lasting changes in grass biomass were evident from season long mat placement, showing the resiliency of these ecosystems when recovery is possible. Maintenance of native perennial grasses is important as most recruitment of tillers (99%) are from buds and not from seed germination and establishment (Ott and Harnett 2015 and Russel et al. 2015), and season-long placement resulted in loss of perennial grasses and prevent revegetation from crown tillers. Early season treatments impact early season C_3 species, such as western wheatgrass and needle-and-thread grass, more than late season C_4 species, such as blue grama grass, which would have remained dormant under the mats while the soil was still cool in the early season. C_4 species require warmer soil temperatures and the matting acted as insulation prolonging winter cold temperatures; C_4 species came up after the soil was able to warm up with solar radiation. This would explain why early season traffic and mats caused more to damage early growing cool-season grass species (such as western wheatgrass, needle and thread) as compared to warm-season species (blue grama), which would remain largely dormant through much of the early season treatments. As grass cover declines with increased cumulative disturbances (Milchunas et al. 2000), the importance of maintenance of grasses increases, as grasses maximize water infiltration and prevent erosion (Hamza and Anderson 2005). Timing of traffic will also play a role in regulating the level of impact as Althoff and Thien (2005) found that traffic on wet soil significantly reduced grass biomass compared to non-traffic areas. Liddle (1974) found that the root mass beneath tussocks of bunchgrasses was highly elastic and cushioned shoots when compressed by vehicle traffic, providing an additional potential explanation for recovery of grasses under direct traffic treatments.

Once mats were removed plants likely began to regrow from rhizomes (Althoff et al. 2009), likely triggered by plant stress or from damaged crowns (Liddle 1974) in short duration mat placement (6 Weeks) (personal observations). Vegetation re-establishment from the seed bank was also more likely in matted treatments, once the impediment to solar radiation and precipitation were removed and favorable growing conditions restored. Moreover, the latter could have been favored by increased seed to soil contact (Raper and Kirby 2006), abundant moisture found under the mats (Chapter 2), and possibly soil warming. Blue grama grass (*Bouteloua gracilis*), a warm-season grass, was visually observed to have increased inflorescences, seed heads, and biomass on the early short (E6) duration mat placements, although these seed heads were delayed compared to the Control areas by roughly six weeks (personal observations). The mats may have acted as insulators delaying warming of soil until removal, along with the increased moisture would explain the delayed growth and increase inflorescences in the C_4 grasses. Aguilera and Lauenroth (1993) found that reduced below ground root competition favored number of adventitious roots of *Bouteloua gracilis* seeding. Placement of mats in the spring, coupled with a long winter and late spring warm-up, may have kept the plant community in an extended state of dormancy.

Introduced forb biomass increased during the first season after disturbance treatments were applied, with the greatest amounts on mat treatments where previous established native perennial grass community was most visually reduced. A flush of annuals weeds and native forbs is known to occur after soil disturbance (Gramineae 2013) as was seen in this experiment on treatments twelve weeks or longer in duration, regardless of placement season, and is similar to the investigation by Dollhopf et al. (2007) in their study on construction mats. Annual and introduced forb cover is known to temporarily increase with increased disturbance in grasslands, as perennial forb, grass and shrub cover decrease (Milchunas et al. 2000). As many (though not all) introduced forbs are annuals, recovery of these species would occur from the seed bank following the disturbance, and would not rely on the survival of propagules in the bud bank.

Litter biomass was only impacted in the first year after treatment application within the early applied 12 week duration mat treatments on loamy-sand soils. Environmental conditions under mats would have been dark and moist, with compressed vegetation in contact with the soil surface, and reduced moisture and nutrient demand from plants unable to photosynthesize in the absence of light. The environment under mats would increase decomposition of litter given sufficient time, as seen on the loamy-sand season long mat treatment. The initial increase in litter, on loamy-sand early applied 12 week mat treatment, would stem from the compression of the abundant dead standing dead plant material that was compressed under the mat but did not have sufficient time to decompose. Two years after treatment litter was reduced on loamy-sand soils on the early applied 12 week and season long 24 week mat treatment. Notably, treatments with reduced litter in the second year coincided with the highest levels of introduced forb biomass the previous year and declines in grasses biomass. Introduced forbs were largely composed of early growing ruderal forbs that shed their leaves by mid-summer. The decomposition of litter under mats placed on moist soil early in the year and changes in dominance of functional groups, from grasses with leaves that stay attached to introduced forbs with readily shedding leaves, would account for the reduced litter. Litter, as noted by Adams et al. (2013) and Deutsch et al. (2010), is vital in the DMGP as it regulates soil temperature, reduces wind speed and evaporation, and conserves scarce moisture. Greater fluctuations of temperature were noted by Dormaar and Willms (1993) on semiarid grasslands with less litter cover. The forage biomass yields from late-seral and climax stage plant communities are more stable and produce adequate amounts of litter residue to conserve moisture (Adams et al. 2013). Production of biomass can be reduced by 60% due to litter removal (Willms et al. 1986), highlighting the important of litter and moisture conversation in the DMGP. Soils with higher sand content are known to be more sensitive to disturbances (Raper and Kirby 2006) due to their less cohesive nature (Braunack 1986) and easily erode if stabilizing vegetation is lost. On loamy-sand soils grass and root biomass decreased on the same treatments that experienced litter losses the following year, the litter was likely no longer held in place after the death and decomposition of plant roots.

Unlike introduced forbs, native forb biomass was reduced by both treatments with and without mats in the year of application, with the exception of the pair of early six week applied treatments and season long mat treatment. Native forbs were one of the few functional groups impacted by direct traffic effects. Direct wheeled traffic may have negatively impacted both the viability of native forb buds by crushing, and reduced their emergence from the soil due to compaction (see Chapter 2). Althoff and Thien (2005) found, as with this study, that traffic on dry soil significantly reduced forb biomass compared to non-traffic areas, as can be seen with in the late applied treatments, both direct traffic and mats having reduced biomass. Dickson et al. (2008) found forbs suffered immediate losses from surface traffic, with perennial species decreasing and annual species increasing, in this study only the early applied pair of direct traffic and mat and the season long mat treatments did not result in a decrease of native forb biomass. Dickson et al. (2008) further speculated that the deep root system of native plants may aid survival of traffic-induced soil damage compared to shallow rooted introduced species, the reduction in the pair of late applied six week treatment do not follow this finding. As most native forbs are perennial species in these grasslands, their recovery after disturbance will rely on the presence of viable propagules in the bud bank (i.e. plant crowns and root buds). In contrast to the direct traffic, matting led to increases in native forbs for up to two years. As this occurred only in the season-long treatment, it is likely that this response is in response to the reduction in other vegetation. Milchunas et al. (2000) also found that forb cover temporarily increased after traffic as grass and shrub cover decreased. Succession back to mid-grass dominated communities often starts with various forbs, including those of introduced and native origin (Adams et al. 2013). The functional group that suffered the most under direct traffic was native forbs, similar to previous research (Althoff and Thien 2005; Dickson et al. 2008; and Prosser et al. 2000);

although forbs with deep tap root can recover from the root (Coffin and Lauenroth 1990). Grasses would likely have suffered the loss of any culms that had extended at the time of traffic application, with new growth occurring from tillers of the damage plant (Coffin and Lauenroth 1988).

Root biomass was reduced on loamy-sand sites by the TWM treatments the year following treatment application. This loss of roots was likely due to the associated reduction in grass biomass. Detection of reduced root biomass would be from death and decomposition which would explain the reduction in the year after treatment application; Chang et al (2016) found the half-life of dead roots to be 135 days in the top 0-15 cm of soil, and much slower at 277 days in the 15-30 cm. Schweitzer (1996) examined construction in fragile wetlands with hardwood mat systems and found root systems were not compromised, with a short recovery of the area that had been under the mats. Unger and Kaspar (1994) noted that roots are not uniformly exposed to the same level of compaction and unimpeded roots can have compensatory growth. Where PR values changed but BD did not, roots may have declined at the very surface but increased below, leading to no net change in root mass. Dickson et al. (2008) in their study on traffic on grasslands offer another possible explanation, that native plants tend to have deeper root system that may help them to survive soil damage. Traffic applied in this study compressed the soil and created a visible depression but did not otherwise cause visible disturbances such as shearing or dig up the soil. Roots may have bent but not broken and survived the compacted, although growth may be restricted in the compacted soil (Liddle 1974).

3.4.2 Herbage Quality

In the first year of recovery matted treatments on loamy-sand soils had increased forage quality of grasses (CP, digestibility) while decreasing the quality of introduced forbs. Levels of

CPY typically mirrored the biomass responses, with high biomass levels of introduced forbs maximizing CPY despite decreased crude protein concentrations due to matting. Introduced forbs were weedy or annual species that grow early in the year and by the heat of summer were overly mature, and would explain the declining crude protein levels (Newman et al. 2006). In contrast, warm season grasses would be at their peak of forage biomass with high quality in mid-summer. Forage quantity and quality reflect the regrowth costs in plants after damage is sustained to aboveground biomass. As Biligetu and Coulman (2011) and Bokhari (1977) found, the energy to re-grow after defoliation comes from stored carbohydrates in plant stems and roots. Plants, especially grasses, have evolved to be grazing tolerant or intolerant, due to evolution with or without growing season grazing (Caldwell et al. 1981). Compared to grazing intolerant grass species, grazing tolerant grass species have higher photosynthetic rates, more vegetative tillers, fewer reproductive tillers, rapid tiller regrowth, and quicker mobilization of stored carbohydrates (Caldwell et al. 1981), which results in less cost to plants when leaf material is removed.

Introduced forbs CP values were extremely low, and suggest by the time sampling occurred in 2016, that these plants had essentially cured on the stem. The difference in timing of growth of C_3 and C_4 grasses would account for the increased crude protein values in grass on loamy-sand sites, as the grass would still be actively growing, not yet cured like the early growing introduced forbs. The loamy-sand sites would have seen more growth as the soil warmed, while the loam sites would have had cool season grasses growing early in the season, accounting for the difference in ADF, especially under mats that acted as soil insulators delaying warm up.

Regressions showed total live biomass and total crude protein yield were positively correlated to increased nitrogen supply rates on loamy-sand soils (chapter 2), but were slightly negatively correlated with increased nitrogen on loam soils (chapter 2). Great decomposition of vegetation resulted in more available nitrogen (chapter 2), which in turn translated into more biomass production following mat removal. The greater alteration of vegetation on the loamy-sand ecosites explains the higher vegetation responses on these loamy-sand ecosites. These finding suggest that factors of compaction which impact water infiltration and holding capacity (chapter 2) have a larger impact on biomass than nutrient releases. Notably, the proportion of biomass comprised of introduced species was positively associated with increased nitrogen on both loam and loamy-sand soils, with mat treatments expressing the greatest increase in biomass proportion with nitrogen increase and direct traffic and Control at similar although less amounts. Introduced vegetation, largely weedy and/or ruderal forb species, was likely able to germinate within the seed bank early in the spring and grow rapidly to opportunistically capitalize on the release of nutrients within the more disturbed treatments (Hooper and Vitousek 1998).

3.5 Conclusion

Direct traffic created localized soil compaction with limited impacts to vegetation, while mats mitigated the traffic caused soil compaction and had limited impacts to vegetation for short duration places or late season placements. Mats caused increasingly negative impacts to the vegetation, and litter, when in place all season long. The level of traffic in this study was vastly reduced compared to construction traffic on actual construction project; recommend use of direct traffic would not transfer to increased levels of traffic. If traffic was limited to the slight amount applied in this study then direct traffic would be better than mats due to the impacts to vegetation being less under direct traffic. Given that real world construction would require more passed then applied in this study mats would provide a better platform for construction than direct traffic, as mats create a buffer between the traffic and the vegetation, if durations are kept short.

Coarser textured soils resulted in more pronounced differences of treatments compared to finer textured soils, this trend was consistent in root and vegetation quantities and aspects of quality, such as protein concentration and digestible fibers. The direct traffic, applied in the limited amounts of this study, had few impacts on vegetation biomass and quality, with little lasting impact. In contrast, traffic occurring on mats reduced most vegetation biomass components for two years, particularly when placed in spring or for longer periods of time, and increased introduced (largely annual and ruderal) forb biomass at the expense of grasses. Root mass was also unaffected by traffic, but reduced by mats, although this reduction was evident only in the second year after mat placement. Protein concentrations were not impacted by traffic, though mats increased protein concentrations. The phonological differences at time of harvesting, introduced forbs more developed and grasses less developed would account for the differences in forage values.

Traffic driven over live vegetation with or without mats impacted vegetation as live tissue was broken off, growing points damaged, and water infiltration was reduced. Matted areas increase negative impacts on vegetation, although mats did mitigated soil compaction. Duration of mat placement will reach a point of irrecoverable carbohydrate loss and result in reduced regrowth or outright death and decomposition of vegetation. Mild levels of damage to vegetation (based on biomass responses) occurred with duration of mat placement of up to six weeks, with more severe levels of damage from twelve weeks, and the most severe damage from duration of longer periods, in this case 24 weeks.

Results of community level regression indicate that changes in plant communities has similar impacts on DMGP as overgrazing by herbivores, with prescribed solution rest for a number of years. The longest mat placements, at 24 weeks, reduced quantity of forage community shift almost completely reversed from dominant perennial grass with few weeds present to an almost total loss of perennial grasses and dominance by weedy annual and introduced species. Secondary success of these areas would require regrowth from seedbank and edge creep, as crowns of perennial grasses and deep roots of perennial forbs were lost and so the associated tillers and re-sprouting ability. Recovery of this level of impact has an unknown time frame, as competition by introduced species, such as Kentucky bluegrass, may alter the trajectory for this community as it recovers from mat created disturbance.

Ultimately, there is a balance needed between the benefits to soil structure and negative impacts to vegetation, a recovery strategy and timeline is need for impacted vegetation to be provided effective rest to promote regrowth. Treatment durations in this study presented a clear picture that mats caused increased amounts of damage to vegetation the longer they were in place, with more negative impacts also in spring than fall. Perennial grasses were increasingly reduced and replaced with introduced forbs. Forage lost under mats was higher than amounts lost under traffic only. Recovery timelines will continue to be monitored from this study to give a better indication of how long the plant community needs to recover from mat placement.

Results of this study indicate there are both benefits and damages incurred from mat use in Mixedgrass Prairie ecosystems. Vegetation recovered on short mat placements within two years, it is yet unknown how long it will take for the season long mat placements to fully recover after the perennial grasses are lost. Invasive species may increase in abundance and quantity due to availability of resources, such as space, soil nutrients, and soil moisture created from loss of perennial grasses; texture may influence vegetative and soil structure recovery. Widespread use of access mats placed for extended periods of time may result in landscape-scale shifts in plant communities, with a decrease in native perennial grass vegetation. Proper placement duration is short, ideally six weeks, certainly not over 12 weeks, with season of placement better later than earlier in the year.

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Table 3–1. Treatment application timeline and treatment name abbreviation details.

Treatment	Season	Weeks	Start	End	Visual Timeline
Control	Season Long	24	30-Apr	15-Oct	**Control**
E6 TWM	Early	6	30-Apr	10-Jun	**Early 6 Mat**
E6 TWOM	Early	6	30-Apr	10-Jun	**Early 6 Traffic**
E12 TWM	Early	12	30-Apr	22-Jul	**Early 12 Mat**
E12 TWOM	Early	12	30-Apr	22-Jul	**Early 12 Traffic**
L6 TWM	Late	6	22-Jul	3-Sep	**Late 6 Mat**
L6 TWOM	Late	6	22-Jul	3-Sep	**Late 6 Traffic**
L12 TWM	Late	12	22-Jul	15-Oct	**Late 12 Mat**
L12 TWOM	Late	12	22-Jul	15-Oct	**Late 12 Traffic**
SL24 TWM	Season Long	24	30-Apr	15-Oct	**Season Long 24 mat**
SL24 TWOM	Season Long	24	30-Apr	15-Oct	**Season Long 24 Traffic**

Treatment breakdown consisting of: abbreviated treatment name, application season and duration in weeks, application date for 2015, and timeline visual representation. Traffic with mats (TWM) =traffic imposed on mats placed directly on the grassland, traffic without mats (TWOM) =traffic imposed directly on the grassland. Control = non-treated native grassland; E6 TWM = traffic imposed on mats placed early in the growing season (April 30 to June 10) for 6 weeks; E6 TWOM = traffic imposed directly on grassland early in the growing season (April 30 to June 10) over 6 weeks; E12 TWM = traffic imposed on mats placed early in the growing season (April 30 to July 22) for 12 weeks; E12 TWOM = traffic imposed directly on grassland early in the growing season (April 30 to July 22) over 12 weeks; applies only to soil pH, salinity, organic matter content, nutrient supply, and bulk density in 2015; L6 TWM = traffic imposed on mats placed late in the growing season (July 22 to Sept 3) for 6 weeks; L6 TWOM = traffic imposed directly on grassland late in the growing season (July 22 to Sept 3) over 6 weeks; L12 TWM = traffic imposed on mats placed late in the growing season (July 22 to Oct 15) for 12 weeks; L12 TWOM = traffic imposed directly on grassland late in the growing season (July 22 to Oct 15) over 12 weeks; SL24 TWM = traffic imposed on mats placed throughout the growing season (April 30 to Oct 15) for 24 weeks; SL24 TWOM = traffic imposed directly on grassland throughout the growing season (April 30 to Oct 15) over 24 weeks.

Table 3–2. ANOVA summary of vegetation biomass by functional group.

	ANOVA							
	Grass†		Litter†		Introduced Forb‡		Native Forb‡	
	F-stat§	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$1.03_{1,2}$	0.417	$1.31_{1,2}$	0.371	$1.16_{1,2}$	0.395	$1.87_{1,2}$	0.305
Treatment (Trt)	$8.91_{10,152}$	**< 0.0001**	$1.34_{10,152}$	0.216	$38.0_{10,152}$	**< 0.0001**	$4.51_{10,152}$	**< 0.0001**
Eco × Trt	$4.43_{10,152}$	**< 0.0001**	$2.00_{10,152}$	**0.0373**	$2.83_{10,152}$	**0.0030**	$1.35_{10,152}$	0.209
Year (Yr)	$35.4_{1,154}$	**< 0.0001**	$6.53_{1,154}$	**0.0115**	$567.6_{1,154}$	**< 0.0001**	$44.3_{1,154}$	**< 0.0001**
Eco × Yr	$6.94_{1,154}$	**0.0093**	$6.07_{1,154}$	**0.0149**	$11.8_{1,154}$	**0.0008**	$2.40_{1,154}$	0.124
Trt × Yr	$3.30_{10.154}$	**0.0007**	$2.35_{10,154}$	**0.0132**	$31.9_{10,154}$	**< 0.0001**	$3.10_{10,154}$	**0.0013**
Eco × Trt × Yr	$1.51_{10,154}$	0.140	$2.24_{10,154}$	**0.0184**	$6.22_{10.154}$	**< 0.0001**	$1.13_{10,154}$	0.345

† Data were square root transformed for analysis

‡ Data were log transformed for analysis

§ F-stat subscripts indicate the numerator and denominator degrees freedom, respectively.

Summary of the ANOVA response of grass, litter, introduced forb, and native forb biomass (kg ha^{-1}) in relation to ecosite type, disturbance treatment, year, and their interactions, within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively. Year was assessed as a repeated measure.

Table 3–3. Grass biomass (kg ha^{-1}) results by ecosite and disturbance treatment.

Ecosite × Treatment

	μ					
Ecosite	------------------------ Loam† ------------------------			------------------------ Loamy-Sand ------------------------		
Treatment	TWOM	TWM		TWOM	TWM	
Control	1200.1 a			1640.7 ab		
SL24	1257.9 a	971.9 a	N.S.‡§	1492.5 ab	345.8 d	**< 0.0001**
E12	1005.9 a	981.3 a	N.S.	1220.1 b	1347.1 ab	N.S.
E6	1111.1 a	1131.0 a	N.S.	1311.9 ab	866.8 c	**< 0.0001**
L12	959.3 a	1065.5 a	N.S.	1451.8 ab	1604.2 a	N.S.
L6	1159.4 a	1030.9 a	N.S.	1428.5 ab	1695.6 a	N.S.

† Within each ecosite x treatment combination, means (n = 8) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ N.S., non-significant.

§ Pairwise comparisons of TWOM and TWM treatments within an ecosite.

Interaction of ecosite type and disturbance treatments on mean grass biomass (kg ha^{-1}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively (F-stat $4.43_{10,152}$, p < 0.0001), with SEM (±212.7 kg ha^{-1}). See Table 3–1 for treatment definitions.

Table 3–4. Grass biomass (kg ha^{-1}) results by year and disturbance treatments.

Year × Treatment

			μ			
Year	2016†			2017		
Treatment	TWOM	TWM		TWOM	TWM	
Control	1277.1 a			1563.7 ab		
SL24	1005.1 ab	497.9 c	**< 0.0001**‡	1417.9 ab	819.8 c	**< 0.0001**
E12	1323.9 a	904.3 b	**0.0005**	1263.9 b	1093.4 bc	N.S.§
E6	1108.1 ab	754.5 bc	N.S.	1618.4 a	1471.5 ab	N.S.
L12	1036.4 ab	1275.9 a	N.S.	1374.6 ab	1052.5 bc	N.S.
L6	1210.8 ab	1309.9 a	N.S.	1458.9 ab	1440.4 ab	N.S.

† Within each year x treatment combination, means (n = 16) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ Pairwise comparisons of TWOM and TWM treatments within an ecosite.

§ N.S., non-significant.

Interaction of year and disturbance treatments on mean grass biomass (kg ha^{-1}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively (F-stat = $3.30_{10, 154}$, p = 0.0007), with SEM (±170.7 kg ha^{-1}). Table 3–1 for treatment definitions.

Table 3–5. Litter biomass (kg ha^{-1}) results by ecosite, disturbance treatment, and year of sampling.

Ecosite × Treatment × Year

		µ				
Ecosite	---------- Loam ----------					
Year	---------- 2016† ----------			---------- 2017 ----------		
Treatment	TWOM	TWM		TWOM	TWM	
Control	1232.4 a			1082.0 a		
SL24	815.5 a	1013.0 a	N.S.‡§	747.1 a	987.1 a	N.S.
E12	944.0 a	856.1 a	N.S.	811.0 a	875.8 a	N.S.
E6	1077.8 a	606.8 a	N.S.	902.9 a	842.8 a	N.S.
L12	971.6 a	858.1 a	N.S.	712.8 a	645.3 a	N.S.
L6	918.4 a	601.5 a	N.S.	796.6 a	900.8 a	N.S.
Ecosite	---------- Loamy-Sand ----------					
Year	---------- 2016 ----------			---------- 2017 ----------		
Treatment	TWOM	TWM		TWOM	TWM	
Control	1386.1 bc			1584.6 a		
SL24	1309.1 bc	966.6 c	N.S.	1385.7 a	676.4 b	**0.033**
E12	997.9 bc	2539.5 a	**< 0.0001**	1052.7 ab	542.3 b	N.S.
E6	2136.6 ab	2077.5 ab	N.S.	1328.4 a	1114.1 ab	N.S.
L12	1718.5 bc	1031.4 bc	N.S.	1261.4 a	944.3 ab	N.S.
L6	1117.5 bc	1722.7 b	N.S.	1579.5 a	1326.7 ab	N.S.

† Within each ecosite x year x disturbance treatment combination, means (n = 8) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ Pairwise comparisons of TWOM and TWM treatments within an ecosite.

§ N.S., non-significant.

Interaction of ecosite type, disturbance treatment, and year on mean litter biomass (kg ha^{-1}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively (F-stat = $2.24_{10,154}$, p = 0.0184), with SEM (± 375.6 kg ha^{-1}). See Table 3–1 for treatment definitions.

Table 3–6. Introduced forb biomass (kg ha^{-1}) results by ecosite, disturbance treatment, and year of sampling.

Ecosite × Treatment × Year

			μ			
Ecosite	---------- Loam ----------					
Year	---------- 2016† ----------			---------- 2017 ----------		
Treatment	TWOM	TWM		TWOM	TWM	
Control	203.6 c			3.8 a		
SL24	219.4 c	2560.1 a	**< 0.0001‡**	35.5 a	87.9 a	N.S.§
E12	185.5 c	310.8 c	N.S.	6.3 a	42.3 a	N.S.
E6	124.8 c	838.5 b	**< 0.0001**	19.6 a	23.8 a	N.S.
L12	173.6 c	139.4 c	N.S.	18.0 a	61.6 a	N.S.
L6	165.6 c	152.9 c	N.S.	6.0 a	23.5 a	N.S.
Ecosite	---------- Loamy-Sand ----------					
Year	---------- 2016 ----------			---------- 2017 ----------		
Treatment	TWOM	TWM		TWOM	TWM	
Control	202.9 d			6.8 a		
SL24	1127.0 c	3855.5 a	**< 0.0001**	3.0 a	86.9 a	N.S.
E12	164.0 d	1932.9 b	**< 0.0001**	59.1 a	9.0 a	N.S.
E6	77.6 d	985.8 c	**< 0.0001**	78.9 a	2.1 a	N.S.
L12	145.8 d	188.8 d	N.S.	14.5 a	35.6 a	N.S.
L6	157.8 d	159.9 d	N.S.	10.4 a	224.6 a	N.S.

† Within each ecosite x year combination, means (n = 8) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ Pairwise comparisons of TWOM and TWM treatments within an ecosite.

§ N.S., non-significant.

Interaction of ecosite type, disturbance treatment, and year on mean introduced forb biomass (kg ha^{-1}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively (F-stat = $6.22_{10,154}$, $p < 0.0001$), with SEM (± 182.1 kg ha^{-1}). See Table 3–1 for treatment definitions.

Table 3–7. Native forb biomass (kg ha^{-1}) results for year by treatment interactions.

Year × Treatment

	μ					
Year	2016†			2017		
Treatment	TWOM	TWM		TWOM	TWM	
Control	327.1 a			160.4 b		
SL24	176.6 b	347.8 a	**0.0329‡**	143.2 b	290.1 a	**0.0242**
E12	174.2 b	152.9 b	N.S.	81.4 bc	170.3 ab	N.S.§
E6	372.8 a	348.9 a	N.S.	75.9 bc	83.9 bc	N.S.
L12	154.1 b	150.1 b	N.S.	68.2 bc	93.3 bc	N.S.
L6	175.1 b	156.8 b	N.S.	51.1 c	75.6 c	N.S.

† Within a year x treatment combination, means (n = 16) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ Pairwise comparisons of TWOM and TWM treatments within an ecosite.

§ N.S., non-significant.

Interaction of year and disturbance treatments on mean native forb biomass (kg ha^{-1}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 and 2017 growing seasons one and two years after treatment, respectively (F-stat = $3.10^{10,154}$, p = 0.0013), with SEM (±53.1 kg ha^{-1}). See Table 3–1 for treatment definitions.

Table 3–8. ANOVA summary and treatments results of root biomass (g m^{-2}) in the top 7.5 cm of soil.

ANOVA				
	------------------------ 2015 ------------------------		------------------------ 2016† ------------------------	
	F-stat	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$0.21_{1,2}$	0.652	$0.90_{1,2}$	0.443
Treatment (Trt)	$1.60_{2,42}$	0.213	$\mathbf{4.34_{10,152}}$	**<0.0001**
Eco × Trt	$1.36_{2,42}$	0.268	$1.47_{10,152}$	0.156

	µ		
Treatment	TWOM	TWM	
Control	893 b		
SL24	975 ab	582 c	**0.0005**
E12	1068 ab	791 b	**0.0132**
E6	1076 a	1102 a	N.S.‡
L12	998 ab	809 b	N.S.
L6	1004 ab	1102 a	N.S.

† Within year column, treatment means (n = 16) followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

‡ N.S., non-significant.

Interaction of disturbance treatments on root biomass (g m^{-2}) within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2015 and 2016 growing seasons one and two years after treatment, respectively, with 2016 SEM (± 88 g m^{-2}). Soil cores were taken in 2015 to a depth of 7.5 cm, and 7 cm in 2016. See Table 3–1 for treatment definitions.

Table 3–9. ANOVA summary and ecosite by treatment results of crude protein concentrations (% of plant mass) for grass, introduced forb and native forbs.

ANOVA						
	Crude Protein Concentration					
	Grass		Introduced Forbs		Native Forbs†	
	F-stat	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$0.16_{1,2}$	0.726	$0.01_{1,2}$	0.9372	$25.79_{1,2}$	**< 0.0001**
Treatment (Trt)	$7.47_{2,40}$	**0.0018**	$7.63_{2,37}$	**0.0017**	$0.58_{2,40}$	0.564
Eco × Trt	$11.32_{2,40}$	**0.0001**	$3.65_{2,37}$	**0.0356**	$1.03_{2,40}$	0.362

			µ	
Eco × Trt				
Ecosite	Loam‡	Loamy-Sand	Loam	Loamy-Sand
Control	7.56 a	6.93 b	0.91 a	0.96 a
E12 TWOM	7.66 a	7.29 b	0.89 a	1.00 a
E12 TWM	7.42 a	8.78 a	0.84 a	0.67 b

† Data were log transformed for analysis.

‡ Within a column, mean grass (n = 8) or introduced Forb (n = 8) values followed by the same letter are not significantly different according to a post-hoc Tukey's mean comparison (0.05).

Summary of the ANOVA response of crude protein concentration (% of plant mass) for grass, introduced forbs, and native forbs in relation to ecosite type, disturbance treatments, and their interaction, within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 growing season the first year after treatment, with SEM (± 0.28 % of plant mass) for grass, and (± 0.061 % of plant mass) for introduced forb. See Table 3–1 for treatment definitions.

Table 3–10. ANOVA summary, treatment and ecosites by treatment results of crude protein yield of vegetation functional groups.

	ANOVA							
	-- Crude Protein Yield --							
	Grass†		Introduced Forbs		Native Forbs		Total	
	F-stat[1]	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$0.36_{1,2}$	0.6105	$4.19_{1,2}$	0.0474	$0.01_{1,2}$	0.9215	$4.16_{1,2}$	0.1779
Treatment (Trt)	$1.91_{2,40}$	0.1618	$5.62_{2,39}$	**0.0071**	$5.28_{2,38}$	**0.0095**	$2.74_{2,40}$	0.0767
Eco × Trt	$1.17_{2,40}$	0.3216	$6.95_{2,39}$	**0.0026**	$0.16_{2,38}$	0.8554	$5.59_{2,40}$	**0.0072**
				µ				
Treatment								
Control	905.8		261.0 b		372.2 a		1406.5	
E12 TWOM	992.4		165.6 c		221.7 a		1330.3	
E12 TWM	750.7		747.8 a		207.1 a		1655.8	
SE	± 106.8		± 89.1		± 85.8		± 144.7	
				µ				
Eco × Trt								
Ecosite			Loam	Loamy-Sand			Loam	Loamy-Sand
Control			217.1 a	304.9 b			1267.9 a	1545.2 b
E12 TWOM			179.1 a	152.7 c			1266.0 a	1394.6 b
E12 TWM			150.2 a	1345.5 a			1137.9 a	2173.7 a

† Within vegetation functional group columns, means for treatment (n = 16), and means for ecosite by treatment interaction (n = 8). Ecosite x treatment means followed by the same letter are not significantly different according to a post-hoc Tukey mean comparison (0.05).

Summary of the ANOVA response of mean crude protein yield (kg ha^{-1}) for grass, introduced forbs, native forbs, and the combined total in relation to ecosite type, disturbance treatments, and their interaction, within the DMGP at the Mattheis Research Ranch, as sampled throughout the 2016 growing season the first year after treatment, with treatment SEM of grass (± 106.8), introduced forbs (± 89.1), native forbs (± 85.8), and total (± 144.7 kg ha^{-1}); for ecosite by treatment interactions SEM of introduced forbs (± 126.0) and total (± 204.6 kg ha^{-1}). See Table 3–1 for treatment definitions.

Table 3–11. ANOVA summary of acid detergent fiber (ADF) concentrations (%) for vegetation functional groups.

	Grass†		Introduced Forb		Native Forb	
ANOVA	**F-stat**	**p-value**	**F-stat**	**p-value**	**F-stat**	**p-value**
Ecosite (Eco)	$1.98_{1,2}$	0.3029	$0.15_{1,2}$	0.7380	$0.05_{1,2}$	0.859
Treatment (Trt)	$2.39_{2,40}$	0.1050	$21.9_{2,36}$	**< 0.0001**	$0.46_{2,36}$	0.6409
Eco × Trt	$3.70_{2,40}$	**0.0335**	$0.75_{2,36}$	0.4775	$3.75_{2,36}$	**0.0337**
			μ			
Treatment						
Control			36.7 b			
E12 TWOM			37.8 b			
E12 TWM			50.1 a			
	μ				**μ**	
Eco × Trt						
Ecosite	Loam	Loamy-Sand			Loam	Loamy-Sand
Control	41.6 a	41.3 a			43.7 a	44.1 a
E12 TWOM	41.9 a	40.7 ab			43.5 a	41.6 a
E12 TWM	42.1 a	38.2 b			40.7 a	39.1 a

† Within vegetation functional group columns, means of treatment (n = 16), and means for ecosite by treatment interaction (n = 8). Ecosite x treatment means followed by the same letter are not significantly different according to a post-hoc Tukey mean comparison (0.05).

Summary of the ANOVA responses for mean acid detergent fiber concentrations (%) as determined under various industrial traffic treatments in the DMGP. Data are based on biomass collected from August 1 through 12, 2016. The first growing season the year after treatment, with SEM for grass (± 1.1 %), introduced forbs (± 3.9 %), and native forbs (± 4.0). See Table 3–1 for treatment definitions.

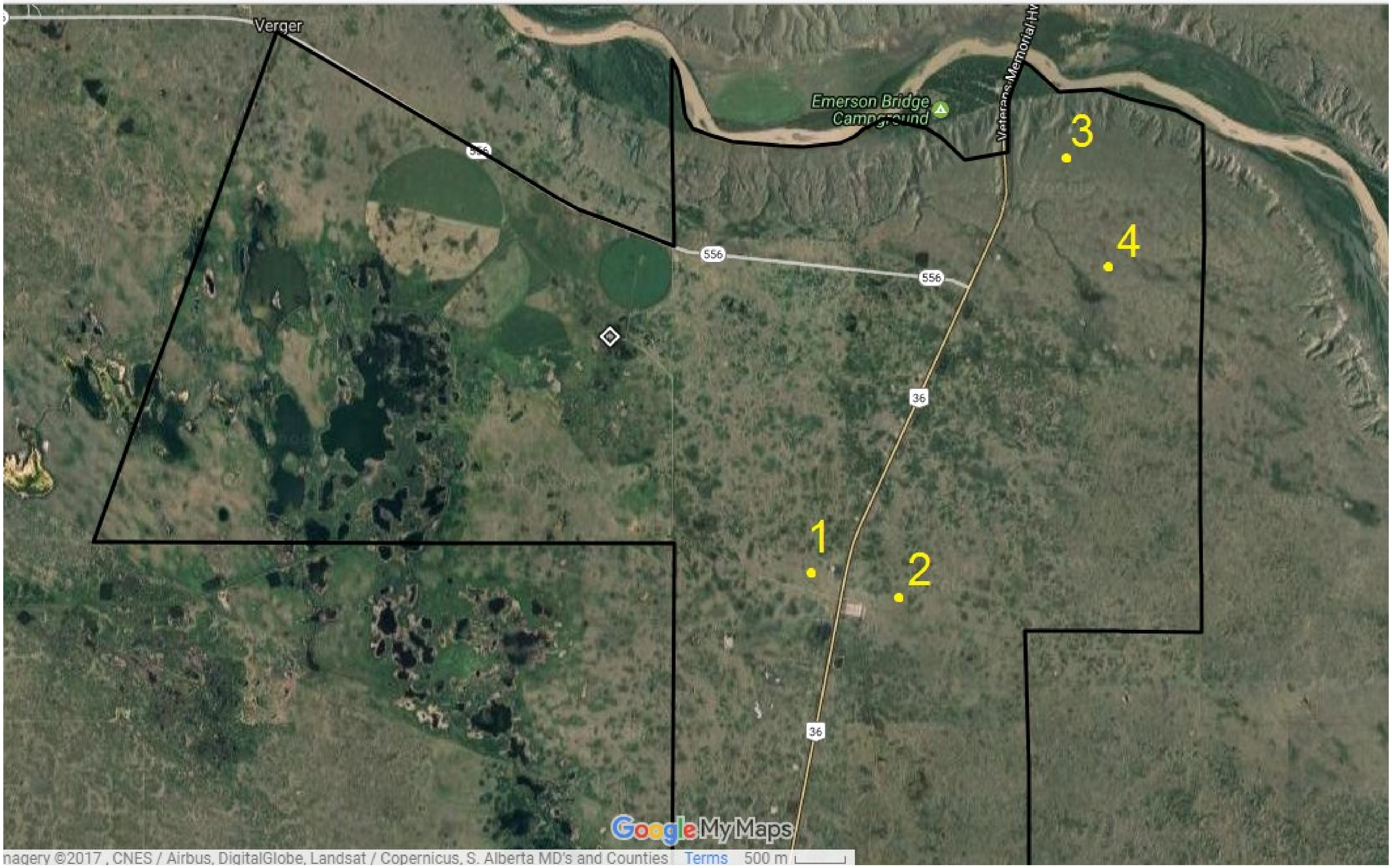

Figure 3–1. Outline of University of Alberta Mattheis Research Ranch.

Mattheis Research Ranch is part of the Rangeland Research Institute. Study sites are labeled in yellow (sites 1 and 2 on loamy-sand soils and 3 and 4 on loam soils) and ranch boundary in black.

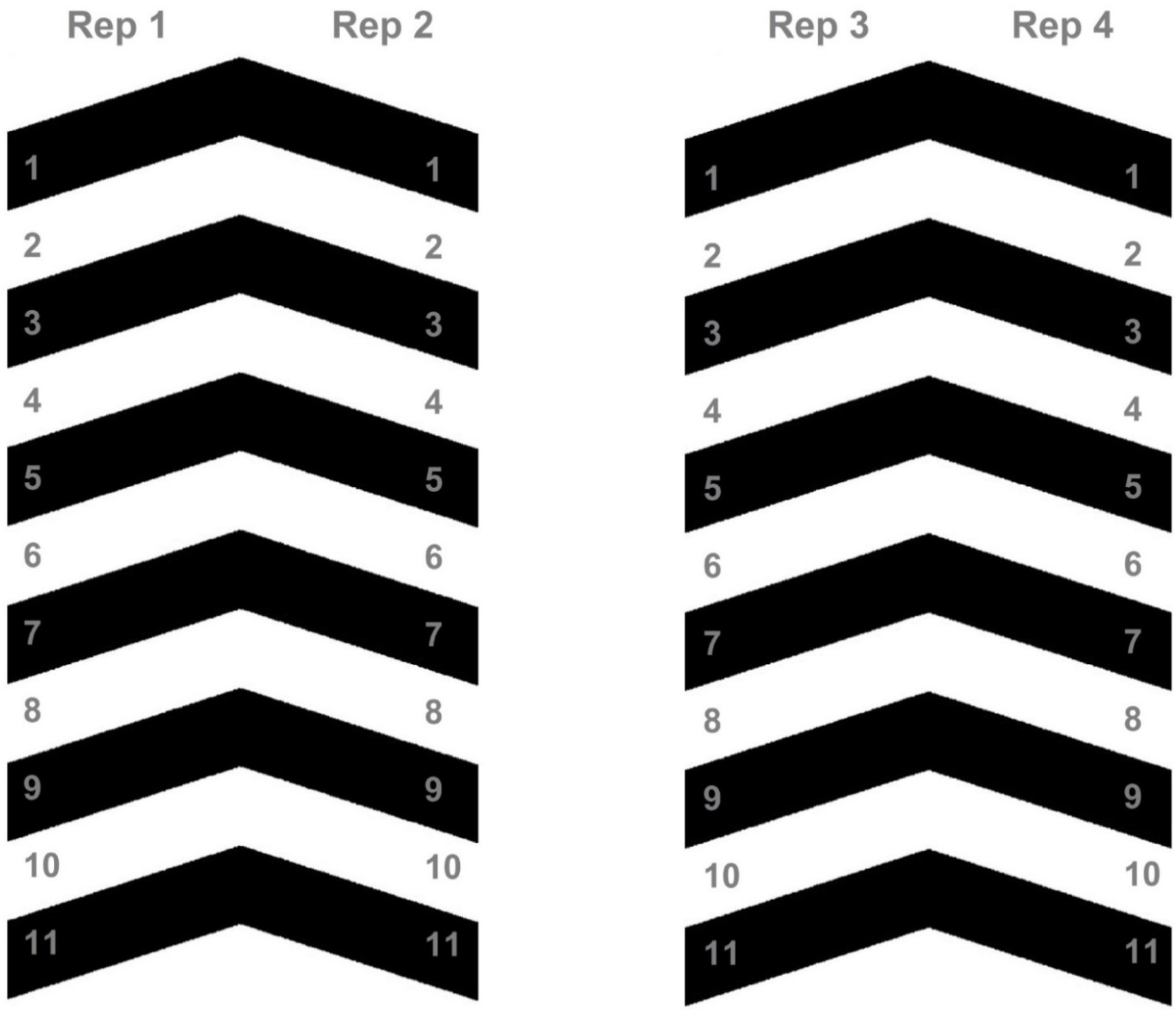

Figure 3–2. Representative site diagram.

Site diagram with replicate blocks of 11 treatments in two paired rows on either side of travel lane.

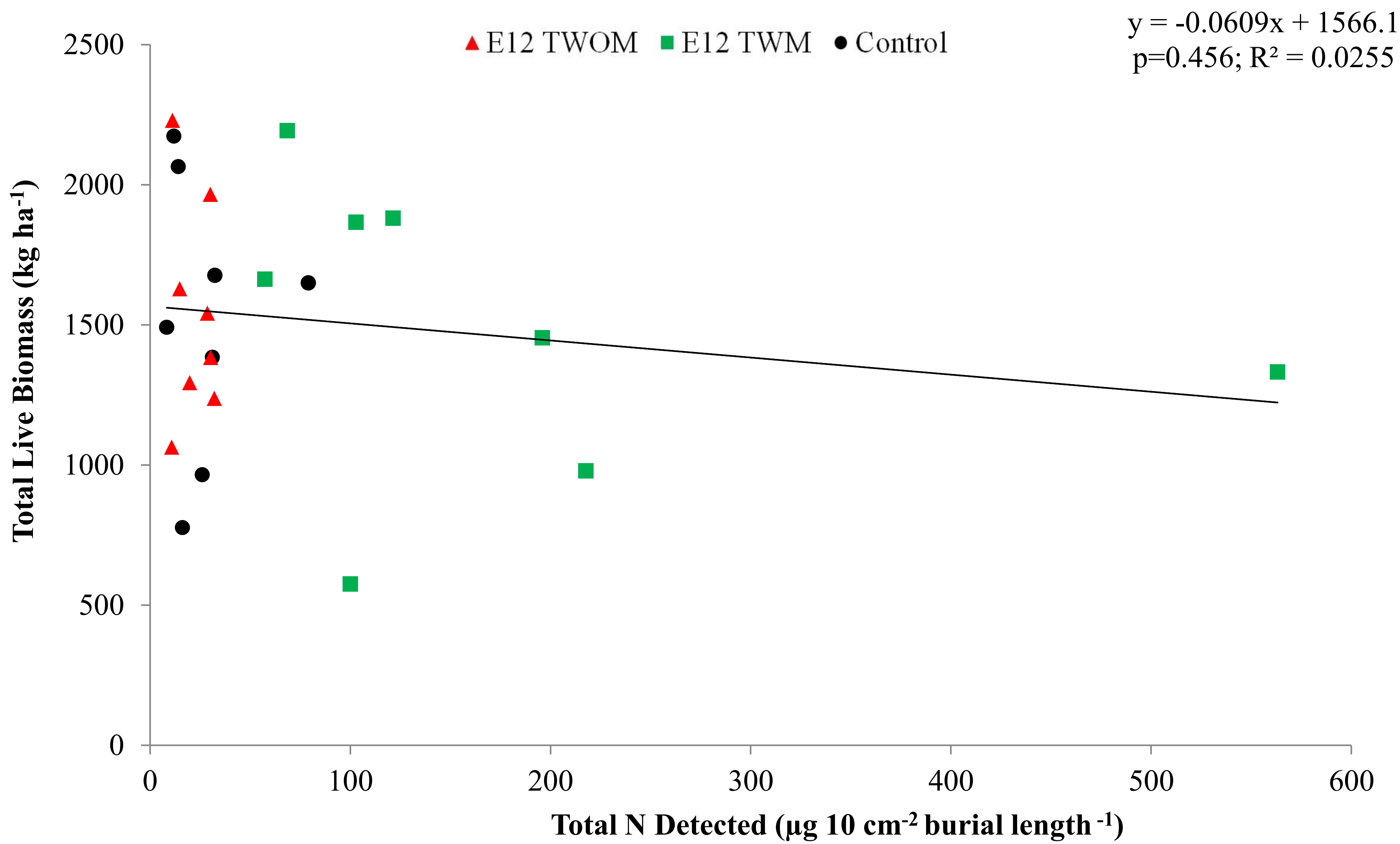

Figure 3–3. Regression of total live biomass (kg ha^{-1}) against total nitrogen (µg 10 cm^{-2} burial $length^{-1}$) within the loam soil.

Regression of total live biomass (kg ha^{-1}) verses total nitrogen release (µg 10 cm^{-2} burial $length^{-1}$) per installation period, on loam soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

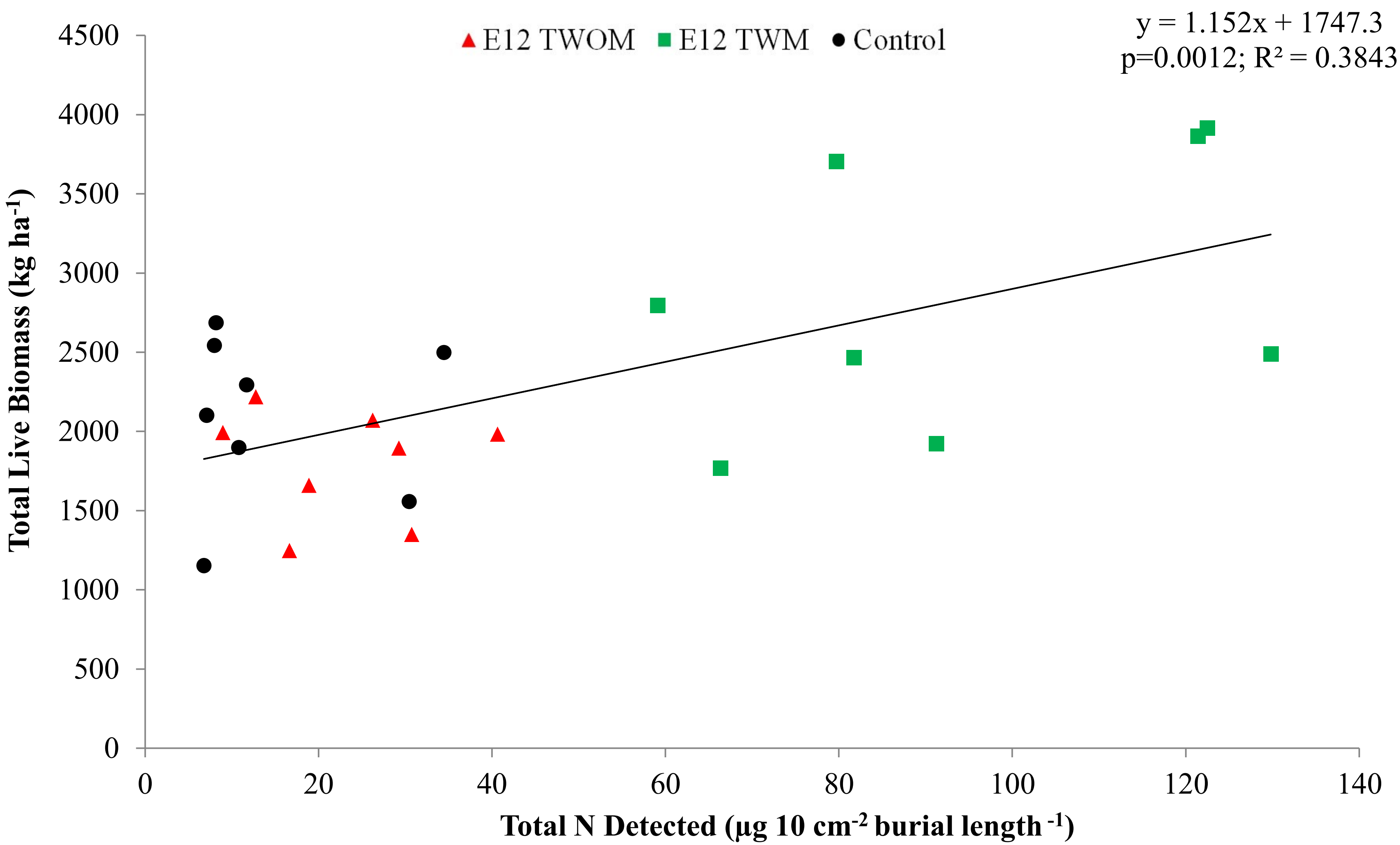

Figure 3–4. Regression of total live biomass (kg ha^{-1}) against total nitrogen (µg 10 cm^{-2} burial $length^{-1}$) within the loamy-sand soil.

Regression of total live biomass (kg ha^{-1}) verses total nitrogen release (µg 10 cm^{-2} burial $length^{-1}$) per installation period, on loamy-sand soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

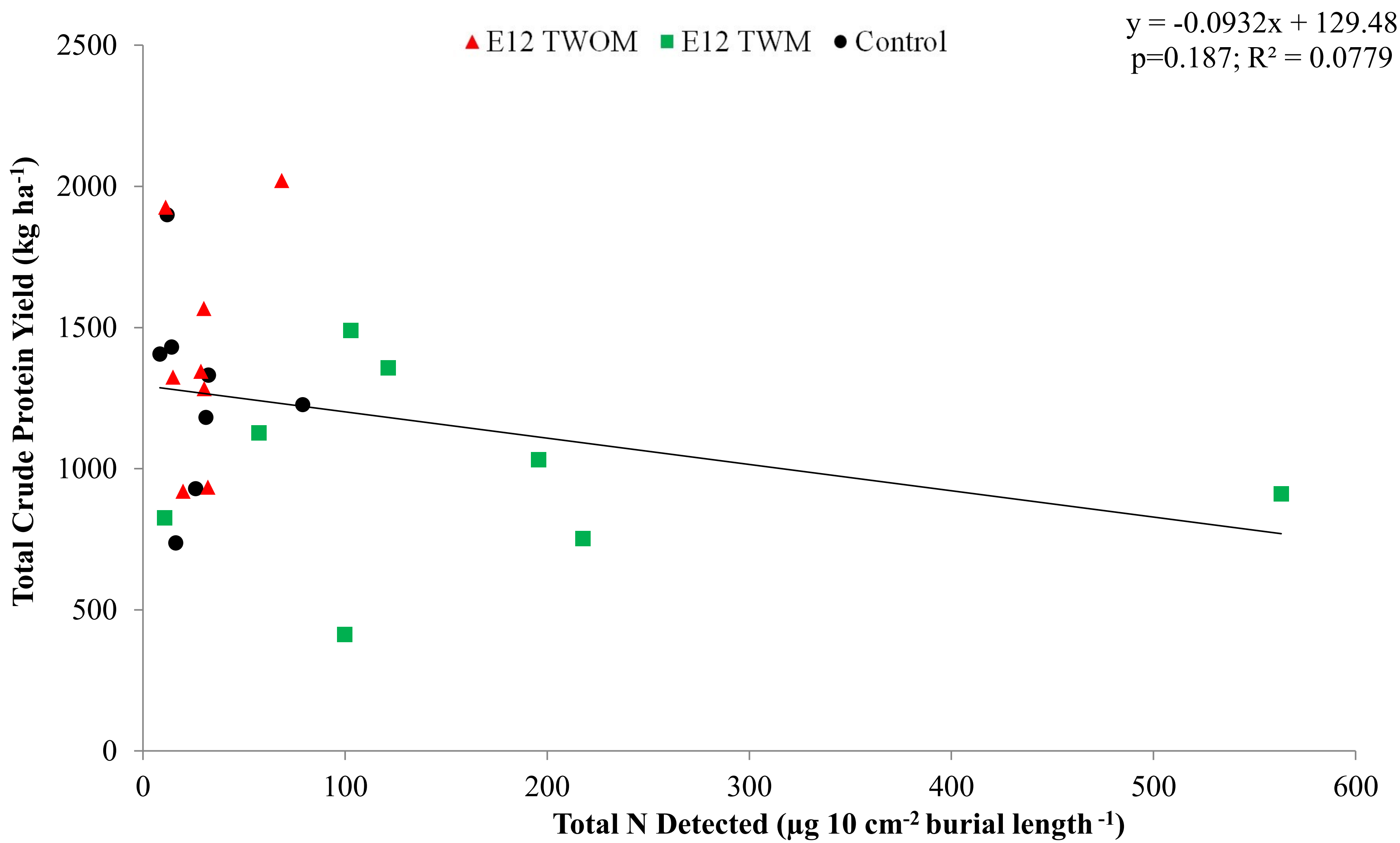

Figure 3–5. Regression of total crude protein (kg ha^{-1}) against total nitrogen (µg 10 cm^{-2} burial length $^{-1}$) within the loam soil.

Regression of total crude protein concentration (kg ha^{-1}) verses total nitrogen release (µg 10 cm^{-2} burial length $^{-1}$) per installation period, on loam soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

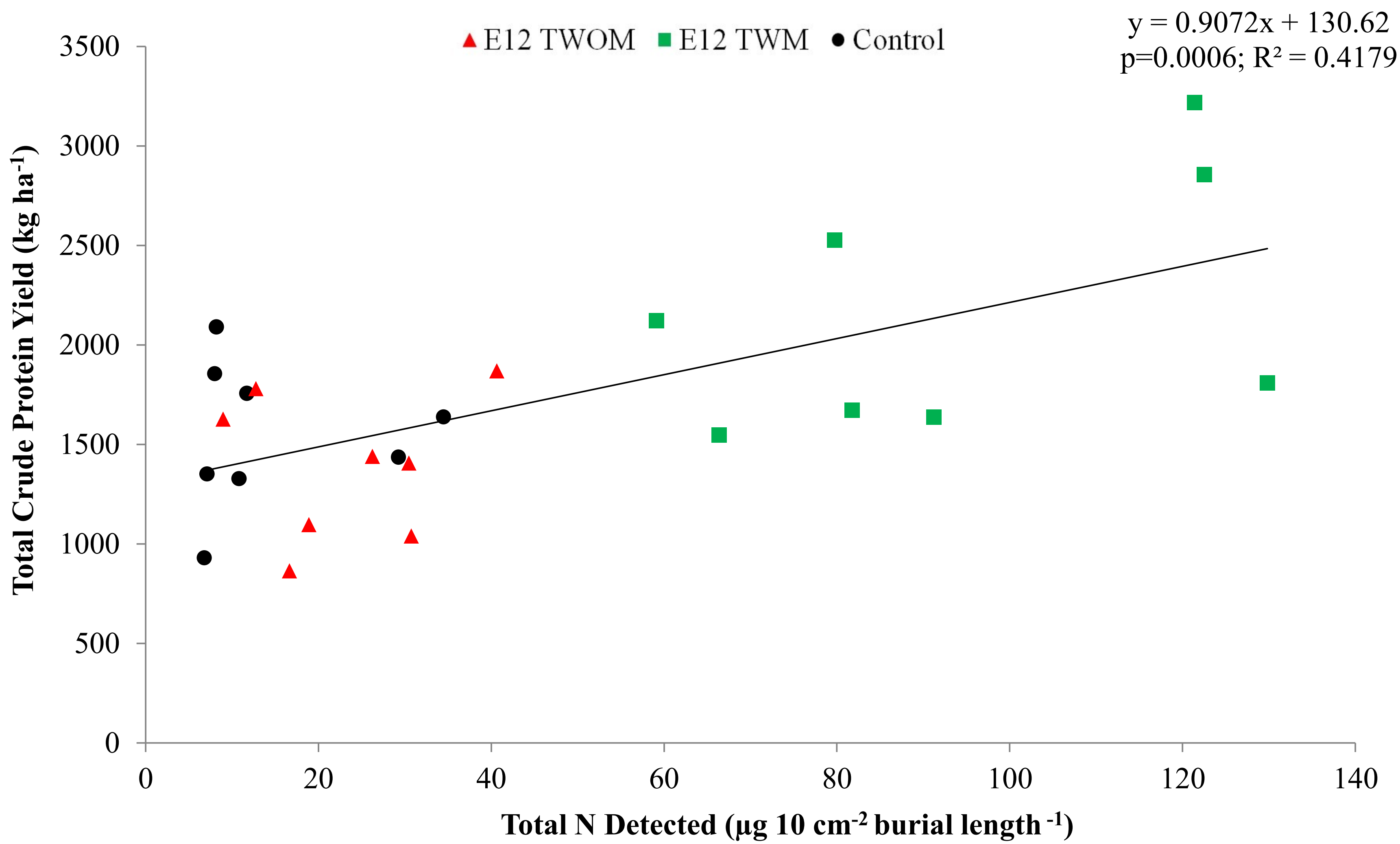

Figure 3–6. Regression of total crude protein (kg ha^{-1}) against total nitrogen (µg 10 cm^{-2} burial $length^{-1}$) within the loamy-sand soil.

Regression of total crude protein concentration (kg ha^{-1}) verses total nitrogen release (µg 10 cm^{-2} burial $length^{-1}$) per installation period, on loamy-sand soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

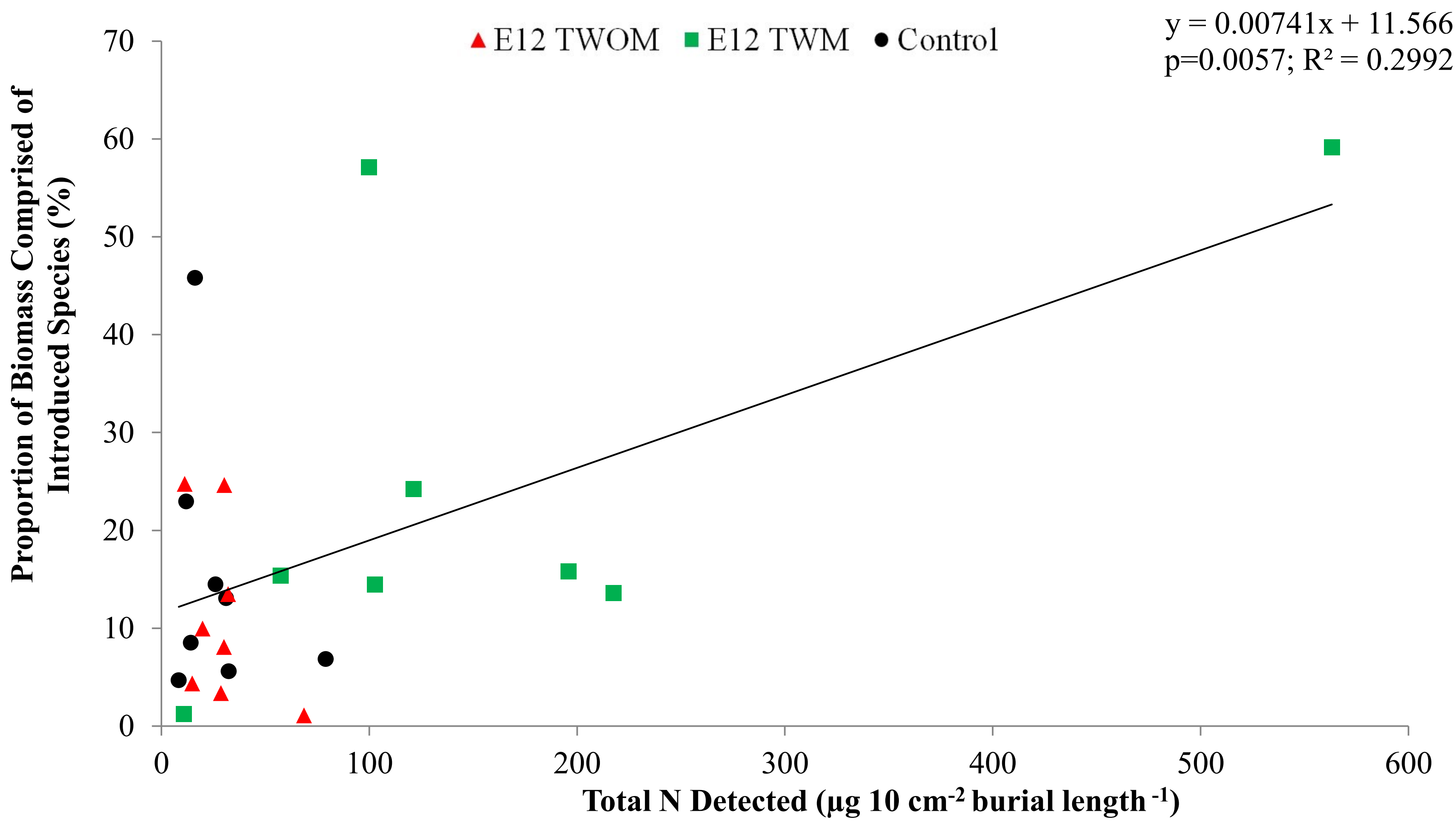

Figure 3–7. Regression of proportion of live biomass comprised of introduced forbs (%) against total nitrogen (µg 10 cm^{-2} burial $length^{-1}$) within the loam soil.

Regression of proportion of live biomass comprised of introduced forbs (%) verses total nitrogen release (µg 10 cm^{-2} burial $length^{-1}$) per installation period, on loam soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

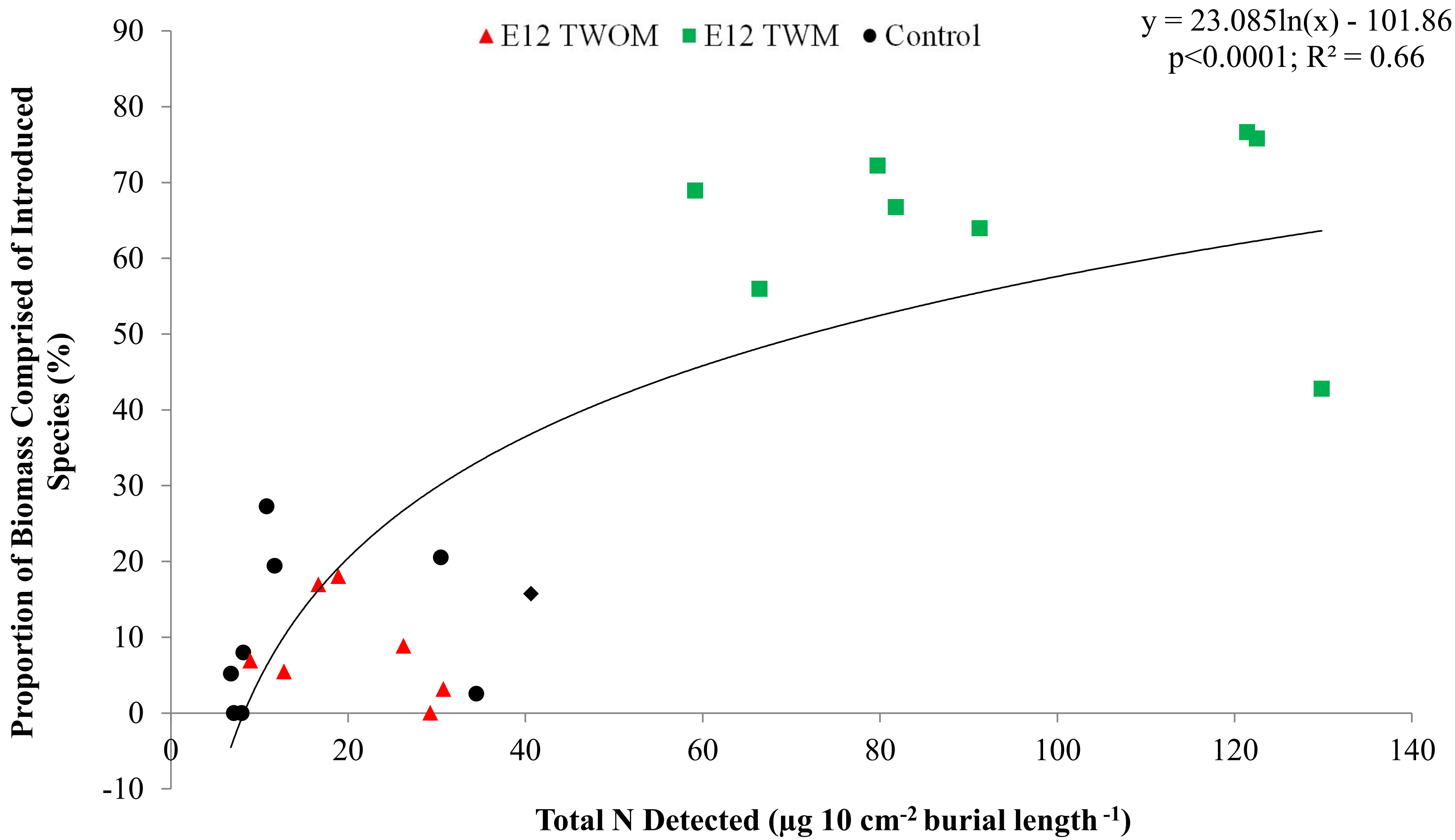

Figure 3–8. Regression of proportion of live biomass comprised of introduced forbs (%) against total nitrogen (µg 10 cm^{-2} burial length^{-1}) within the loamy-sand soil.

Regression of proportion of live biomass comprised of introduced forbs (%) verses total nitrogen release (µg 10 cm^{-2} burial length $^{-1}$) per installation period, on loamy-sand soil within the DMGP at the Mattheis Research Ranch; PRS® probes installed for burial lengths of 12 weeks in 2015, and 18 weeks in 2016. See Table 3–1 for treatment details.

Chapter 4: Can Access Mats Mitigate Industrial Traffic Impacts?: A Synthesis of Findings

4.1 Synthesis

Research objectives were to quantify the impacts of direct traffic compared to traffic occurring over access mats on the Dry Mixedgrass Prairie (DMGP) soils and vegetation. Activities on the prairies, such as infrastructure construction and ranching, can have divergent impacts on vegetation depending on priorities; a compromise is needed that allows for ongoing industrial construction that also allows for the long-term conservation of native prairies. This research addressed one such traffic mitigation strategy, access mats, and studied their effects over the growing season. Combinations of five disturbance treatments in pairs of direct traffic and traffic over mats were studied at four sites on the Mattheis Research Ranch in the DMGP to account for varied duration and season of access mat use, as well as ecosite types, specifically soil texture.

Impacts to soil physical properties, vegetation biomass, quality, and soil nutrient supply from traffic directly on DMGP were localized under the tire tracks. Soil surface compaction, based on penetration resistance and associated hydrologic function although not bulk density, remained present to some degree into the second year of recovery. Traffic was spaced at least six weeks apart for this study; vegetation damaged in the first direct traffic event was able to recover lost photosynthetic material before the next traffic treatment was applied. In general, direct traffic, albeit a limited number of passes caused no lasting reductions in vegetation biomass. The impacts of direct traffic by wheel and tracked vehicles is a well-studied topic, but further studies would be needed to distinguish the impact of increasing the number of direct passes by wheeled traffic.

Mats used in this study appeared to successfully redistribute equipment weight and reduced the localized soil impacts of traffic as demonstrated by penetration resistance, although some blockage and disconnect of soil pores must have occurred as hydrologic function was reduced in the second year after mat removal. Substantial damage to above ground vegetation and below ground root biomass appear to be trade-offs of using matting to reduce soil impacts. This negative impact was evident as changes within late seral plant communities, dominated by native perennial grasses, were reduced in grass biomass and had increased biomass of introduced and ruderal forbs. Although vegetation is quite resilient, mats kept in place for long periods will lead to reductions in perennial grasses and temporary increase in introduced forbs as plant death occurs and alters the current plant community. Due to the loss of perennial grasses, recovery would need to occur from the seed bank, seed rain, or tiller creep from the still intact surrounding vegetation. The key is to avoid continuous mat placement for long periods, and allow adequate recovery of the vegetation community after mat removal.

This study looked at both ecosites of loam and loamy-sand textured soils, two relatively divergent soil types associated with the ATCO transmission line as it crossed on the Mattheis Research Ranch. Soils higher in sand content have inherently less cohesive structure; these soils expressed stronger responses in vegetation, with larger changes to vegetation functional groups, and more negative soil impacts from traffic. Fragile soils, like these loamy-sands, are easily eroded if soil holding vegetation is disturbed. Caution is recommended for mat use on soils that are prone to easy damage, wet soil and less cohesive soils. These sensitive soils will be more susceptible to soil damage, and soil erosion from losses of stabilizing vegetation. Additional caution is advised using mats on wet soil as the distribution of weight will have a point where the mats will sink into the soil, and create more damage upon removal, if removal is possible. These soils may seem like ideal candidates for access mat use to limit ruts and compaction, but the vegetation may be easily damaged by prolonged mat placement.

Based on results of this study mat use to provide temporary travel lanes over DMGP for short durations, six weeks or less, would be recommended to mitigate compaction. Caution is advised against the blanket adoption of mats without regard for other considerations, as their use could inadvertently cause larger areas of impact in an effort to reduce localized compaction. Also, the use of mats based on this study can only be recommended for equipment with similar weights and similar frequencies to those used for treatments, as heavier equipment, or those with smaller wheels, or at increased frequencies of use, may further alter impacts to soil and vegetation.

Further study is needed for vehicles of heavier weights or increased traffic frequency. When larger equipment is used mats will likely reach a point where their surface area is insufficient to spread equipment weight enough to limit compaction. Caution is also recommended when using mats on ground surfaces of varying or high levels of soil moisture, such as in chinooks, or spring thaw. Dry soils are known to support increased levels of traffic, while wet soils are known to be weaker, support less weight, and create bare soil from the loss of traction and slippage under tires. Although not tested here, previous research highlights that wet soils are more sensitive to traffic compaction (Althoff et al. 2010, Raper and Kirby 2006, Thurow et al. 1996, Voorhees et al. 1989, and Wortmann and Jasa 2003), therefore the increased SMC initially upon mat removal may elevate the risk of compaction of matted areas. As such, direct wheeled traffic on these areas should be avoided until SMC levels have been reduced, which in this study occurred six weeks after mats were removed.

Although levels of traffic in this study did not cause negative impacts to root biomass on loam soils higher amounts of traffic likely would lead to increased negative effects as traffic increases in frequency. Future considerations are that sandier soils usually have no aeration problems, even under compaction in the root zone (Unger and Kaspar 1994), while compaction in clay and clay-loam soil can limit oxygen flow to plant roots, to a point of being too low to fully meet plant's needs (Unger and Kaspar 1994). This compaction in clay and clay-loam soils may cause carbon dioxide, or other substances, to accumulate which may cause root death or interfere with water uptake, nitrogen fixation, and microbial activity (Unger and Kaspar 1994).

Plant impacts, such as the loss of plant roots and associated decomposition, along with high levels of soil moisture, would make areas under long duration mat placement more susceptible to compaction from traffic, particularly if traffic were applied before soil moisture levels decreased and the soil hardened. Traffic on higher clay soils would likely form a hard pan crust that would impede the infiltration of water and lateral root growth. Compacted soil may also lead to increased run off, creating a drier site further impairing the long-term recovery of soils and vegetation. Water content levels in trapped vegetation may also affect decomposition rates, mats placed on vegetation with higher water content (i.e. vegetation actively growing compared to dormant) may increase microbial activity levels, and lead to increased decomposition. Repeated placements of mats on the same area without adequate rest and sufficient recovery would likely compound the negative impacts on soils and vegetation. Vegetation covered again by mats while still recovering from a prior placement may be further damaged. If mats are applied to soils before regrowth can occur, access mats may do more damage to the plant community.

Loamy-sand soils increased water infiltration into the soil profile where it is could be temporarily stored, compared to loam soils where high clay content and smaller pores reduces the rate of infiltration and causes water to pool on soil surface. The latter in turn, can reduce infiltration and associated water availability for plant growth (Noy-Meir 1973, and Hamza and Anderson 2005). Warm season grasses generally had increased productivity on loamy-sand sites compared to loam sites (Bork and Irving 2015).

There are costs for every activity undertaken, and mats placed on DMGP to provide a durable travel and work surface, maintain soil physical structures, and increase work windows, comes at the cost of vegetation biomass quantity and quality. The combination of blocked solar radiation, crushed and broken vegetation, and increased contact with soil, likely led to increased plant death and quicker decomposition, especially in high moisture environment under mats, and when imposed for longer periods of time. Benefits and costs of mats to mitigate traffic impacts should be balanced with the duration of placement and known recovery patterns to allow for maximum conservation of both soils and vegetation.

In general, the loamy-sand sites had an increased proportion of biomass associated with the matting treatments, which consisted of increased amounts of introduced and ruderal forb biomass relative to grasses. Mat placement that occurred earlier in the season (E6, E12, and SL24) or for longer periods of time (12 and 24 weeks) also were more likely to alter the relative biomass of different functional groups. Mat use reduced biomass of grasses and native forbs but increased biomass of introduced forbs. Althoff et al. (2009) and Thurow et al. (1996) found that traffic and the effects of traffic, soil compaction, exposed soil and damage to vegetation, often led to an undesirable shift from grasses to annual and invasive grasses as well as forbs, it appears that even traffic over mats will have this same result.

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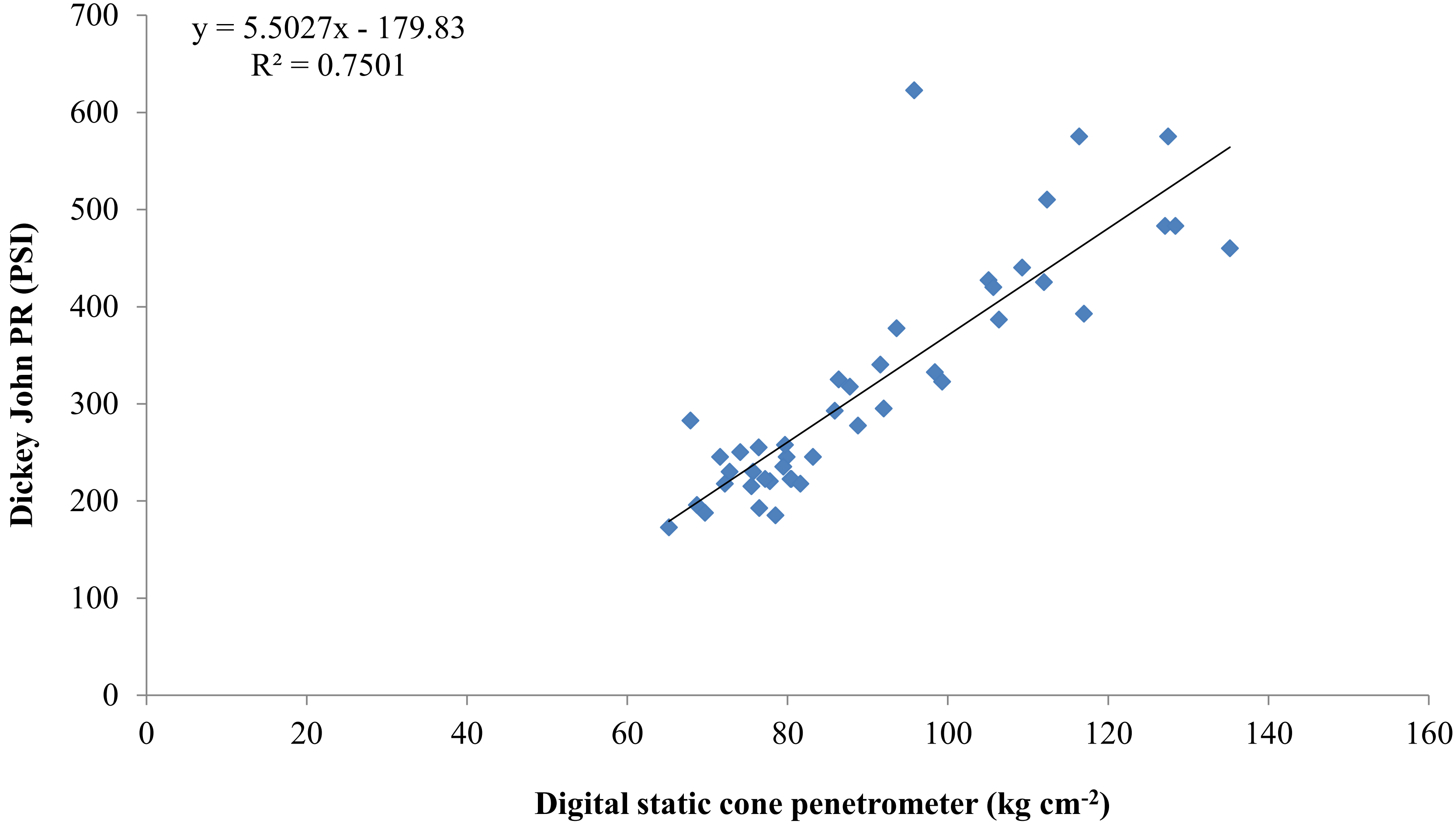
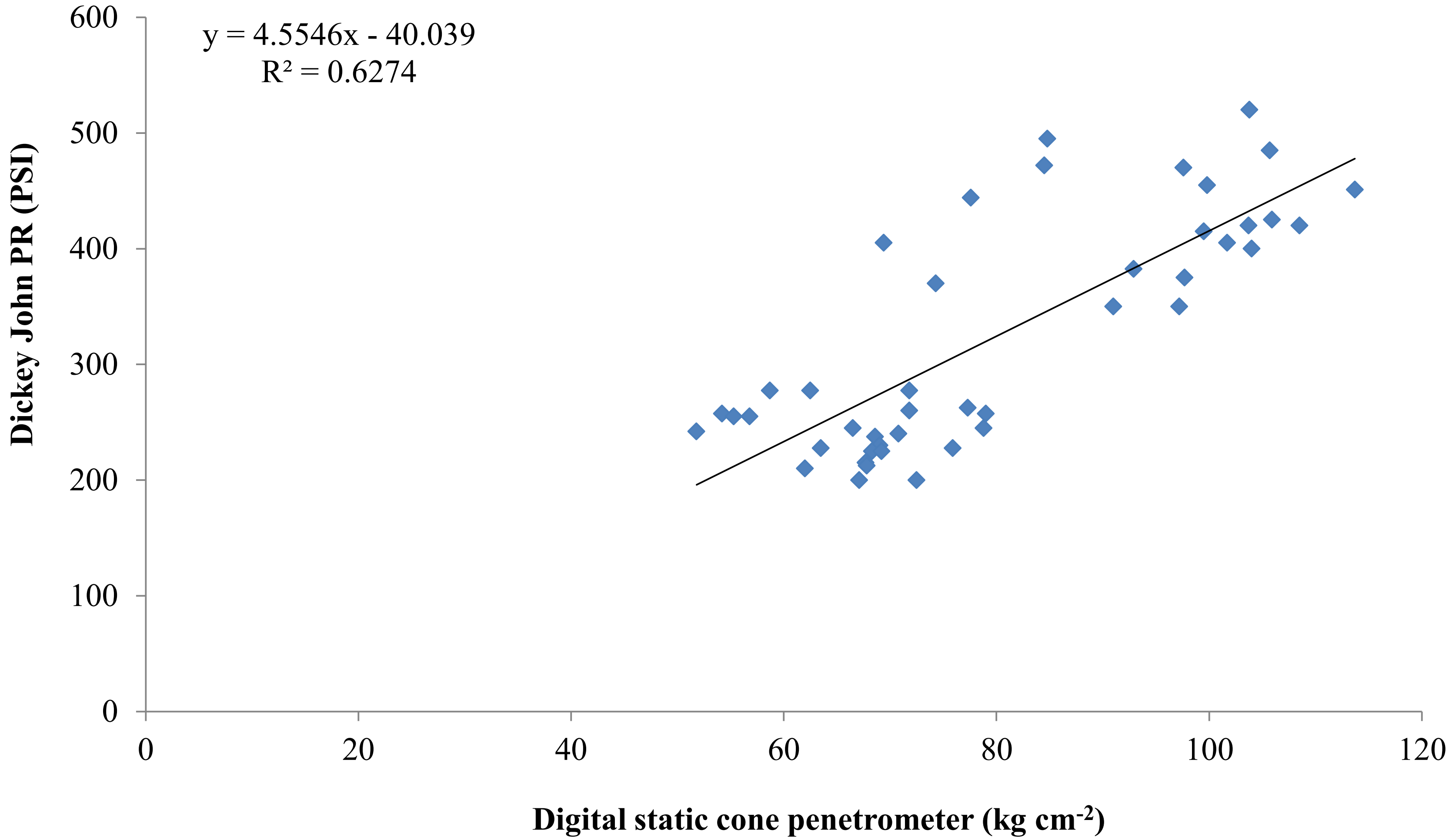
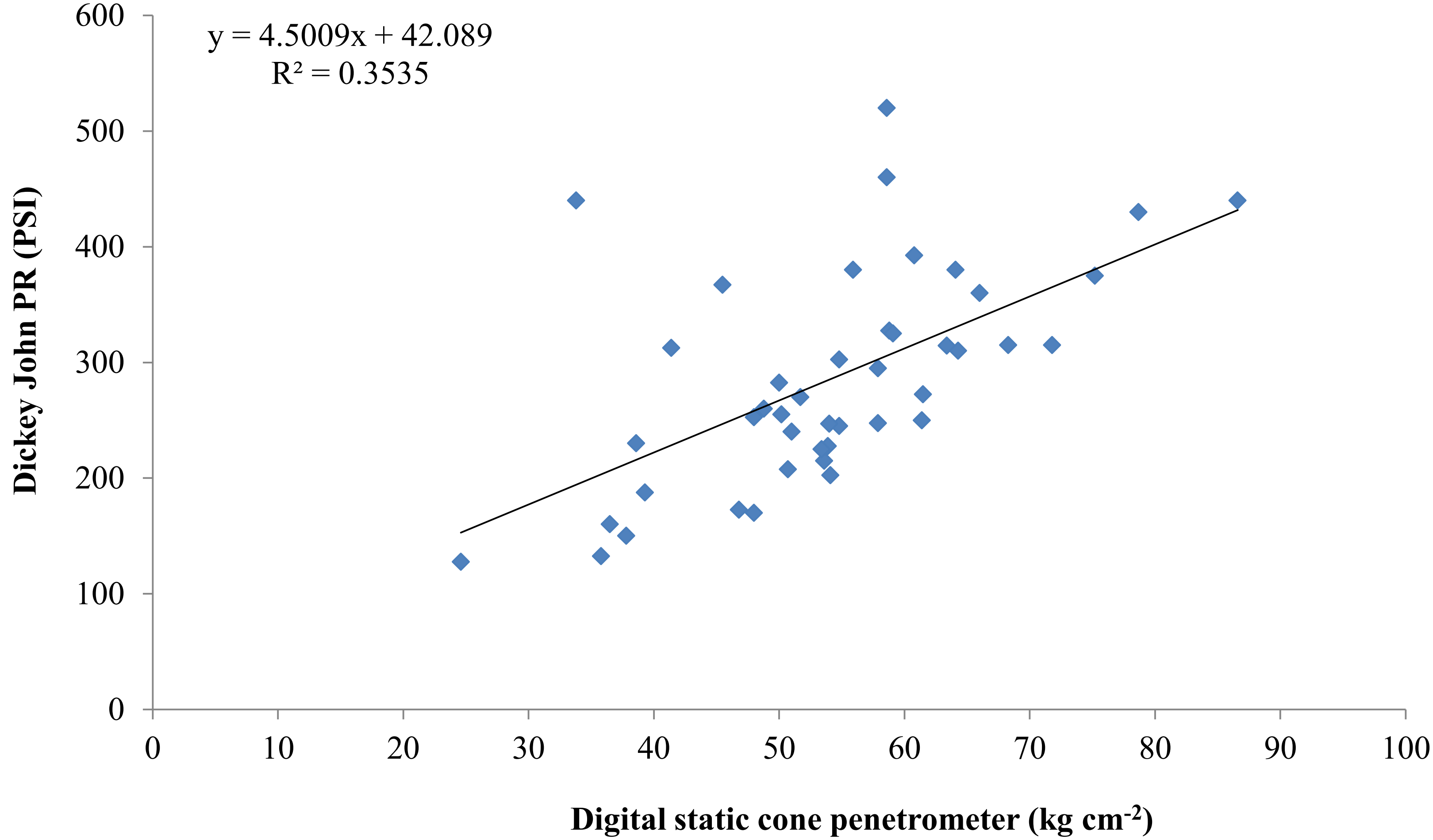


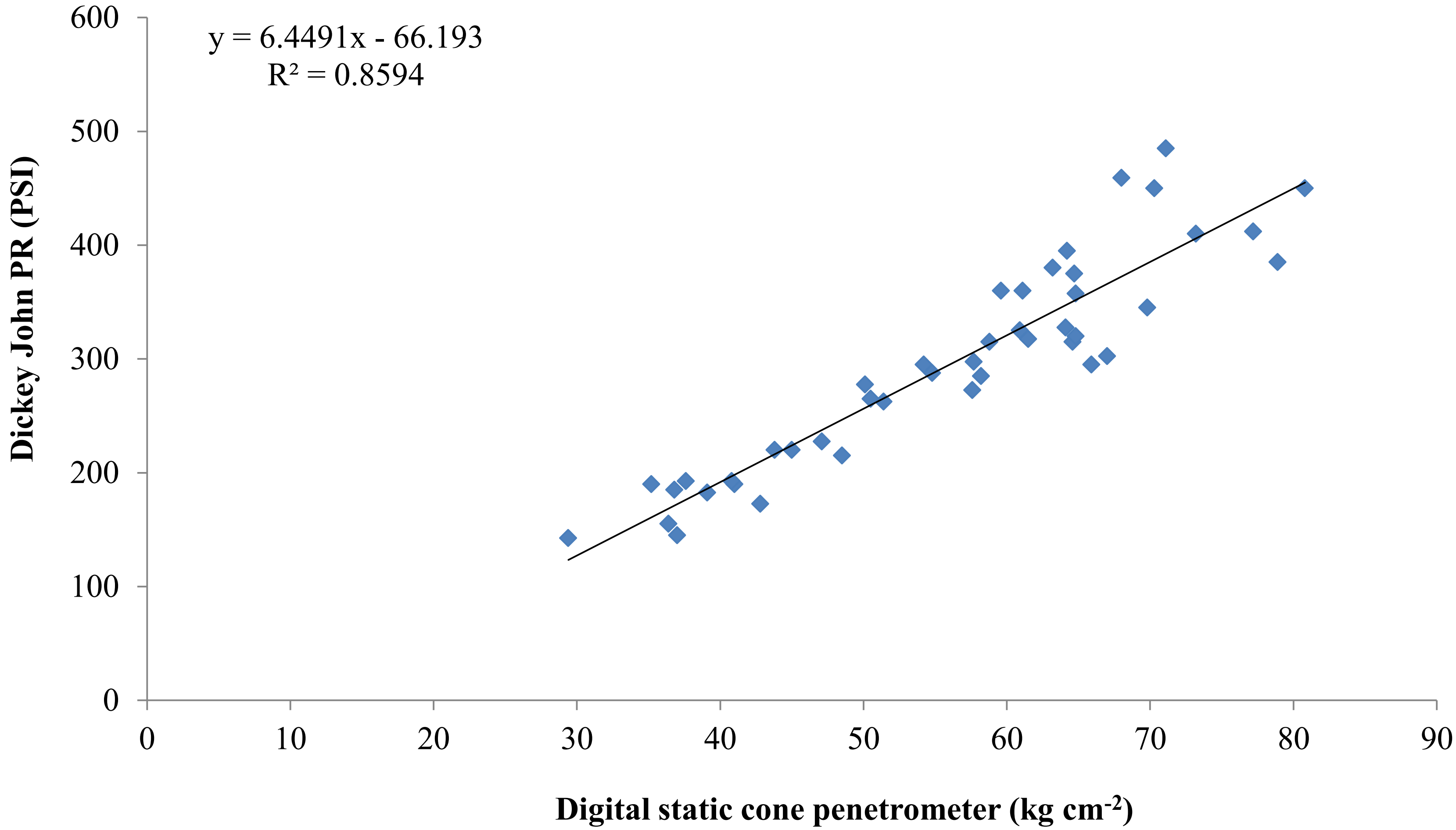
Appendix 1. Penetration resistance (PR) of Site 1 regression to convert DSCP to soil compaction tester by a linear regression.



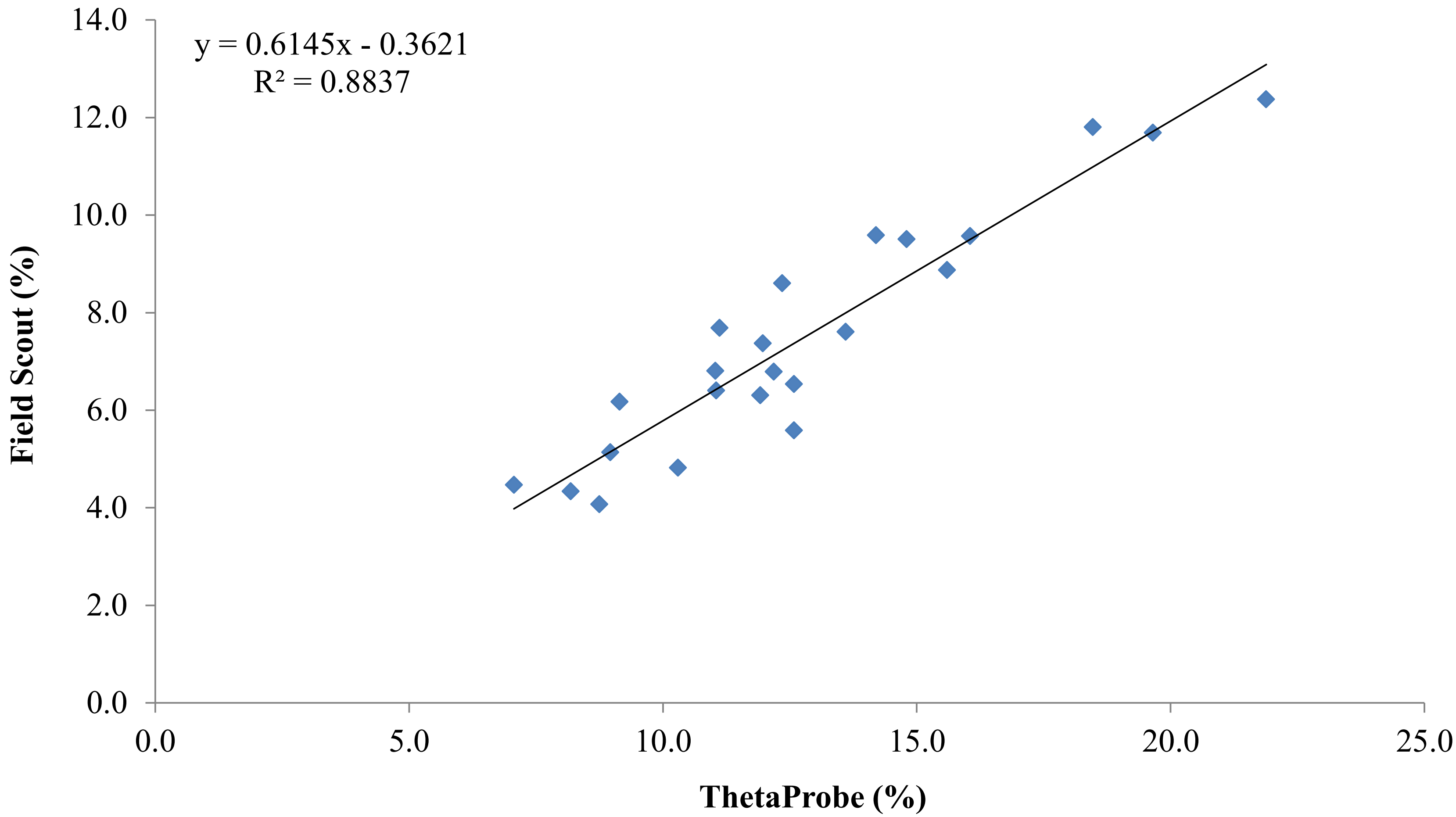
Appendix 2. Penetration resistance (PR) of Site 2 regression to convert DSCP to soil compaction tester by a linear regression.



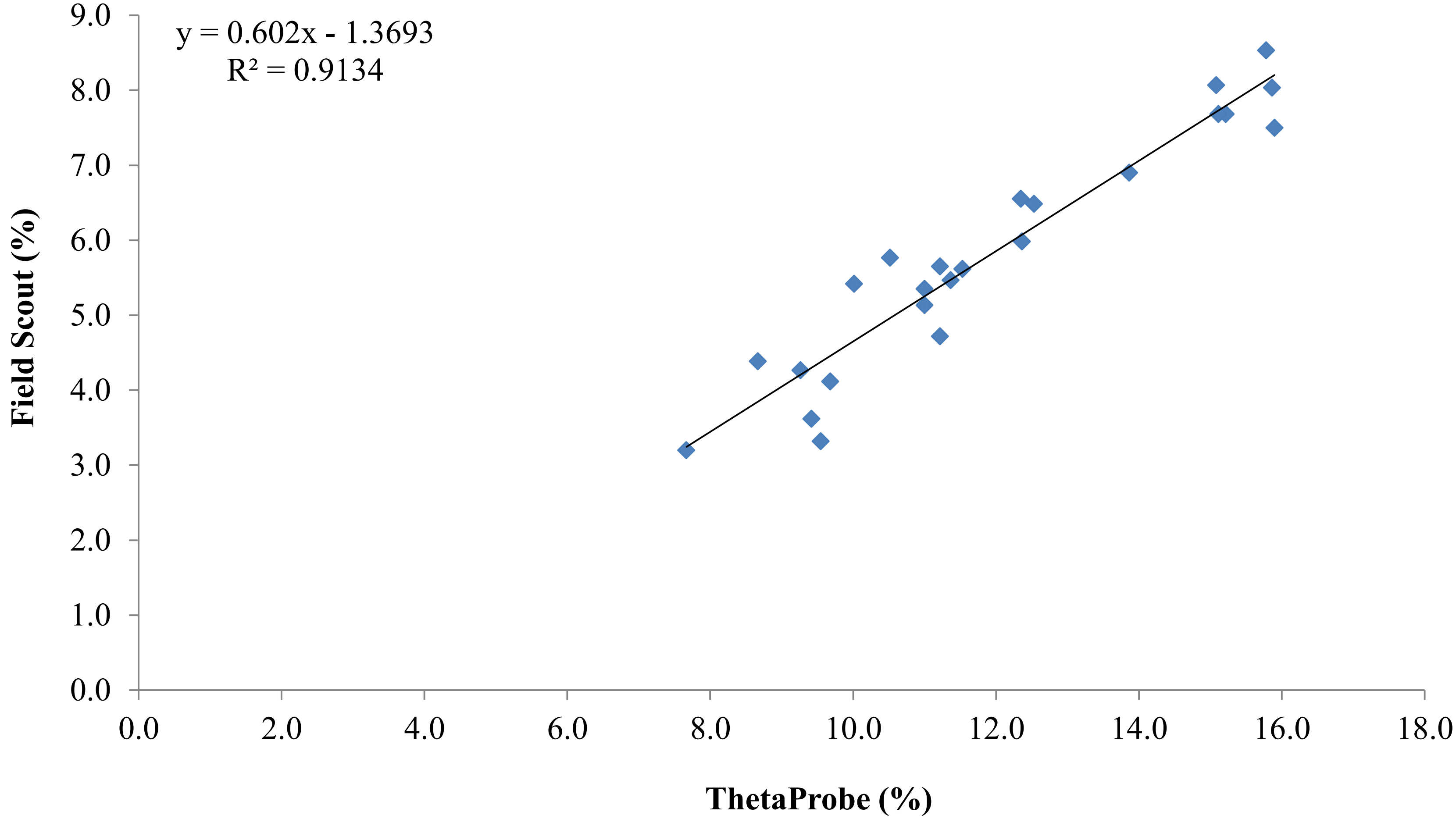
Appendix 3. Penetration resistance (PR) of Site 3 regression to convert DSCP to soil compaction tester by a linear regression.



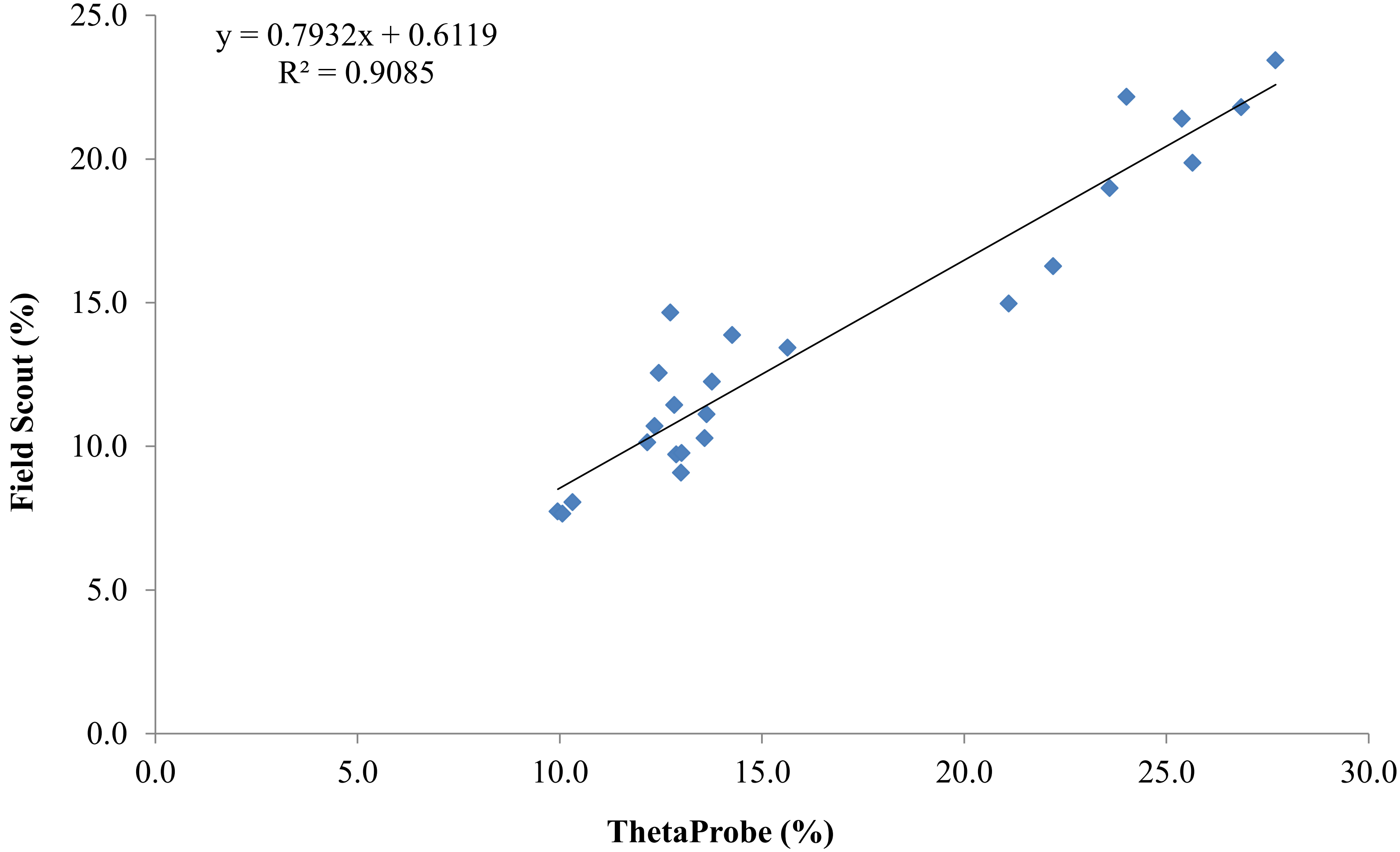
Appendix 4. Penetration resistance (PR) of Site 4 regression to convert DSCP to soil compaction tester by a linear regression.



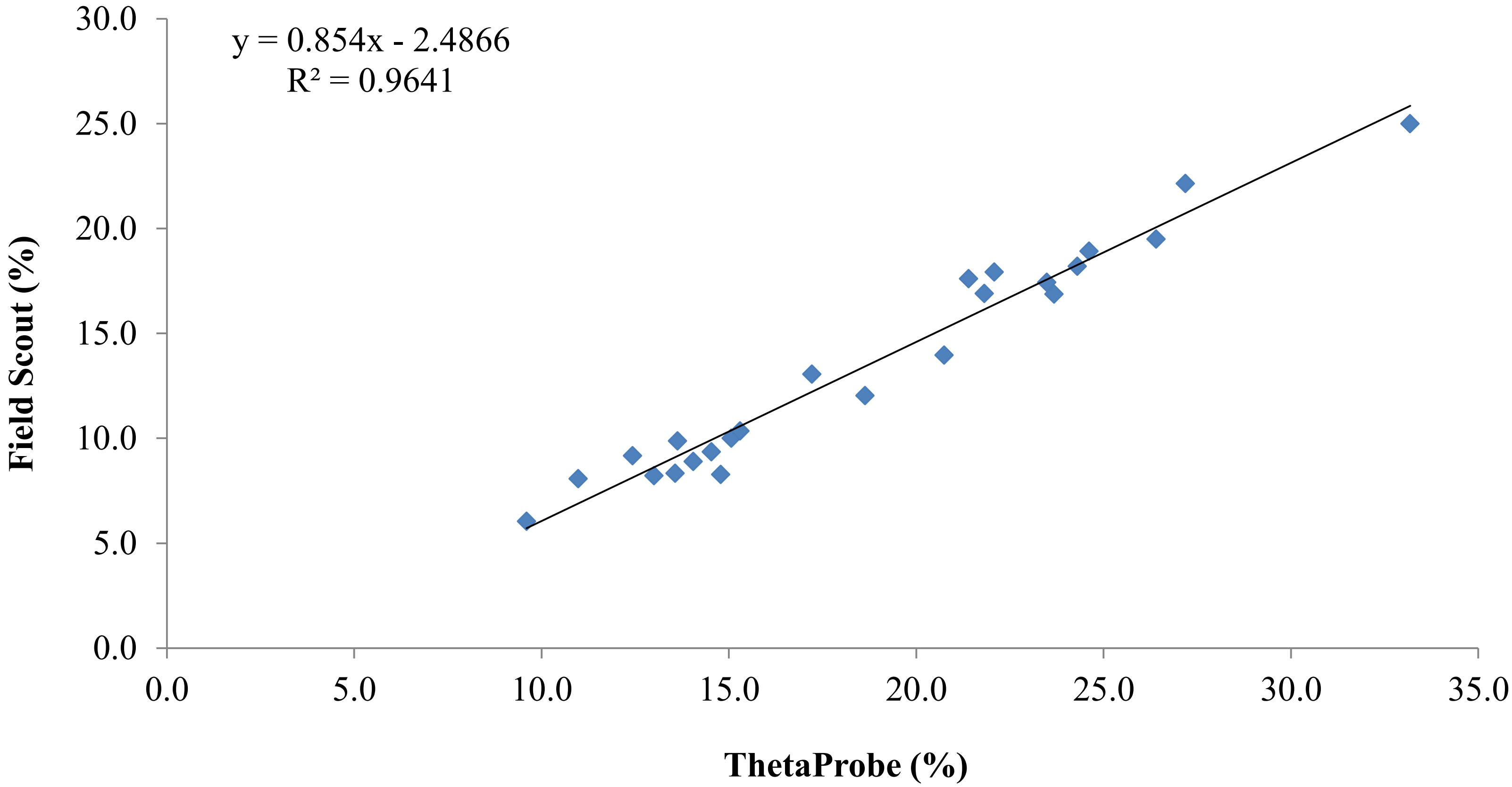
Appendix 5. Soil Moisture Content (SMC) of Site 1 regression to convert ThetaProbe to Field Scout by linear regression.



Appendix 6. Soil Moisture Content (SMC) of Site 2 regression to convert ThetaProbe to Field Scout by linear regression.



Appendix 7. Soil Moisture Content (SMC) of Site 3 regression to convert ThetaProbe to Field Scout by linear regression.



Appendix 8. Soil Moisture Content (SMC) of Site 4 regression to convert ThetaProbe to Field Scout by linear regression.