EFFECTS OF CALCIUM BASED SURFACE AMENDMENTS ON HYDRAULIC CONDUCTIVITY AND SELECTED PHYSICAL PROPERTIES OF SUBSURFACE DRAINED SODIC SOILS

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

DOCTOR OF PHILOSOPHY

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ABSTRACT

Managing excess soil water in agricultural fields in the Northern Great Plains through subsurface drainage increases the risk of sodification in high-risk soils. Leaching sodic soils with low electrical conductivity (EC) water, rainfall, may result in the swelling of soil, dispersion of clay particles and consequently the breakdown of soil structure leading to changes in physical and mechanical properties of soils (e.g., reduced infiltration, hard-setting and reduced trafficability). In this dissertation, the effectiveness of calcium amendments of gypsum and spent lime, a byproduct of the processing sugar beets, with water-management treatments of free drainage (FD) and no drainage (ND) on improving physical properties of the soil were examined.

The first objective was to evaluate the effects of drainage and surface treatments on the penetration resistance (PR). The second objective was to use infiltration tests with a mini-disk tension infiltrometer and a Cornell sprinkle infiltrometer to investigate changes in hydraulic properties. Lastly, a drawbar dynamometer was used to measure draft on a chisel plow as it was pulled across the plots by a tractor equipped with an auto-guidance system and instrumentation interfaced with the controller area network of the tractor.

The results show that the PR values of plots with gypsum application at high rate of 22.4 Mg ha^{-1} (GH) were significantly higher than other surface amendments. GH increased the hydraulic conductivity of the soil matrix compared to spent lime application at rate of 22.4 Mg ha^{-1} (SL); however, the overall flow of water through the soil profile, including the soil matrix and the macropores, was not affected. Both GH and gypsum application at high rate of 11.2 Mg ha^{-1} (GL) lowered the drawbar power requirements compared to spent lime application. For many farmers, drainage enables early planting and the adding of ameliorants will safeguard against further sodification of their fields.

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To God, without whom none of this would be possible.

DEDICATION

To

My wife, Miriam

My parents, James and Mary Wamono

"Blessed is the one who finds wisdom,

and the one who gets understanding,

for the gain from her is better than gain from silver

and her profit better than gold."

Proverbs 3:13-14

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1. GENERAL INTRODUCTION

1.1. Background

The installation of tile drainage and tilling of long-term Conservation Reserve Program (CRP) and pasture or hay lands poses a risk of transforming saline-sodic soils to sodic conditions on the Northern Great Plains (NGP). Due to the high levels of soil water content during spring and fall seasons that have become common on the NGP as result of the recent wet cycle, land managers are turning to tile drainage to address this problem. In saline/sodic soils with a high water table under non-drained conditions, the leached solutes (nutrients and salts) move back to the surface layers of the soil with capillary water movement. However, tile drainage prevents this upward movement of nutrients and salts by lowering the phreatic zone. Yet, leaching sodic soils having low electrical conductivity (EC) may result in the dispersion of clay particles where these dispersed particles plug pores in the soil hampering water flow and therefore reducing the water infiltration and hydraulic conductivity (Sahin et al., 2011).

The dispersion of particles and the breakdown of soil structure changes physical properties of the soil that pertain to tilth and thus increasing the risk of compaction, increasing the penetration resistance when dry, and conversely lowering penetration resistance when wet. Calcium based surface amendments have been used to ameliorate the effects of sodification in soils. In sodic soils, chemical amelioration with calcium based surface treatments may increase hydraulic conductivities (Ilyas et al., 1997) and therefore the efficiency of the tile drainage. Moreover, soil amendments have been shown to increase the Atterberg limits (plastic limit and liquid limit) of the soil, and therefore the moisture content range in which the soil can be worked without permanent damage (Aksakal et al., 2013).

Compaction of the soil leads to loss in crop productivity and other disastrous environmental concerns such as increase in soil erosion, runoff, and subsurface drainage difficulties (Materechera, 2009; Taghavifar & Mardani, 2014). As opposed to free drainage, controlled drainage, where inline flow control structures are used to manage the water table, offers a process where moisture in the soil is reduced in times of excess (spring and fall) and water is retained in soil during drier months (summer). Sodification can be reduced in controlled drainage systems where Ca^{2+} ions and other nutrients are recycled back by capillary water movement to natric layers. Therefore, sodification risks may be reduced by utilizing a controlled drainage system. Different cropping systems (crop rotation, cover crops, and deep rooting crops) have been employed in the management of sodic soils. Cropping systems coupled with surface amendments and drainage systems have been employed with varying success (Ilyas et al., 1997).

1.2. Salt-affected soils

The problem of salts in soils is widespread with over 930 million hectares worldwide (Szabolcs, 1989) and over 10 million hectares on the NGP (J. Brennan, personal communication, NRCS North Dakota, 2008). The distribution of salt affected soils is across many continents (Table 1), however, the intensity and the magnitude have been exacerbated by poor land use and water management practices (Qadir et al., 1998).

Salt affected soils are grouped into saline, sodic, and saline-sodic on the basis of the total amount of salt content and the proportion of sodium present in the soil (Table 2). The exchangeable sodium percentage, sodium adsorption ratio, percent sodium, and EC are the basis for quantifying the salt content and proportion of the sodium on the soil exchange sites or the soil water solution. Salinization of a piece of land is caused by dissolved salts in the irrigation water or because of possible upward movement of salts through capillary action (Beltrán, 1999). The majority of the salt affected soils occur in semi-arid and arid soils under irrigation where loss in soil quality as result of excess exchange of sodium leads to swelling, and dispersion of clay particles, therefore lowering the hydraulic conductivity (Bagarello et al., 2006).

Table 1. Distribution of salt affected soils in the world (Squires, 2004)

Continent	Saline (Mha)	Sodic (Mha)	Total(Mha)
Africa	122.9	86.7	209.6
South Asia	82.2	1.8	84.0
North & Central Asia	91.4	120.1	211.4
Southeast Asia	20.0	-	20
North America	69.4	59.8	129.2
Mexico/central America	2.0	-	2.0
Australasia	17.6	340	357.6
Global total	411.7	617.9	1029.5

Table 2. Classification of salt affected soils (U.S. Salinity Laboratory Staff, 1954).

Normal Soils	Saline soils	Sodic Soils	Saline-sodic soils
EC < 4 dS m^{-1}	EC> 4 dS m^{-1}	EC< 4 dS m^{-1}	EC >4 dS m^{-1}
SAR <13	SAR <13	SAR >13	SAR >13
ESP < 15%	ESP < 15%	ESP >15%	ESP >15%

EC = electrical conductivity; SAR=$[Na^+]/\{([Ca^{2+}]+[Mg^{2+}])/2\}^{1/2}$ concentration expressed in mmol L^{-1}, ESP= [(exchangeable Na^+, $cmol_c\ kg^{-1}$)/(cation exchange capacity, $cmol_c\ kg^{-1}$)] x100

1.3. Remediation of salt affected soils

The conventional approach for remediating saline-sodic and sodic soils involves first applying a calcium based amendment followed by leaching (Qadir et al., 1998), whereas leaching good quality waters is sufficient for saline soils. The calcium ion replaces the sodium ion on the cation exchange sites. Sources of calcium include gypsum, calcium carbonate and calcium chloride; however, if a calcareous layer exists in the profile, then application of an acid can be used instead to release calcium ions. For calcareous saline-sodic soil, phytoremediation, which involves the growth of salt tolerant plant species with root systems that dissolve the indigenous calcium compounds to replace sodium ion on the exchange sites, can be employed.

Phytoremediation has been adopted on marginal land with several plant species (Qadir et al., 2001). Singh et al. (2013) were able to reduce the exchangeable sodium percentage by 70% using plants Barbados nut or physic nut (*Jatropha curcas*) and Velvet mesquite (*Prosopis Juliflora*) in a period of six years. Improvements were reported in other physical properties (for example, water holding capacity, bulk density, electrical conductivity, organic carbon). Similarly, microbes have been used in conjunction with gypsum to remediate saline-sodic soils. The microbes accelerated the dissolution of the gypsum and increased the amount of exchange calcium ions in the soil (Sahin et al., 2011).

Changes in the hydraulic conductivity were used to evualate improvements in physical properties of the saline-sodic soil. In poorly drained saline-sodic soils with a high water table, subsurface (tile) drainage improves the productivity of soil by lowering the water table. Lowering the water table improves the aerobic condition in the root zone which leads to increased productivity of the soil (Jia et al., 2012). Secondly tile drainage facilitates faster drying of the soil which leads to better trafficability of the soil.

1.4. Soil penetration resistance

Soil penetrability is a measure of the resistance ease or difficulty encountered by an object as it is driven in the soil (Blake & Hartge, 1986). A penetrometer is any device that is designed to measure this resistance. The penetration resistance is used by several professions to gather information on the soil properties such as relative density, shear stress and bearing capacity. For agricultural production, penetration resistance relates to root growth, crop yield and other soil properties that are descriptive of tilth. There are various categorizations of penetrometers that include: cone penetrometers, flat-tipped penetrometers, static penetrometers, dynamic penetrometers, mechanical cone penetrometers and hand held penetrometers (Blake &

Hartge, 1986; Hillel, 1998). These categorizations are made depending on one or more characteristics of the penetrometer. The cone penetrometer (ASABE Standards, 2009) which reads penetration resistance as a cone index (the force per unit base area) is very popular. Physical and mechanical properties can be studied using penetrometers. For example, Silva et al., (2009) evaluated changes in the structure of a soil on a sugarcane field due to heavy machinery. In this study, the cone index was used to identify the hard pan from which soil samples were tested for Atterberg limits. Penetration resistance of a soil is affected by bulk density, soil moisture status, soil depth and its compaction cycles. Gao et al. (2012) used applied stress, density, matric potential, void ratio, air entry potential and soil structure, with the concept that penetration resistance is proportional to the shear modulus, to evaluate to the increase in penetration resistance with applied pressure, density, air entry potential and matric potential. For a wet soil, an increase in the penetration resistance followed drying.

Soil compaction, which is the reduction in porosity of the soil, affects many process including reduction in saturated hydraulic conductivity and increase in runoff (Keller et al., 2013). Little research has been focused the soil deformation process itself. Soil deformation, which is the response of a soil to an applied pressure, is dependent upon the soil stress, soil strength and how this stress is transmitted in the soil (Keller et al., 2013). The strength of tilled soil changes immensely with the amount of moisture in the soil, which in turn affects its trafficability. Bachmann et al. (2006) used penetration resistance (PR) and vane shear test (VS) to determine compaction state of the soil. A simplified approach was taken where the horizontal stress was equal to overburden stress from the specific weight of soil and the influence of vertical stress was constant. The results show a high correlation between the PR and VS values obtained from both methods. An increase in the compaction state of the soil shown by higher PR and VS values was observed when the land-use was changed to pasture, and this compacted layer expanded to deeper the lower layers the longer the land was left under pasture.

Soil compaction, which saline-sodic soils are susceptible to, can be described using Atterberg limits. Aksakal et al. (2013) used Atterberg limits together with compression curves derived from a consolidometer to evaluate if pre-consolidation pressure, which is the maximum pressure an unsaturated soil can take without compaction, had been exceeded. Atterberg limits, like penetration resistance, offer a good description of the mechanical properties of the soil. Furthermore, the effects of diatomite, which is a low density sedimentary rock made up predominantly of fossilized silica, have been evaluated as a soil conditioner using bulk density, Atterberg limits and other mechanical properties (Aksakal et al., 2013). The application of diatomite led to a reduction in bulk density and an increase in resistance to mechanical forces of the soil.

1.5. Infiltration

Saline-sodic soils often present challenges of water movement together with salts. Infiltration, which is the movement of water into the soil, is a complex process that involves distribution of water in the matrix by forces of cohesion and adhesion, displacement of air in the pore spaces, filling of the pores, and progression of the wetting front (Parhi et al., 2007). The theory of infiltration is based on the conservation of mass and Darcy's law.

Naturally occurring soils have permeabilities that vary with depth either as a result of surface crusting, which reduces the infiltration in the upper layer, or surface modification (e.g. tillage and use of cover crops), which enhances infiltration (Corradini et al., 2011). Surface sealing and crusting is a physical process resulting from raindrop impact on the soil surface, which leaves a hard layer. Another form of surface modification is the application of gypsum to the soil surface. Gypsum application leads to aggregation of soil particles. Aggregation refers to the arrangement of soil particles into stable structures and this chemical process is facilitated by soil organic carbon, gypsum and ion exchangeable ions (Badorreck et al., 2013). Therefore, changes in infiltration as a result of surface amendments to saline-sodic soils can be evaluated using infiltration measurements.

1.5.1. Water infiltration models

Models used to estimate infiltration are generally classified as physically based models or semi-empirical or empirical models. Very little information can be garnered from empirical models (for example Horton, Philip and Kostiakov) despite their simplicity (Ma et al., 2010). The Philip (1957) equation was developed for ponded conditions and is given by

$$i(t) = \frac{1}{2\sqrt{t}}\, S + K \qquad (1)$$

where *i(t)* is the infiltration rate ($L\ T^{-1}$) at t, any given time (T); S is the sorptivity of the soil which is a measure of the rate at which water is drawn into an unsaturated soil ($LT^{-1/2}$) and K is the hydraulic conductivity of the soil ($L\ T^{-1}$). The Horton (1941) equation was developed to describe overland flow where the layers on top are saturated, with wetting front moving down the soil profile. The infiltration rate under these conditions is given by

$$i(t) = i_c + (i_o - i_c)e^{\alpha t} \qquad (2)$$

where *i(t)* is the infiltration at a given time, i_o is the initial infiltration rate, in i_c is the final infiltration rate, α is a constant based on the hydraulic conductivity. The Kostiakov (1932) equation estimates the instantaneous infiltration rate using time as a power function of two constants b and c (Bamutaze et al., 2010) and is given by

$$i(t) = bct^{\alpha - 1}\,. \qquad (3)$$

The second class of infiltration models is physically based models that substantially describe the infiltration process (Ma et al., 2010). In this class, the Richards's equation and the Green Ampt model are the most common. The Richards equation is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K\left(\frac{\partial h}{\partial x} + 1\right)\right] - S_k \quad (4)$$

where h is the soil water pressure head (L), θ (L^3 L^{-3}) is the volumetric water content, *t* is time, z is the vertical height, K is the unsaturated hydraulic conductivity, and S_k is the sink term (L T^{-1}). Richards's equation (1931) represents the transient state for movement of water in unsaturated soils. It was derived by applying continuity (conservation of mass) to Darcy's law. The Green-Ampt (1911) equation is

$$i = K_s\left(1 + \frac{H_o + S_f}{Z_f}\right) \quad (5)$$

where *i* is the infiltration rate, K_s is the hydraulic conductivity of the upper saturated soil column, Z_f is the depth of the wetting front, S_f suction pressure on the wetting front, and H_o is the ponding depth. Infiltration in the saturated part of the soil profile is driven by the ponding depth; while at the wetting front, the infiltration is driven by suction pressure of the unsaturated soil.

1.5.2. Disc infiltrometer

From the infiltration models, several designs of infiltrometers have been developed. One class is the disc infiltrometer. The infiltrometer is made of a graduated water reservoir on a disc base and an air bubble tower (Latorre et al., 2013). To insure that the base of the infiltrometer is in contact with the soil surface, a contact layer usually made of sand is employed. However, researchers must consider that adding this layer of sand might influence the natural process of infiltration. The use of disc infiltrometers has grown in popularity among researchers because of the relative ease of its application in the field and the number of soil-water properties that are estimated by the tool. These include the hydraulic conductivity, sorptivity, the size of macro and meso pores which are vital to soil and hydrological sciences. A number of these soil properties can derived from infiltration curves of the disc infiltrometer (Moret-Fernández & González-Cebollada, 2009). The soil hydraulic properties are based on transient water conditions and not steady state; this reduces time and water constraints in infiltration determination. The soil hydraulic properties are calculated from cumulative infiltration curves in the classical design and infiltration rate curves in newer designs with micro-flow meters and pressure transducers (Moret-Fernández, Latorre, & González-Cebollada, 2012).

1.5.3. Ponded infiltrometers

A second class of tools for measuring infiltration is the ponded infiltrometer. A constant pressure head ring infiltrometer has been used to measure saturated soil hydraulic conductivity, K_s, (Bagarello et al, 2009) where a metal ring is inserted at a shallow depth, and the hydraulic pressured head is maintained at a constant inside the ring. Single ring pressure infiltrometers can be set up at one ponding depth, two ponding depths and multiple ponding depths, where each depth influences the rational analysis of data and estimation of key parameters in evaluation of hydraulic conductivity (Elrick et al, 1990). A single ring infiltrometer yields an infiltration rate that is a combination of both lateral and vertical flow of water in the soil. An increase in the ring diameter to at least 0.15 m (Chowdary et al., 2006) results in a consistent reading. To check the lateral component of infiltration, a double ring infiltrometer design has been developed and deployed although its effectiveness is unclear. For example, (Chowdary et al., 2006) evaluated several configurations for diameters in both double ring and single infiltrometers and concluded that lateral movement could not be eliminated but managed. They stated that in single ring infiltrometers at an insertion depth of 0.07 m and ring diameter of 0.3 m, the infiltration process is a function of ponding height, saturated hydraulic conductivity and initial moisture content (Chowdary et al., 2006).

1.5.4. Rain simulators

Another class of infiltration measuring tools is rain simulators. Rainfall simulators are categorized either as non-pressured (drop forming) (Aksoy et al., 2012) or pressured (nozzle spraying). The drop forming rainfall simulators produce energy fluxes that are smaller than natural rainfall events while the pressured rainfall simulators produce terminal velocities and intensities higher than natural rainfall (Abudi et al., 2012). In comparison to the disc infiltrometers and ponded ring infiltrometers, rain simulators enable the reproduction of intensities, raindrop sizes and energies similar to natural rainfall events. Other advantages of this tool include: the quick collection of data at constant conditions over the area of interest, a relatively cheap cost, and the ability to be move the rainfall simulator from one location to another (Abudi et al., 2012). Rainfall simulators have been applied to investigate the role of antecedent rainfall, soil cover, and microtopography on crust formation and resultant infiltration of fields (Battany & Grismer, 2000; Freebairn & Gupta, 1990). One of the greatest areas of application for both pressurized and drop forming rainfall simulators is in erosion and runoff studies (Guerrant et al., 1990; Wierda & Veen, 1992).

1.5.5. Cornell sprinkler infiltrometer

The benefits of the rainfall simulators and ring infiltrometer have been harnessed in the Cornell sprinkler Infiltrometer (Ogden et al., 1997). The Cornell sprinkler infiltrometer is a fusion of a rain simulator and single ring infiltrometer. The droplet size from the rain simulator is constant within the range of hydraulic pressures experienced in the unit. Characteristic of all drop forming simulators, the Cornell sprinkler has a narrow range of intensities with limited choice for size of rain drops. Therefore, the Cornell sprinkler wets the soil in a manner similar to a natural rainfall, moderates contributions of macro pore flow prevalent with ponded infiltrometers, and maintains the influence of soil surface roughness on infiltration (Ogden et al., 1997). The Cornell sprinkler infiltrometer is a low cost, highly portable tool with the ability to generate a range of rain fall intensities. It consists of a 241-mm (9.5-inch) diameter ring on which a portable rain simulator is placed.

1.5.6. Field infiltration studies

The hydraulic conductivity of saline-sodic soils has been extensively investigated under laboratory conditions using air dried, sieved and repacked soil cores (Bagarello et al., 2006). Under these conditions, the soil is often saturated and chemically in equilibrium with the sodic water, which rarely occurs under field conditions (Bagarello et al., 2006). In order to obtain flow regimes that are comparable to infiltration of fields under natural rainfall events, hydraulic conductivity can be estimated using single ring infiltrometers (Bagarello et al., 2006), where the antecedent moisture content and soil structure are maintained. To compare the infiltration of different soils using ring infiltrometers, care must be taken to ensure that depth penetration into the soil and ponding head of the infiltrometers are maintained constant (Chowdary et al., 2006).

1.6. Objectives of research

This project evaluated effectiveness of calcium based surface amendments under drainage and non-drainage conditions on improving hydraulic and mechanical soil properties. The project developed guidelines and recommendations for removing excess water, improving trafficability and workability, and reducing the drawbar power requirements of sodic-saline soils. The research project focused on the quantifying the effects of surface treatments on the soil hydraulic properties of fields with different water management strategies (free drainage and no drainage). Physical properties of the soil that pertain to soil strength under different surface treatments were analyzed.

1.6.1. Specific objectives of research

Penetration resistance (PR) of the soil and drawbar forces on a tractor pulling a chisel plow were measured to compare changes soil physical properties, for example compaction and trafficability of the soil. Surface infiltration using a Cornell sprinkler infiltrometer and a tension infiltrometer were used to compare changes in the hydraulic properties under various surface treatments.

1.7. Organization of dissertation

This dissertation is comprised of six chapters which are: a general abstract, general introduction, three manuscripts that are under review for publication in suitable scientific journals, and a general conclusion. The general abstract provides a brief summary of findings of each of the three papers. The general introduction provides an overview of the problem statement, the objective of the research and how this study relates to other research work in sodium affected soils. The general introduction also introduces the distribution of salt affected soils both regional and international, sodic soil characterization, and their effects on the physical properties of soil, and land use. A detailed literature review is provided in each chapter. The first paper uses penetration resistance to investigate the effects of drainage and calcium surface amendments on trafficability of sodic soils. The second paper assesses the effects of gypsum and sugar beet spent lime application on hydraulic properties of subsurface drained sodic soils. The third paper presents the effects of calcium amendments on the drawbar power of subsurface drained sodic soils. The general conclusion presents the findings from the research studies. References are listed at the end of each chapter except for the general conclusion.

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2. EFFECTS OF CALCIUM BASED SURFACE AMENDMENTS ON THE PENETRATION RESISTANCE OF SUBSURFACE DRAINED SODIC SOILS[1]

2.1. Abstract

In Northern Great Plains saline/sodic and sodic soils, subsurface drainage can inadvertently result in clay particle dispersion if the surface soils are leached with rainwater. Under these conditions, penetration resistance (PR) in wet soil can be used to examine the effectiveness of free drainage (FD) vs. no drainage (ND) treatments and surface amendments consisting of a high rate of gypsum (GH), a low rate of gypsum (GL), spent lime (SL, a byproduct from the processing of sugarbeets), and no amendments [or check plots (CK)] on improving soil trafficability. The PR and soil moisture contents were determined from 0 to 45 cm depth for sodic soil plots near Wyndmere, North Dakota, during June 2015. The effects of drainage and surface amendments on the PR were evaluated using analysis of variance, with gravimetric moisture content incorporated as a covariate. Significant differences were considered at $P<0.05$. The mean PR values of ND (450 and 936 kPa) and FD (428 and 917 kPa) for the 0- to 15-cm and the 15- to 30-cm layers, respectively, were not significantly different. The PR value for the surface 15 cm for GH was higher (485 kPa) than for the other surface amendments. In the 15- to 30-cm layer, the PR for GH (1050 kPa) was significantly higher than for GL (954 kPa)

[1] The material in this chapter was co-authored by Anthony Wamono and D.D. Steele, Z. Lin, T.M. DeSutter, X. Jia and D. Clay and was approved on 17 May 2016 for publication in the *Trans ASABE* Journal as manuscript number NRES-11689-2015. Anthony Wamono had primary responsibility for collecting data in the field, analyzing the data collected, interpreting the results, and developing the conclusions that are advanced here. Anthony Wamono also drafted and revised all versions of this chapter. Co-authors served as technical and editorial consultants in the development of the manuscript represented by this chapter.

which was in turn higher than for SL (866 kPa) and CK (839 kPa). Benefits from the combined effects of drainage and surface amendments were more evident in the 15- to 30-cm layer than in the 0- to 15-cm layer. In the 0- to 15-cm layer, the NDGH (498 kPa) had PR means similar to all other treatments, except it was higher than for FDSL (384 kPa). In the 15- to 30-cm layer, the FDGL (1007 kPa) had similar means to FDGH (1074 kPa) and NDGH (1027 kPa) which showed that drainage coupled with a lower gypsum rate achieved the similar results as the higher rate of gypsum application.

2.2. Introduction

Regionally and internationally, salt-affected soils are a serious and growing problem, and it is estimated that high salt concentrations impact productivity on over 10 million hectares of land in the Northern Great Plains (J. Brennan, personal communication, NRCS North Dakota, 2008) and over 930 million hectares worldwide (Szabolcs, 1989). Farmers and engineers are struggling with the management of these soils. One of the most critical periods occurs in the spring when the soils are wet and farmers are attempting to cultivate and plant the fields. Trafficability, the ability of the soil to support vehicle traffic, is dependent on the soil strength, which is the ability of the soil to withstand stress without undergoing failure. Soil trafficability and strength are also influenced by texture, organic matter, vegetation, moisture content, and soil structure (Daigle et al., 2005). The potential damage to soil structure and compaction of soils when worked beyond their bearing capacity coupled with increased equipment costs pose a risk to drained sodic soils. A soil's drainage status impacts the infiltration rate, moisture profile, the amount of saturation and consequently its load bearing capacity (Müller et al., 1990). The permeability of the soil and a shallow water table, if one exists, will impact the ability of the soil to support heavy agricultural machinery (Daigle et al., 2005). Lowering the water table through subsurface drainage (flexible perforated plastic pipes that collect and move excess water to a sump or any other drainage feature) has been used to improve soil trafficability. However, subsurface drainage by itself in sodic soils may be insufficient and may actually may make trafficability worse.

The application of calcium-based amendments, such as gypsum, to sodic soils, increases the flocculation of dispersed aggregates and thus increases macro-porosity (Ilyas et al., 1997), which in turn improves soil structure and load bearing capacity. Replacement of Na with Ca on the soil's exchange complex also reduces the water holding capacity of the soil because charged Na^+ ions prefer to be hydrated while the Ca^{2+} ions prefer to be bound to the clay particles (He et al., 2015). Reduction in the water holding capacity and flocculation of dispersed soil aggregates should lead to better trafficability in sodic soils treated with Ca. Gypsum application in the reclamation of sodic soils has widely been reported with success in deep, poorly drained soils (Sansom et al., 1998; Wheaton et al., 2008). However, Tirado-Corbalá et al. (2013) reported reduced drainage due to clogging of pores with secondary carbonates after gypsum application in moderately drained non-sodic soils. Other management practices have also been employed for the remediation of sodic soils. In hydrological regimes characterized by upward movements of water, crops with deep roots and high transpiration rates decrease the upward movement of salts (Sansom et al., 1998). The use of crop residue or mulch in semi-arid areas maintains soil moisture that facilitates the dissolution of gypsum (Tejedor et al., 2003). $CaCO_3$, in forms of ground limestone or by-product lime from processing sugarbeets (spent lime), has been found to be a suitable amendment for sodic soil with low pH (Abro et al., 1988).

Evaluation of surface amendments and management practices on soil trafficability can be realized through analysis of changes in a soil's mechanical properties. Earl (1997) lists a range of properties, for example shear stress, bulk density and plastic limit, that predict the mechanical state of the soil. Other properties like moisture content and unsaturated hydraulic conductivity could be used as input data for models that estimate soil trafficability and workability. A number of models to simulate optimal conditions for trafficability based on moisture content have been suggested (Earl, 1997; Wösten & Bouma, 1985); however, the resolution of these models has been on the scale of months and seasons rather than days. Moreover, these moisture-based models require a comprehensive knowledge of the soil water characteristic curve and consistency limits (Aksakal et al. 2013a; Kandel et al., 2013; Mueller et al., 2003).

Mechanical soil properties pertaining soil trafficability can be reliably estimated by cone penetrometers, which measure the penetration resistance (ASABE Standards, 2009). Penetration resistance (PR) is a representative quantity of the forces encountered by a metal object as it is driven through the soil. The forces include metal to soil friction, internal cohesion of the soil, and shear stress (Hillel, 1998). Penetrometers are simple, cost effective, and user friendly and can be used to rapidly take field measurements (Weaich et al., 1992). Bachmann et al.(2006) found penetrometer results comparable to vane shear data while studying stress that represents soil strength in pastures in Chile. Motavalli et al. (2003) used cone penetrometers to detect the presence of clay pans and evaluate the effects of surface applied poultry litter on PR in clay pans.

The objective of this study was to determine the impact of calcium-based surface amendments on a sodic soil's mechanical properties for plots with and without subsurface drainage.

2.3. Materials and methods

2.3.1. Site selection and characterization

The experimental site (97.25° W, 46.2° N and elevation ~326 m) was located near Wyndmere in Richland County, North Dakota, on a predominantly Exline soil (Fine, smectitic, frigid Leptic Natrudolls) with some Stirum-Arveson complex (Stirum: Coarse-loamy, mixed, superactive, frigid Typic Natraquolls; Arveson: Coarse-loamy mixed, superactive, frigid Typic Calciaquolls) on the easternmost edge of the plots. This site has natric characteristics and had been under pasture/hay production for more than 30 years prior to initiation of this study's field research in 2013. Corn (*Zea mays*) was grown on the field in 2013, 2014, and 2015. The site has a drainage class of somewhat poorly drained with depth of the restrictive feature [saturated hydraulic conductivity (K_{sat}) less than 0.025 cm hr^{-1}] between 12.5 to 30 cm (NRCS, 2014). While flooding is uncommon, surface ponding and a high water table in the spring are common. Subsurface drainage was installed in December 2012 at a depth of approximately 1.2 m (4 ft), a spacing of 24.4 m (80 ft), and a drainage coefficient of 9.5 mm d^{-1} (3/8 in. d^{-1}). The 2015 rainfall totals, averaged from onsite duplicate manual rain gauges, were 196 mm in May and 77 mm in June. Penetration resistance measurements were sampled on 11, 23, and 24 June 2015, twenty-five months after the surface amendments (discussed below) were applied.

2.3.2. Experimental design

A completely randomized design using a split plot arrangement was employed with three replicates in the whole plots (drainage treatments) and surface amendments serving as the split plots (see The whole plots were 24.4 m by 107 m (80 ft by 350 ft) and the split plots were 24.4 m by 21.3 m (80 ft by 70 ft). The drainage treatments consisting of no subsurface drainage (ND), free drainage (FD) and controlled drainage (CD) were tested with overlying surface amendments of 22.4 Mg ha^{-1} (10 t ac^{-1}) of gypsum (GH, defined as the high gypsum rate), 11.2 Mg ha^{-1} (5 t ac^{-1}) of gypsum (GL, defined as the low gypsum rate), 22.4 Mg ha^{-1} (10 t ac^{-1}) sugarbeet spent lime (SL), cover crops (CC) and check (CK) plots receiving no surface amendment.

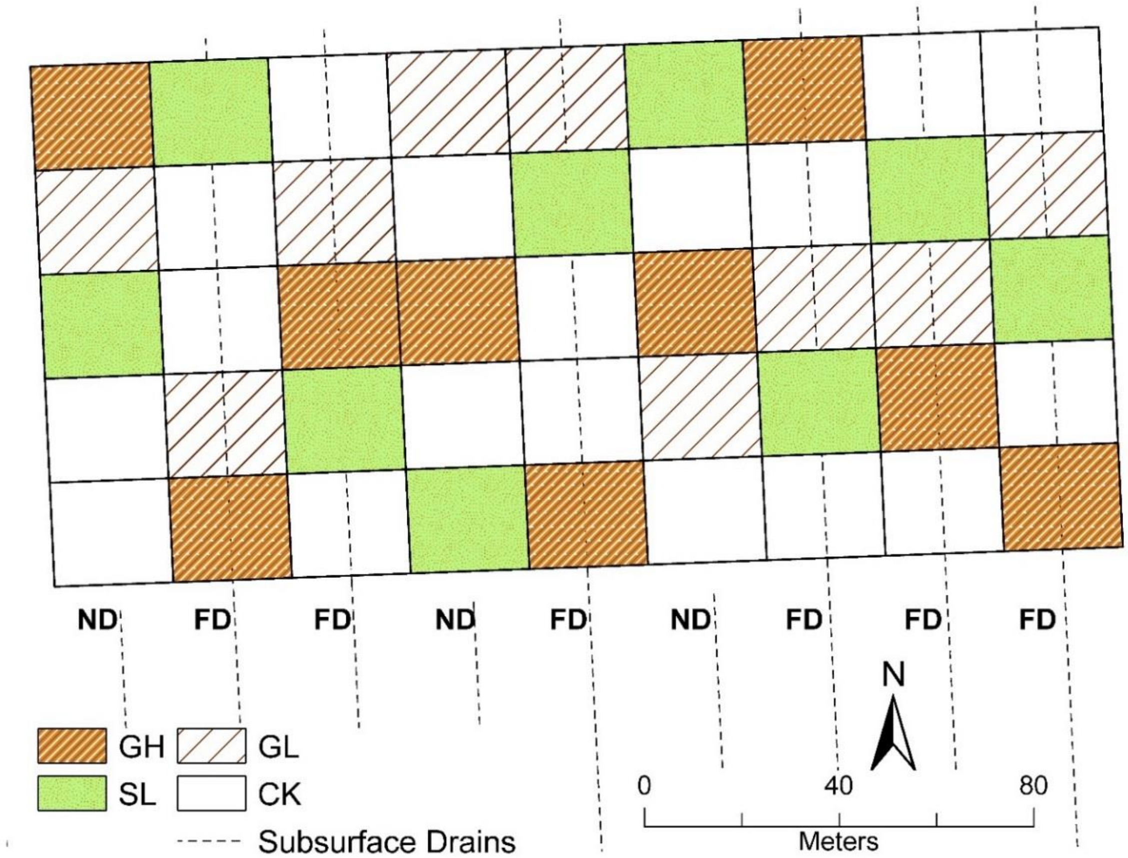

Figure 1. Field-plot layout of the Wyndmere site in Richland County, North Dakota. The surface amendments designated in the legend are: GH, gypsum at high rate [22.4 Mg ha^{-1} (10 t ac^{-1})]; GL, gypsum at low rate [11.2 Mg ha^{-1} (5 t ac^{-1})]; SL, sugarbeet spent lime [22.4 Mg ha^{-1} (10 t ac^{-1})]; and CK, check plots receiving no surface amendment. The drainage treatments are: FD (free drainage) and ND (no drainage).

Corn was planted at site, which leaves no time after harvest for growing cover crops, therefore CC was treated as CK plots. Manual flow control structures (Inline Water Level Control Structures™, Agri Drain Corporation, Adair, Iowa, USA) were installed to manage the depth of the water table in the CD plots while in the FD plots, water flowed out of the plots with no restriction. No flow management was done in the CD during 2015 due to low flow volumes and the CD treatment was essentially operated as FD; therefore, the CD and FD treatments were combined and labeled FD.

The three calcium surface amendments (i.e., GH, GL, and SL) were applied on 14 and 15 May 2013. Pellets of gypsum (Calcium Products Inc., Ames, IA USA) were applied using a machine spreader wagon pulled by a tractor and by hand using shovels to deliver gypsum at desired rates for GH plots. Known quantities of spent lime powder and gypsum were spread manually using shovels to deliver the desired application rate for SL and GL plots, respectively. A field cultivator was used in May 2013 on all plots to incorporate the surface amendments to a depth of 10 cm immediately after their application and prior to planting. The post-spreading tillage, the farmer's annual tillage each fall, and freeze-thaw cycles over the two years after application was expected to have alleviated the compaction from wheel traffic and helped to spread the hand-applied spent lime and gypsum for the GL. We avoided penetrometer sampling at all locations where wheel traffic was evident.

2.3.3. Penetrometer

The cone index (CI), which is a pressure measurement, was taken against depth in all plots using a hand driven cone penetrometer (Field Scout SC 900®, soil compaction meter, Spectrum Technologies, Inc., Plainfield, Illinois, USA) with data logging capabilities synchronized with a GPS unit for spatial coordinates. The penetrometer had an inbuilt ultrasonic sensor at its base which measures the depth of penetration. The penetrometer was pushed into ground at a uniform rate of approximately 30 mm s^{-1} (ASABE Standards, 2009). A cone size diameter of 12.7 mm was used to take readings at 2.5 cm depth intervals from 0 to 45 cm. The penetrometer had depth and pressure resolutions of 2.5 cm and 35 kPa, respectively, accuracies of 1.25 cm and 103 kPa, and ranges of 0 to 45 cm and 0 to 7000 kPa, respectively, with a maximum speed 182 cm min^{-1}. To ensure that PR measurements were not influenced by neighboring drainage treatments or surface amendments, only an inner 1.2 m by 9.1 m (4 ft by 30 ft) sampling area was monitored (see shaded area in Figure 2).

Pre-sampling surveys of the plots were done on a smaller area equivalent to the experimental split plot where 30 PR measurements were taken (Figure 2). From the pre-sampling survey, the minimum number of PR measurements n was determined as 10 using an accuracy of 10% and with a Student's t-test confidence interval of 90 % (Hillel, 1980; ASABE Standards, 2009). That is, n=10 penetration profiles were taken per split plot in subsequent measurements.

2.3.4. Soil sampling and moisture content measurement

Gravimetric moisture contents were determined on soil samples collected from 0- to 15-cm, 15- to 30-cm, and 30- to 45-cm (0 to 6, 6 to 12, 12 to 18 inches) depths in each experimental plot where PR profiles were measured. A soil probe (Brown moisture probe, AMS Inc., American Falls, Idaho, USA) which had a modified auger tip to trap the soil and its depth marked at depth increments noted above, was used to retrieve soil samples for moisture determination. The probe was pushed into the soil vertically by hand to the desired depth and augured. Soil samples trapped in the auger at each depth were placed in sealed containers to prevent moisture loss. Samples were returned to the laboratory for determination of gravimetric moisture content by oven drying at 106 ºC for a minimum of 24 hours (Dane & Topp, 2002).

Soil samples for chemical analysis were collected in 15 cm increments using a Giddings soil probe of 6 cm diameter (Blake & Hartge, 1986) and analyzed in the laboratory for K, Na, Ca, and Mg for the calculation of the SAR using saturated paste extracts for the 2012 samples (Bower et al., 1952) and percent sodium (%Na) for the 2015 samples and converted to SAR using SAR = 1.04 x (%Na) – 0.35 (DeSutter et al., 2015).

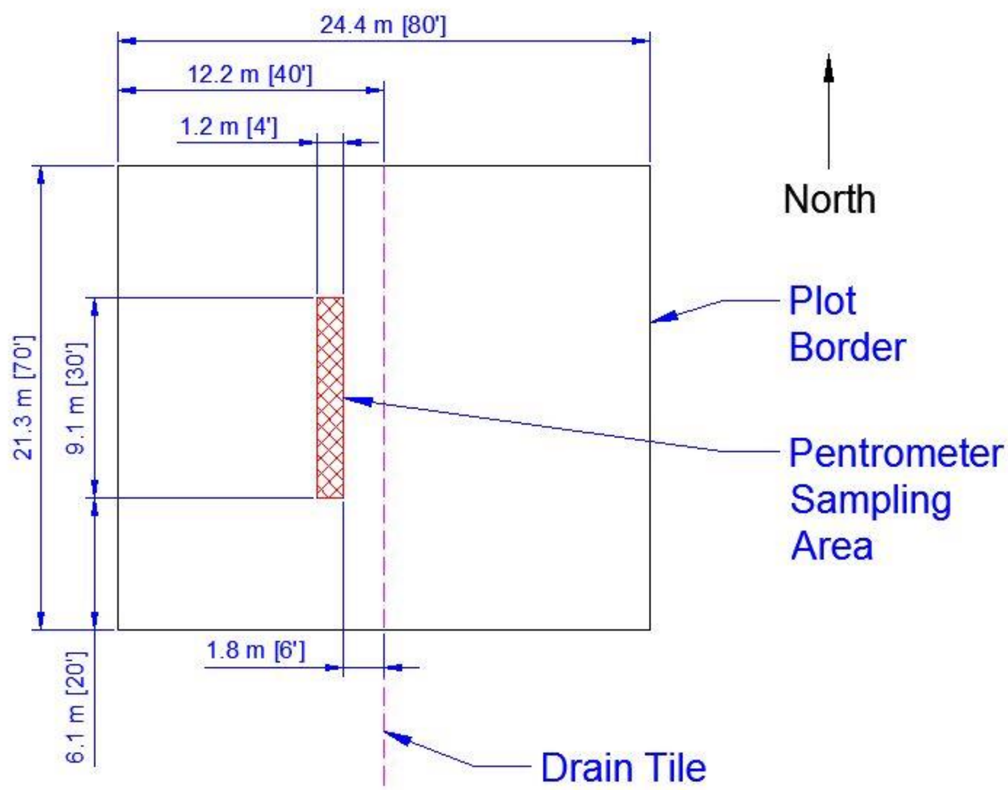

Figure 2. Layout and dimensions of the penetrometer sampling area in a split plot.

2.3.5. Statistical analysis

A general analysis of the penetration resistance profiles is presented in qualitative terms and then followed by a detailed statistical analysis. The results are presented in three major categories (i.e., drainage treatments, surface amendments, and the combined effects of drainage and surface amendments). In each category, analysis of results was done for the 0- to 15-cm layer and the 15- to 30-cm layer separately, while the 30- to 45-cm layer was not considered because changes in the mechanical properties in lower layers are considered a result of annually cumulative compaction and might be ameliorated immediately by special tillage treatments like sub soiling (Jorajuria & Draghi, 1997). The effects of drainage type and surface amendment on

PR were analyzed using a two-way factorial in a split plot design where the whole plot factor was the drainage type and the split plot (or subplot) factor was surface amendment in completely randomized design (Figure 1). The mean PR values for the CK treatment were obtained from 18 split plots (9 CK and 9 CC plots). Since soil moisture content has been reported to be inversely correlated with PR (Müller et al., 1990; Vaz et al., 2011), the gravimetric moisture content was included in a generalized linear model as a covariate. The PR means presented in the results sections were adjusted for the effects of soil water content. The statistical model for the analysis of variance of PR and Tukey tests for means comparisons were implemented using PROC MIXED in SAS 9.4 (SAS Institute Inc., 2014) and considered to be significant at $P<0.05$.

2.4. Results and discussion

The SAR values estimated from soil samples from 18 plots with surface treatments (9 GH plots and 9 CK plots) taken before and after application of the surface amendments are summarized in Table 3.

Table 3. Soil sodium adsorption ratios, averaged over surface amendments for layers 0 to 15 cm and 15 to 30 cm.

Depth (cm)	Year	Check Plots (No Ca Amendments)	Gypsum High Rate Plots (22.42 Mg ha^{-1})
		Sodium Adsorption Ratios	
0-15	2012	5.39^{a}*	2.48^{a}
	2015	1.62^{a}	0.75^{b}
15-30	2012	5.88^{a}	3.92^{a}
	2015	2.13^{a}	2.03^{a}

*Means within the same column for each depth with the same letter are not statistically different at P=0.05 using the Student's t-test between 2012 and 2015.

There was a general reduction in the SAR of the plots in 2015 compared to 2012. Changes in the soil's chemical composition are expected to occur as salts move with leaching, capillary rise, and with the upward or downward movement of the water table. This may explain the differences in the SAR between the two years. However, only in the 0-15 cm layer of the GH plots was the reduction significant. This decrease in SAR in gypsum plots is attributed to Ca added through gypsum and also to a decrease in Na which was substituted with Ca and leached to the lower parts of the soil profile. Changes in soil chemical properties can reduce or promote dispersion and swelling which can then influence field capacity moisture content and thus penetration resistance and trafficability (He et al., 2015).

2.4.1. Drainage treatments

The effect of moisture content on the PR values was significant in 0- to 15-cm layer (P=0.0001) and not significant for the 15- to 30-cm layer (P=0.367). For means that were adjusted for the effects of soil water content, the mean PR for the ND plots (450 kPa) was not significantly different from the mean PR for the FD plots (428 kPa) in the 0- to 15-cm layer. Similarly, there were no significant differences in the adjusted mean PR values for the ND plots (936 kPa) and the FD plots (917 kPa) for the 15- to 30-cm layer. The effects of subsurface drainage on increasing the PR values of soil has been reported to increase with time (Müller et al., 1990) as lower water tables produce improvement in soil structure and development of macropores. However, even with good soil structure, the trafficability of a soil is greatly reduced when its moisture state is close to the point of saturation.

2.4.2. Surface amendments

The mean PR values without adjustment for soil water content for each 2.5 cm depth interval for the surface amendments are shown in Figure 3.The GH plots had mean PR values that were generally higher than other treatments. Overall, the PR profiles had lower values in the top layers and higher values at the deeper parts of the soil profile.

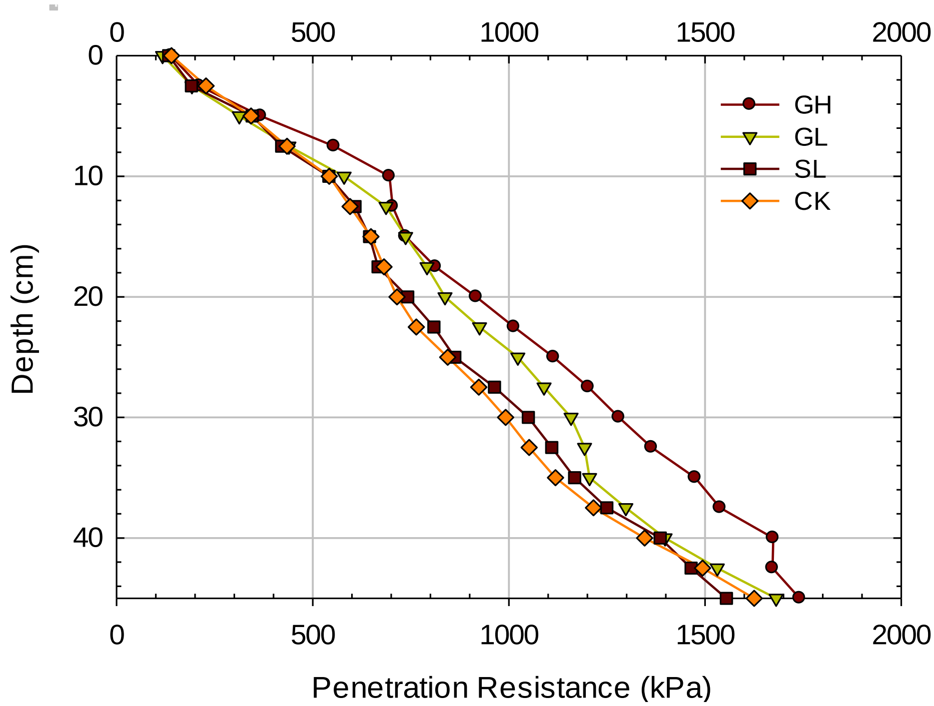

Figure 3. Mean values of penetration resistance (kPa) of all plots for various surface amendments at the Wyndmere site. These mean values were not adjusted for soil water content. The treatments designated in the legend are: gypsum at high rate (GH) [22.4 Mg ha^{-1}], gypsum at low rate (GL) [11.2 Mg ha^{-1}], sugarbeet spent lime (SL) [22.4 Mg ha^{-1}] and check plots receiving no surface amendment (CK).

The increase in PR values with depth is a result of the increasing weight on the soil with depth that leads to increased bulk density (Jonard et al., 2013). Also, this increase in bulk density may be attributed to clay accumulation which is characteristic of soil genesis in areas with natric conditions. The lower PR means in the 0- to 15-cm layer are also reflective of the effects of tillage. The loosening up of soil layers due to tillage reduces the soil's bulk density and temporarily lowers the penetration resistance. However, traffic from heavy equipment can lead to higher PR values for soils under tillage. The mean PR values for each split plot are shown in Figure 4 for the 0- to 15-cm layer and Figure 5 for the 15- to 30-cm layer; the mean PR values were not adjusted for the effects of moisture in these figures. The adjusted means for the surface amendments are summarized in Table 4 for the 0- to 15-cm and the 15- to 30-cm layers. The PR of the GH plots were significantly higher than other surface treatments in the 0- to 15-cm layer, while in 15- to 30-cm layers, the PR values of the gypsum amendments were higher than for the CK plots. The use of spent lime resulted in PR values that were similar to CK plots.

Table 4. Mean penetration resistance measured in June 2015 for surface amendments applied in May 2013.

Depth (cm)	Symbol	Surface amendments	Mean Penetration Resistance* (kPa)	Standard error (kPa)
0 to 15	GH	Gypsum High, 22.4 Mg/ha	485[a]	15
	GL	Gypsum Low, 11.2 Mg/ha	430[b]	10
	CK	Check	426[b]	5
	SL	Spent Lime, 22.4 Mg/ha	420[b]	14
15 to 30	GH	Gypsum High, 22.4 Mg/ha	1050[a]	14
	GL	Gypsum Low, 11.2 Mg/ha	954[b]	14
	SL	Spent Lime, 22.4 Mg/ha	866[c]	14
	CK	Check	839[c]	10

*Surface amendment means with the same letter are not statistically different at P=0.05 using the Tukey test for comparison of means for each depth. Penetration resistance values were adjusted for soil water content.

Gypsum application in sodic soils has been shown to result in lower PR values when the soil is dry, e.g., a reduction in surface crusts was noted by Mitchell et al. (2000). Hardsetting, often associated with problems of root elongation and hard plow layer, has been managed in Na-smectictic clays soils by Ca-treatment (Greene et al., 2002). Buckley & Wolkowski (2014) observed reductions in bulk density in deeper parts of the soil profile (30 to 60 cm) after application of gypsum, however, only minimal effects were observed in the PR of the same soil. Ellington (1986) saw significant reductions in penetration resistances of acidic soils treated with gypsum in the lower layers of a soil profile containing a hard pan. Ellington (1986) observed that gypsum application helped lower the PR values of a soil after it was cultivated, unlike one with no gypsum where the PR values returned to pre-cultivation levels.

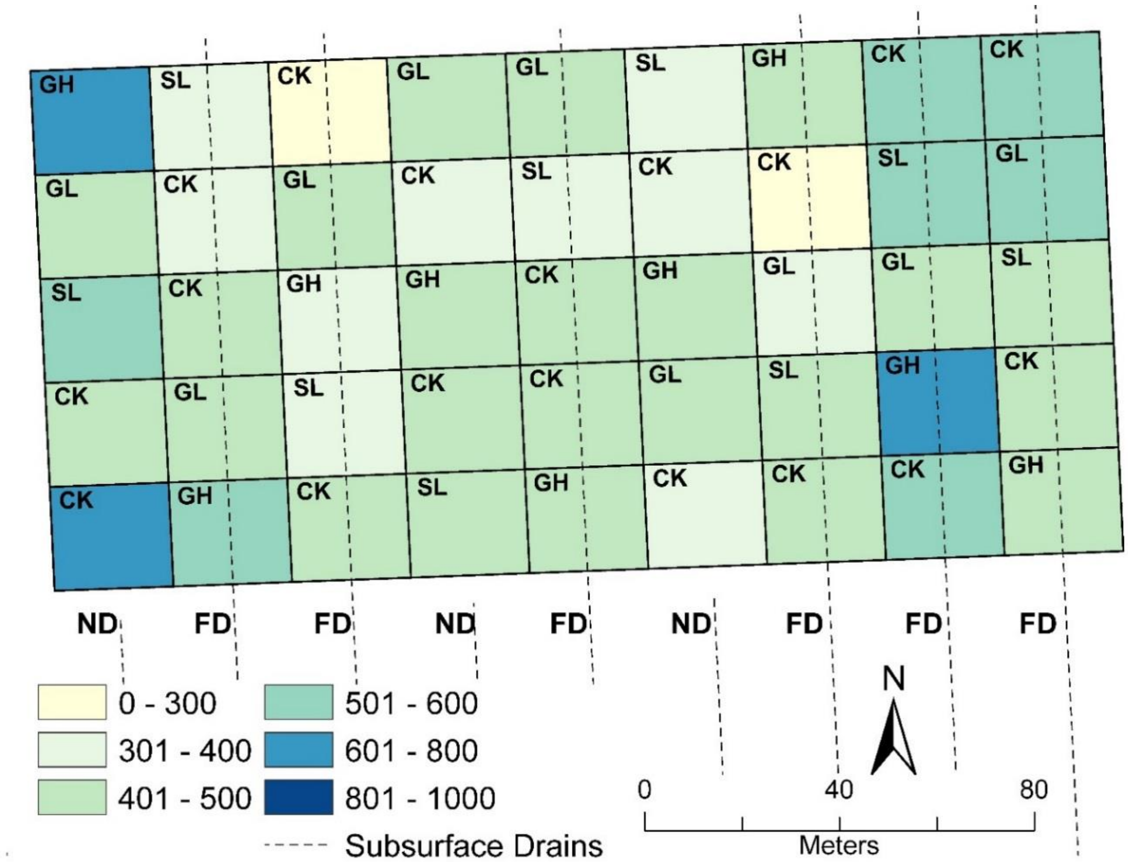

Figure 4. Mean values of penetration resistance (kPa) of all plots for various surface amendments for the 0- to 15-cm layer at the Wyndmere site. The treatments are: gypsum at high rate (GH) at 22.4 Mg ha^{-1}, gypsum at low rate (GL) 11.2 Mg ha^{-1}, sugarbeet spent lime (SL) at 22.4 Mg ha^{-1}, and check plots receiving no surface amendment (CK). The drainage treatments in the legend are free drainage (FD) and no drainage (ND).

Because of the weak structure as result of dispersion of clay particles, sodic soils are soft and unable to support traffic without deformation when wet. In these conditions, gypsum application may result in higher PR values as our results show, which improves trafficability. In addition to improvement in soil structure, for sodic soils with shrink-swell characteristics, the reduction of Na by substitution with Ca also reduces the water holding capacity leading to lower moisture contents. He et al. (2015) observed increased field capacity moisture contents in high Na soil samples compared to soils with low Na samples. By reducing the Na in the soil with Ca-substitution, a reduction in soil's affinity for moisture is expected. Given that lower moisture content corresponds to higher soil strength (Vaz et al., 2011), this also explains why the GH plots had higher PR values. On the other hand, the limited solubility of the spent lime explains why the Ca in the SL plots did not produce similar results.

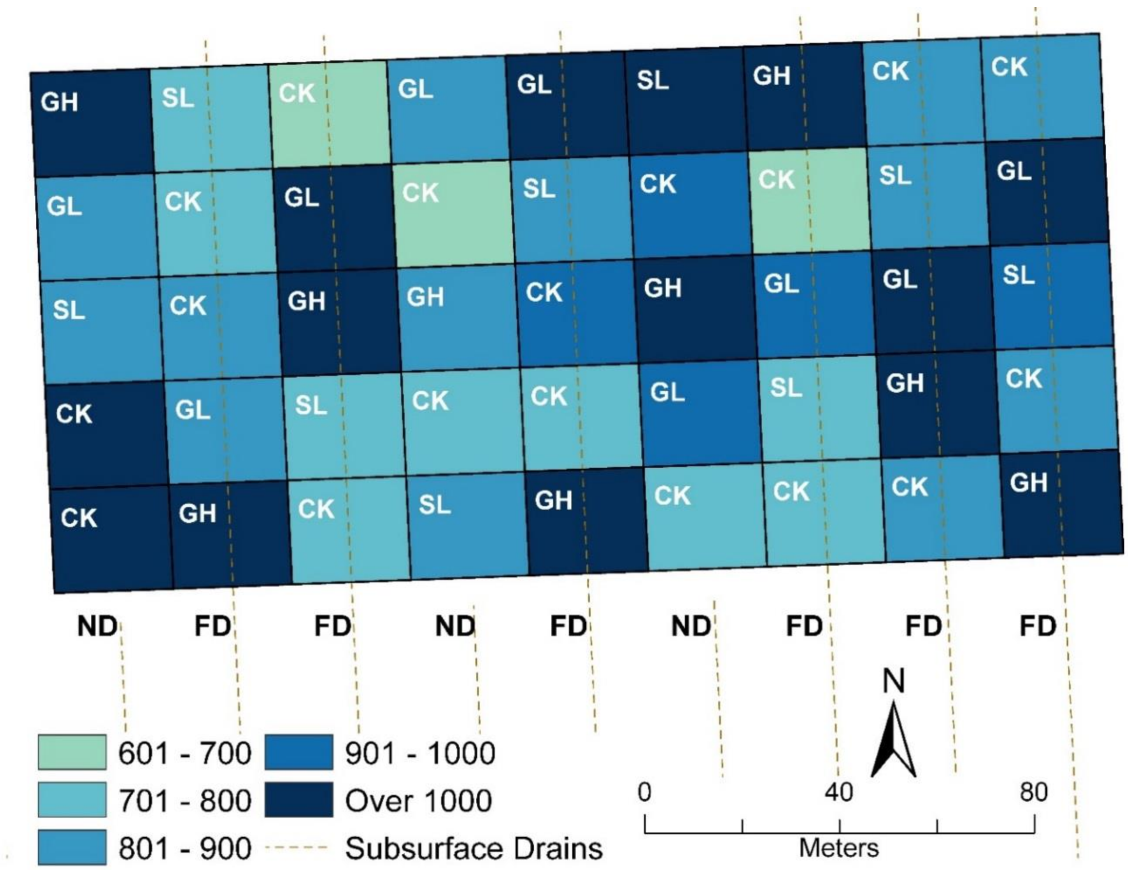

Figure 5. Mean values of penetration resistance (kPa) of all plots for various surface amendments from 15- to 30-cm layer at the Wyndmere site. The treatments are: gypsum at high rate (GH) 22.4 Mg ha^{-1}, gypsum at low rate (GL) of 11.2 Mg ha^{-1}, sugarbeet spent lime (SL) at 22.4 Mg ha^{-1} and check plots receiving no surface amendment (CK). The drainage treatments in the legend are free drainage (FD) and no drainage (ND).

2.4.3. Combined effects of drainage and surface amendments

Statistical analysis of the combined effects of drainage and surface amendments for the top two layers (0 to 15 cm and 15 to 30 cm) is presented in this section. The combined effects between drainage and surface amendment are denoted using drainage and surface amendment acronyms, e.g., FDGH represents the combined effect of free drainage (FD) and high rate of gypsum application (GH) at 22.42 Mg ha^{-1} (10 t ac^{-1}). The adjusted PR means for combined effects of drainage and surface amendments in the 0- to 15-cm layer and the 15- to 30-cm layer are shown in Table 5.

Table 5. Mean penetration resistance measured in June 2015 for the combined effects of drainage installed Dec 2012 and surface amendments applied in May 2013.

Depth (cm)	Drainage and Surface treatment Combinations		Mean Penetration Resistance* (kPa)	Standard error (kPa)
0 to 15	NDGH	No drainage, Gypsum at 22.4 Mg/ha	498^{a}	23
	FDGH	Free drainage, Gypsum at 22.4 Mg/ha	471^{a}	18
	NDSL	No drainage, Spent lime at 22.4 Mg/ha	457^{ab}	23
	NDGL	No drainage, Gypsum at 11.2 Mg/ha	433^{ab}	23
	FDCK	Free drainage, Check	432^{ab}	12
	FDGL	Free drainage, Gypsum at 11.2 Mg/ha	426^{ab}	16
	NDCK	No drainage, Check	420^{ab}	16
	FDSL	Free drainage, Spent lime at 22.4 Mg/ha	384^{b}	16
15 to 30	FDGH	Free drainage, Gypsum at 22.4 Mg/ha	1074^{a}	16
	NDGH	No drainage, Gypsum at 22.4 Mg/ha	1027^{a}	23
	FDGL	Free drainage, Gypsum at 11.2 Mg/ha	1007^{a}	16
	NDSL	No drainage, Spent lime at 22.4 Mg/ha	921^{b}	22
	NDGL	No drainage, Gypsum at 11.2 Mg/ha	901^{b}	22
	NDCK	No drainage, Check	898^{b}	16
	FDSL	Free drainage, Spent lime at 22.4 Mg/ha	811^{c}	16
	FDCK	Free drainage, Check	779^{c}	11

*Drainage and surface amendments combination means with the same letter are not statistically different at P=0.05 using the Tukey tests for comparison of means at each depth. Penetration resistance values were adjusted for soil water content.

The PR means of the 0- to 15-cm layer present an important part for analysis of effects of surface amendments and drainage treatments on trafficability and workability of agricultural soils, especially those with high composition of silt and clay separates. The mean PR values of the NDGH and the FDGH plots were significantly higher than that of the FDSL plots. The remaining treatments were not significantly different from each other. The lower 15- to-30 cm layer is important for trafficability when predominant soil textures are clay or loams (Rab et al., 2005) and also for analyzing the impact of soil mechanical properties on root growth as PR values higher than 2500 kPa impede root growth (Gao et al., 2012; Whalley et al., 2007).

In the 15- to 30-cm layer, the PR means of FDGH, NDGH, and FDGL plots were significantly higher than all other treatments but were not different from each other. The availability of leached Ca from the top layer in addition to that in the applied gypsum may be responsible for higher PR means in FDGH. The higher concentration of Ca in the GH leads to more flocculation of dispersed soil aggregates. Aggregation of dispersed soil particles improves the soil structure; soils with better structure have a higher soil strength and hence higher load bearing capacity compared to those with weak soil structure especially when wet (Carter, 1990).

Lebert & Horn (1991) explain that an increase in bulk density corresponds to an increase of strength when the influence of soil structure is ignored, for example, in non-structured soils or weakly-aggregated soil. However, soil strength becomes more dependent on shear parameters, for example, internal angle of friction and cohesion when the soil is better structured. Therefore, improvement in structure will increase the PR even when there is a reduction in bulk density in wet sodic soils. Where less Ca was applied, as was the case for FDGL, drainage appears to have complemented the Ca application and resulted in PR means that were similar to plots with high rates of Ca application. Drainage facilitates the leaching of Na from the exchange sites on soil particles and provides the Ca from upper layers of the soil profile. The results of our study agree with Cochrane & Aylmore (1991) who noted an improvement in aggregate stability using the modulus of rapture for soils treated with gypsum as a surface amendment. We attribute this improvement in strength to an improvement in soil structure. Better-structured soil because of aggregation has higher porosity and more micro and macro pores compared to dispersed soils with a poor structure. This improvement in aggregation and structure also aids drainage. In the 15- to 30-cm layer, the NDSL, NDGL, and NDCK plots had means that were significantly lower than FDGH, NDGH and FDGL plots but had PR means that were significantly higher than FDSL and FDCK plots. Because the PR values for the NDSL, NDGL, and NDCK plots were not statistically different from one another, we infer that for conditions of no drainage, there was no benefit in the application of spent lime or gypsum at the low rate on increasing the PR for the 15- to-30 cm layer. However, when the sodic soil at this site is drained, no amendment (FDCK) or spent lime (FDSL) result in the lowest PR values.

Challenges in trafficability have been reported by Muller et al. (1990) in soils where the topsoil was dry and firm but lower layers were below the critical penetration resistance of 300 kPa. For this study, a threshold value of 300 kPa was assumed to represent the penetration resistance above which trafficability on agricultural soil is possible (Müller et al., 1990). In contrast, Bueno et al. (2006) observed an estimate of 1000 kPa for the PR as the threshold value for workability of the soil. The lower layer plays an equally important role in assessing the trafficability of agricultural soils. Furthermore, the impacts of subsoil compaction because of heavy machinery are likely to show in this 15- to 30-cm layer. Compaction of subsoil drives up the cost of tillage operations in both time and energy and may lower crop yields. However, it is important to note that PR from penetrometers often overestimates the force encountered by the roots up to a factor of three times due to higher friction encountered by the metal compared to the roots (Whalley et al., 2007).

2.5. Conclusions

Twenty-five months after surface amendment application and 30 months after drainage installation, the drainage treatments were not significantly different from each other in either layer. Across both drainage treatments, the PR means for GH plots were significantly higher than all other surface amendments in the 0- to 15-cm layer. In the 15-to 30-cm layer, PR values for GH plots were significantly higher than all other surface amendments and the PR means of gypsum amendments (GH and GL) were both significantly higher than SL and CK.

For the combined effects of drainage and surface amendments in the 15- to 30-cm layer, FDGH, NDGH, and FDGL had PR means that were significantly higher than NDSL, NDGL and NDCK. Here, drainage complements the lower rate of gypsum in the FDGL plots to produce results similar to higher gypsum rate in FDGH plots. For undrained plots in the 15- to 30-cm layer, the low rates of gypsum or spent lime (NDGL and NDSL, respectively) do not appear beneficial because their PR means were statistically similar to those for NDCK. PR means for the FDSL and FDCK plots were significantly lower than for the NDSL, NDGL and NDCK plots in the 15- to 30-cm layer, which showed that draining the plots without amendments (FDCK) or with spent lime (FDSL) yielded PR means that were smaller than no land modification (NDCK).

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3. EFFECTS OF GYPSUM AND SUGAR BEET SPENT LIME APPLICATION ON HYDRAULIC PROPERTIES OF SUBSURFACE DRAINED SODIC SOILS[2]

3.1. Abstract

In poorly drained sodic soils, application of calcium amendments to the soil surface has been reported to improve soil hydraulic conductivity. This study was carried out to determine the benefits of calcium amendments in the mitigation of sodification risks such as dispersion and swelling when subsurface drainage is installed in high risk soils. The effects of gypsum and spent lime (a $CaCO_3$ byproduct from sugarbeet processing) with drainage treatments of free drainage (FD) and no drainage (ND), on improving the hydraulic properties of the soil were evaluated near Wyndmere, North Dakota. Infiltration tests were carried out using a mini disk tension infiltrometer and a Cornell sprinkle infiltrometer to investigate the impact of drainage (the whole plot factor) and calcium surface treatments (the spilt-plot factor) in a completely randomized design. The surface treatments were 22.4 Mg ha^{-1} of gypsum (GH), 22.4 Mg ha^{-1} sugar beet spent lime (SL) and check plots receiving no surface treatment (CK). Soil samples for moisture content determination were also collected. The mean unsaturated hydraulic conductivity at 2 cm tension [$K_{(\psi=-2\ cm)}$] for the ND and FD plots as measured by the mini disk tension infiltrometer were 48.3 and 37.6 cm day^{-1}, respectively, while the infiltration rates as measured by the Cornell sprinkle

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infiltrometer were 55.4 and 61.2 cm day^{-1} for the ND and FD plots, respectively. For the surface treatments, the mean $K_{(\psi=-2\ cm)}$ as measured by the mini disk tension infiltrometer were 52.5, 42.6 and 33.9 cm day^{-1} for the GH, CK and SL plots, respectively. The mean $K_{(\psi=-2\ cm)}$ in the GH plots was significantly higher than that in the SL plots. The mean infiltration rates as measured by the Cornell infiltrometer were 66.8, 55.7, 52.3 cm day^{-1} for the CK, SL, GH plots, respectively. Our results indicate that GH application increased the hydraulic conductivity of the soil matrix compared to SL; however, the overall flow through the soil profile, including the soil matrix and the macropores, were not affected 14 months after application of the surface treatments.

3.2. Introduction

The installation of subsurface (tile) drainage and tilling of soils having sodium in their parent materials and within the profile may increase the risk of sodification in salt-affected soils on the Northern Great Plains (NGP) of the USA. Due to the high levels of moisture during spring and fall seasons that have become common on the NGP as a result of a regional wet cycle, land managers are turning to tile drainage to address this problem of excess water (Jia et al., 2012).

The opening up of lands with low productivity indexes was driven by increasing commodity prices (Hellerstein & Malcolm, 2011) and has brought idle marginal lands often affected by sodium into agricultural production (He et al., 2015). Tile drainage of sodium affected soils can lead to selective leaching of the more soluble higher charge ions; this causes the sorption and desorption of sodium ions due to the changes in the cationic strength of the soil solution. Sorption and desorption of sodium, coupled with a decrease in the ionic strength of the soil solution, often induces slaking, swelling and dispersion of clay particles (Bagarello et al., 2006; He et al., 2015).The dispersed particles plug the pores while the swelling reduces the size of the pores in the soil, both resulting in reduced hydraulic conductivities (He et al., 2015; So &

Aylmore, 1993). These reductions in hydraulic conductivities could lower the efficiencies of subsurface drainage systems or render them totally ineffective. High levels of sodium in clayey soils also can lead to formation of a virtually impermeable surface crust that hinders water infiltration and seedling emergence (Agassi et al., 1985; Bagarello et al., 2006)

To minimize the risk of sodification in reclamation of salt affected marginal lands for agriculture, a proactive approach is required. In dispersed soils, aggregation and arrangement of soil particles into stable structures is facilitated by Ca^{2+} ions (Badorreck et al., 2013; Sahin et al., 2011). A combination of chemical surface amendments, cropping arrangements and water management strategies can be employed, geared at increasing the rate of replacement of the Na^{+} ions with Ca^{2+} ions at soil exchange sites or maintaining a high electrical conductivity (EC) for the soil water. Gypsum has been used to improve the hydraulic and physical properties in sodic soils or in irrigation water with high exchangeable sodium (Ellington, 1986; Hamza & Anderson, 2002) . The changes in soil water relationships for soils due to chemical and management practices can be exhibited in the hydraulic properties of the soil such as hydraulic conductivity and sorptivity.

Infiltration in agricultural fields is affected by several factors including the permeability of the soil, the presence of surface crusts, or surface modification (Corradini et al., 2011; Wang et al., 2014). Infiltration in the field also depends on many other factors including the presence of root channels, inter-aggregate pores, worm holes, and drainage history as well as management practices (Beven & Germann, 1982; Suarez et al., 2008). Sorptivity, which is a representative quantity of the soil capacity for capillary uptake and release of water, is dependent on the pore size distribution in the soil medium (Philip, 1957). Sorptivity is affected by the intrinsic properties of the soil (e.g. soil texture, soil structure, macro-pores and moisture content). The response of sodic soils to calcium amendments has been extensively investigated using laboratory studies focusing on changes in saturated hydraulic conductivity, K_{sat} (Callaghan et al, 2014; Reading et al., 2012a; So & Aylmore, 1993). Field studies of K_{sat} preserves the soil's antecedent moisture content and soil structure and are a better representation of changes in soil's hydraulic properties than laboratory experiments (Bagarello et al., 2006). Field drainage tests evaluating the hydraulic conductivity involve the whole soil profile and often take longer than infiltration tests that evaluate only a short depth of the profile. Prasad et al. (2010) compared the Van Genuchten parameters from both drainage and infiltration tests and concluded that infiltration tests can be used with confidence to estimate drainage of a soil profile. In this study, field infiltration tests were carried out to determine the short-term benefits of calcium amendments on hydraulic properties of subsurface drained sodic soils.

3.3. Materials and methods

3.3.1. Experiment site

The experimental site was located near Wyndmere in Richland County, North Dakota (97° 15.45' W, 46° 16.89' N and elevation 326 m). The site has a sodium affected soil with a drainage class of "somewhat poorly drained" located on a predominately Exline soil (Fine, smectitic, frigid Leptic Natrudolls) with some Stirum-Arveson complex (Stirum: Coarse-loamy, mixed, superactive, frigid Typic Natraquolls; Arveson: Coarse-loamy mixed, superactive, frigid Typic Calciaquolls). The site was under pasture/hay land for over 30 years prior to commencement of this field research in the 2013 growing season when it was planted with corn. Corn was also grown in 2014. In the fall of 2012, subsurface tile drainage was installed at a spacing of 24.4 m and a depth of 1.2 m, with a design drainage coefficient of 9.5 mm d^{-1}. Each experimental unit or plot was 24.4 m wide by 21.3 m long, with one drain line per plot. Plots designated as "free drainage" (FD) for this study had tile lines installed while plots designated as "no drainage" (ND) had no lines installed; the FD and ND plots were compared as drainage treatments. Surface treatments consisted of 22.4 Mg ha^{-1} of gypsum (GH, defined as the high gypsum rate), 22.4 Mg ha^{-1} sugar beet spent lime (SL), which is a $CaCO_3$ by-product from the sugar beet processing industry, and check (CK) plots receiving no surface treatment. Following the application of the calcium amendments in May 2013, a field cultivator was used to incorporate the amendments to a depth of 10 cm before the crop was planted by the farmer-cooperator.

Infiltration tests were carried out using a mini disk tension infiltrometer (Mini Disk infiltrometer, Decagon Devices, Pullman, WA, USA) from 25 to 29 July 2014 and a Cornell sprinkle infiltrometer (Ogden et al., 1997) from 13 to 19 August 2014. The infiltration tests were used to investigate the impact of both drainage (the whole plot factor) and surface (the spilt-plot factor) treatments on hydraulic properties of the soil. In each plot where infiltration measurements were made, one sample was taken for the Cornell sprinkle infiltrometer while three samples were taken for the mini disk tension infiltrometer. This resulted in a total of 17 infiltration tests (8 for the ND plots and 9 for the FD plots) using the Cornell sprinkle infiltrometer. Three samples were run for the mini disk tension infiltrometer that resulted in 51 infiltration tests. Deionized water with an EC of 9.12 µS m^{-1} and a pH 6.5 was used to run the infiltration tests. This was chosen to mimic rainfall and to minimize the effects that different water chemistry would have on soil water relationships in sodic soil at the site.

Statistical analysis was done using a two-way factorial in a split plot design with three replicates, where the whole plot and split plot factors were drainage and surface treatments, respectively, in a completely randomized design. Wet field conditions in the spring of 2014 prevented the crop from being planted in some plots and as a result, one of the ND plots with SL was not used for statistical analyses. Soil moisture on a gravimetric basis was sampled from 0 to 15 cm depth in each plot where infiltration was measured and was included in a generalized linear model as a covariate. The statistical model for the analysis of variance and Tukey tests for comparison of means were implemented using PROC GLM in SAS 9.4 (SAS Institute Inc., 2014) and differences in means were considered to be significant at $P<0.05$.

3.3.2. Mini disk tension infiltrometer

Mini disk tension infiltrometers (Decagon Devices, 2014a) filled with deionized water and set at a suction head of -0.2 kPa (-2.0 cm) were used to measure the unsaturated water flow into the soil. These infiltrometers consist of a stainless steel porous disk which does not allow water to leak in open air, a lower chamber which contains the volume of water that infiltrates into the soil and an upper bubble chamber filled with water which controls suction. The infiltrometers were carefully placed on the soil surface avoiding areas with cracks, depressions, clods or plant residue. The infiltration rates were calculated with the help of a spreadsheet available from Decagon Devices (2014b) which is based on (Zhang, 1997) by fitting the parameters C_1 and C_2 of the Phillip equation

$$I = C_1 t + C_2 \sqrt{t} \tag{6}$$

where I is the cumulative infiltration (cm), t is time (min), the slope of the curve C_1 is a function of the hydraulic conductivity k (cm min^{-1}), and C_2 is a function of sorptivity (cm min$^{-1/2}$). The hydraulic conductivity is calculated as

$$k = \frac{C_1}{A} \tag{7}$$

where A (cm min^{-1}) is obtained from

$$A = \frac{11.65(n^{0.1} - 1)\ e^{[2.92(n-1.9)\alpha h]}}{(\alpha r_d)^{0.91}} \quad n \geq 1.9. \tag{8}$$

in which h (cm) is a given suction, r_d (cm) is the radius of the disk, and α and n are Van Genuchten parameters based on the soil type (Decagon Devices, 2014a). For suctions from -0.05 to -0.6 kPa (-0.5 cm to -6 cm of water), a disk radius of 2.25 cm and the Van Genuchten parameters α and n for the twelve texture classes (Carsel & Parrish, 1988), the hydraulic conductivity can be obtained from the Decagon spreadsheet (Decagon Devices, 2014b).

3.3.3. Cornell sprinkle infiltrometer

The Cornell sprinkle infiltrometer, which measures infiltration rates into soil, consists of a rainfall simulator and a single infiltration ring (Ogden et al., 1997). The bottom of the air entry tube was set 2.0 cm from the bottom of the graduated scale on the sprinkle cylinder; this was equivalent to a head of 2.0 cm. The infiltrometer ring was typically placed in between the corn rows avoiding the mid row fertilizer disk opening. We chose reasonably flat, level ground and avoided cracks, wheel tracks or artificial disturbances in the soil. Surface residue, such as leaves or corn stalks from the previous year, were gently removed. The ring was driven into the ground to a depth of 7.5 cm until the lower edge of the outflow hole was level with the ground surface (van Es & Schindelbeck, no date). This was done using a hammer, a square piece of wood at least 30 cm length to buffer blows from the hammer, and a spirit level.

The height of the water level in the cylinder of the Cornell sprinkle infiltrometer at the start of each experiment (H_s) was measured. A stopwatch was started at the time of removing the stopper on the air-entry tube. When runoff started to flow out of the tube, the time was recorded as time to runoff (T_{ro}). The water volume (V_w) collected in the outflow beaker was measured periodically by taking the weight using a balance with a precision of 0.1 g with time interval t (min) in which it was collected under the assumption of unity density for water. Care was taken to avoid spills during volume measurement. The initial volumes were weighed at intervals of 30 seconds for the first 3 to 9 minutes, then the interval was increased to 3 minutes. After 30 minutes of running the experiment, the interval for collecting volumes was further increased to 5 minutes until the experiment had run for 60 min. When an infiltration test was run and no runoff was observed, the experiment was repeated at a new location within the same plot with a much higher application rate achieved by raising the head to between 4 cm to 5 cm.

At the end of the experiment, the final water level (H_f) was recorded together with the time T (min) at which it was taken. The application rate R (cm min^{-1}) was determined by

$$R = \frac{H_s - H_f}{T} \qquad (9)$$

The runoff rate, R_o (cm min^{-1}) is based on the relationship

$$R_o = \frac{V_w}{(457.3 \times t_i)} \qquad (10)$$

where V_w is the volume (cm^3) collected in time t_i (min) and 457.3 is the area (cm^2) of the ring. The infiltration rate I_t (cm min^{-1}) for a given time interval was determined as the difference between the application rate and runoff rate for that time interval,

$$I_t = R - R_o \qquad (11)$$

where I_t (cm min^{-1}) is the infiltration rate, R (cm min^{-1}) is the application rate and R_o (cm min^{-1}) is the runoff rate. For the Cornell sprinkle infiltrometer, the final infiltration rate was calculated by taking the average of infiltration rate for the final 20 min of the experiment. The sorptivity in the Cornell sprinkle infiltrometer is given by

$$S = (2T_{ro})^{0.5} \times R \qquad (12)$$

where S (cm $min^{-1/2}$) is sorptivity and T_{ro} (min) is time to runoff (Ogden et al., 1997).

3.4. Results and discussion

A comparison of infiltration rates plotted against time for the Cornell sprinkle infiltrometer for all the treatments is shown in Figure 6. Most of the infiltration rates follow a general exponential decay curve where the initial infiltration is very high due to sorptivity but decreases to a constant value similar to the hydraulic conductivity. There were exceptions, such as the FDGH plots where there is an initial decline in infiltration followed by a rise. The increase in infiltration can be attributed to dissolving of the surface seal thus increasing the infiltration rate.

3.4.1. Drainage treatments

The mean unsaturated hydraulic conductivity at 2 cm tension [$K_{(\psi=-2\ cm)}$] values from the minidisk tension infiltrometers were 48.4 and 37.6 cm day^{-1} for the ND and FD plots, respectively, and these values were not significantly different from each other. The mean final infiltration rates from the Cornell sprinkle infiltrometer were 55.4 and 61.2 cm day^{-1} for the ND and FD plots, respectively, and these values were not significantly different from each other. Smettem et al. (1991) observed that over 50% of the infiltration may be transmitted in the macropores bypassing the matrix. Using infiltration tests, Abid & Lal (2009) measured significant differences in infiltration rates between drained and undrained plots under no-till and tilled plots in Columbus, Ohio. Higher infiltration rates in drained soil were attributed to aggregation of particles leading to better soil structure and pore size distribution. However, tillage of soil breaks up the connectivity of these pores and may eliminate the benefits of drainage in the plow layer. This may explain the higher variability in the infiltration rates from the Cornell sprinkle infiltrometer (see Figure 6).

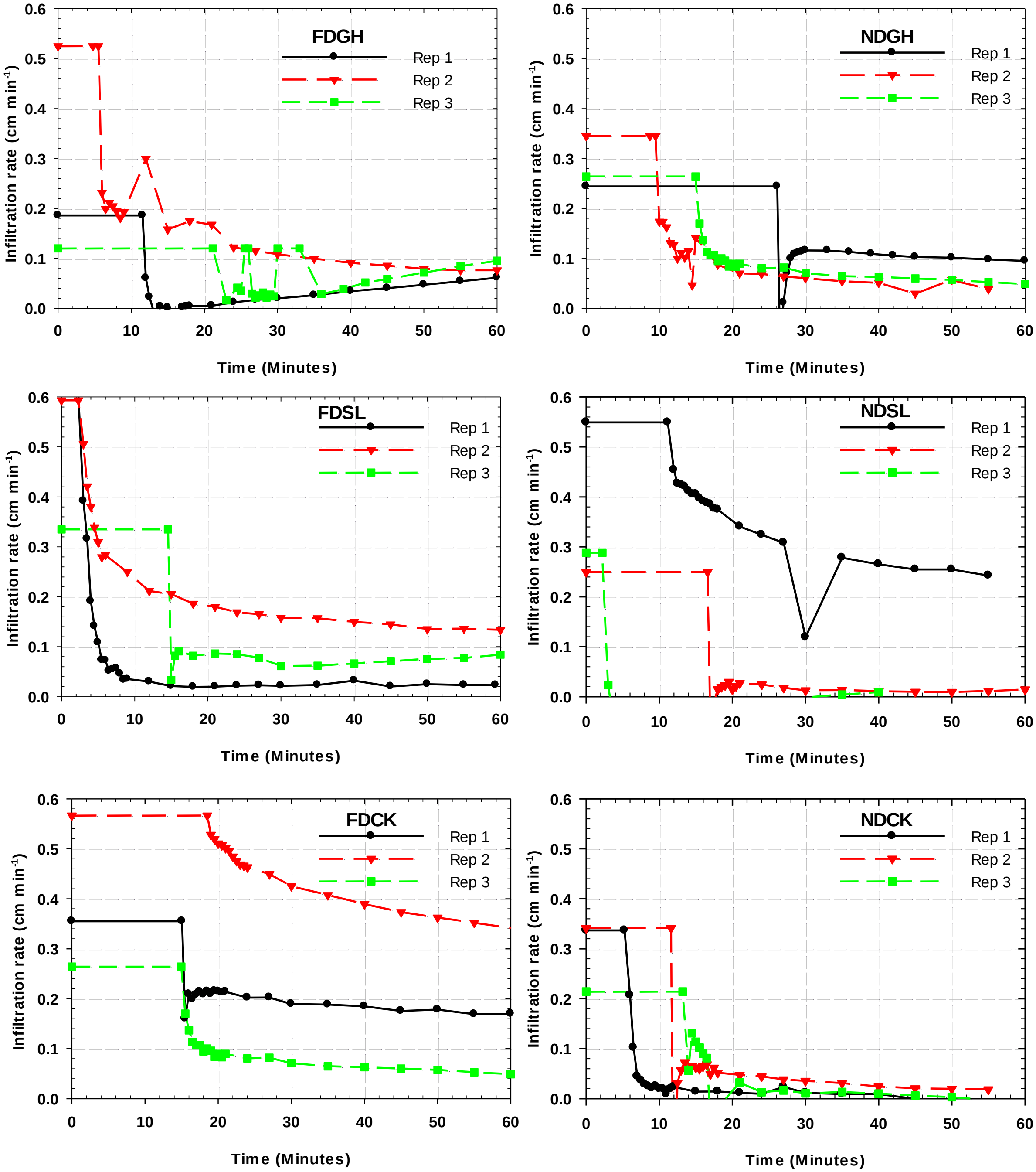

Figure 6. Cornell sprinkle infiltration rates plotted against time. The plots were free drainage and high rate of gypsum (FDGH); no drainage and high rate of gypsum (NDGH); free drainage and spent lime (FDSL); no drainage and spent lime (NDSL); free drainage and check (FDCK) and no drainage and check (NDCK). The application rate for GH and SL was 22.4 Mg ha^{-1}.

While the hydraulic conductivity of the matrix of sodic soils may be reduced due to leaching the soil with a low electrical conductivity water; in the field, other physical factors such as the clay content or clay mineralogy may be more of a determining factor (Callaghan et al., 2014).

The mean sorptivity value from the minidisk tension infiltrometer of the ND plots (193 cm day$^{-1/2}$) and that of the FD plots (150 cm day$^{-1/2}$) were not significantly different from each other. Similarly, the mean sorptivity values from Cornell sprinkle infiltrometer calculated from equation 12 were 165 and 80.3 cm day$^{-1/2}$ for the ND plots and the FD plots, respectively, and were not significantly different from each other.

3.4.2. Surface treatments

For the surface treatments, the highest mean $K_{(\psi=-2\ cm)}$ value from the mini disk infiltrometer was 52.5 cm day^{-1} for the GH plots, 42.6 cm day^{-1} for the CK plots and 33.9 cm day^{-1} for the SL plots. For the mini disk tension infiltrometer, the mean $K_{(\psi=-2\ cm)}$ for the GH plots was significantly higher than that from the SL plots, but the CK plots did not differ significantly from either the GH or the SL plots. The final infiltration rates from the Cornell sprinkle infiltrometer were 66.8, 55.7 and 52.3 cm day^{-1} for the CK, SL and GH plots, respectively. Similarly, the mean sorptivity values from the minidisk tension infiltrometer was 205, 162 and 147 cm day$^{-1/2}$ for the GH, CK and SL plots, respectively. The mean sorptivity values from the Cornell sprinkle infiltrometer were 144.7, 120.6, 102.1 cm day$^{-1/2}$ for the CK, SL and GH plots, respectively. There were no statistically significant differences in the final infiltration rates and sorptivity from the Cornell sprinkle infiltrometer.

For the Cornell sprinkle infiltrometer tests, the soil profile near the surface is fully is saturated. The flow in macropores is dominant and often impacted by preferential flow (Beven &

Germann, 1982; Schwen et al., 2011). The mini disk tension infiltrometer, on the other hand, measured the infiltration rates near saturation (under a tension of 2 cm) where transmission of water in pores greater 1.5 mm was eliminated (Smettem, 1992; Smettem et al., 1991). Therefore, bypasses of the soil matrix by water flow in cracks and fissures was minimized and infiltration rates measured by the mini disk tension infiltrometer are more representative of conductivity of the soil matrix. Improvement in the hydraulic conductivity shown by the higher $K_{(\psi=-2\ cm)}$ for the GH plots compared to the SL plots agrees with many researchers who have shown improvements of hydraulic conductivity after gypsum application (Ilyas et al., 1997; Sansom et al., 1998).

Although spent lime is a waste stream from the sugar beet industry in the Red River Valley and may thus be available at a lower cost compared with gypsum, our study indicates gypsum is a better material for improving the soil hydraulic conductivity near the soil surface.

Table 6. Mean unsaturated hydraulic conductivities at 2-cm tension and sorptivity for the combined effects of drainage and surface treatments for the mini-disk infiltrometer.

Drainage and Surface Treatment Combinations		Hydraulic Conductivity at 2-cm Tension* (cm day^{-1})	Sorptivity* (cm day$^{-1/2}$)
NDGH	No drainage, Gypsum at 22.4Mg/ha	57.8^{a} (6.8) †	226 ^{a} (27.5)†
NDCK	No drainage and check	48.6 ^{ab} (7.6) †	190 ^{a} (30.7)†
FDGH	Free drainage, Gypsum at 22.4Mg/ha	47.2 ^{ab} (7.4) †	184 ^{a} (29.0)†
NDSL	No drainage, Spent lime at 22.4Mg/ha	38.7 ^{ab} (9.1) †	163 ^{a} (36.4)†
FDCK	Free drainage and check	36.6 ^{ab} (6.7) †	134 ^{a} (27.2)†
FDSL	Free drainage, Spent lime at 22.4Mg/ha	29.0 ^{b} (6.7)†	131 ^{a} (27.1)†

* In each column, drainage and surface amendment combination means with the same letter are not statistically different at P=0.05 using the Tukey test for mean comparison.
† The values in parentheses represent the standard error.

Mean $K_{(\psi=-2\ cm}$ and sorptivity values for drainage and surface treatment combinations are summarized in Table 6 for the minidisk infiltrometer. The results show that only the mean $K_{(\psi=-2\ cm)}$ values for the NDGH plots were significantly higher than the FDSL plots. The remaining mean $K_{(\psi=-2\ cm)}$ values for the combined effects of drainage and surface treatments were not significantly different from each other.

Mean final infiltration rates and sorptivity values for drainage and surface treatment combinations are summarized in Table 7 for the Cornell sprinkle infiltrometer. The mean sorptivity for the combined effect of the drainage and surface treatments were not significantly different from each other, for either the Cornell sprinkle infiltrometer. The application of gypsum and spent lime is likely to alter the sodium adsorption ratio (SAR) of the soil. Gypsum contains $CaSO_4$ while spent lime is predominantly a $CaCO_3$ compound with other minerals such as impurities from the sugar juice. There was a weak correlation (r = -0.36) between the infiltration rates from the Cornell sprinkle infiltrometer with SAR values (data not shown) from the same plots. Our results agree with Suarez et al (2008), who observed that increases in SAR reduced infiltration in loam soils but not in clay soils where the clay in the soil increased the variability in the infiltration rates. The clay contents (12% to 22%) at our site may have increased variability in infiltration rates, and masking the effects of the amendments despite the changes in the SAR values. In contrast to gypsum, spent lime is less soluble in soils with high pH. This may explain why our site, with average pH 8.1 as measured in the tile drain effluents, had lower mean $K_{(\psi=-2\ cm)}$ on the SL plots compared to GH because precipitated $CaCO_3$ from the spent lime may have clogged the soil pores (Tirado-Corbalá et al., 2013). Detrimental effects of lime application on infiltration were also reported by Roth & Pavan (1991) who observed surface sealing with $CaCO_3$, however, these negative effects were short-lived and water infiltration into soil increased in the long term with lime application.

Our sorptivity values were variable for both drainage and surface treatments and no statistically significant relations were observed. These results agree with Sepaskhah et al. (2005)

who reported variability in sorptivity for smaller plots (5 m x 5 m). Although sorptivity will impact the infiltration capacity of the soil, especially at the beginning of rainfall, and is a good indicator of the changes in porosity and pore size distribution, the effectiveness of the tile drainage will depend more on the final infiltration rate. In remediation of smectitic sodic soils, high sorptivity may indicate the presence of both macro-pores from aggregation and large cracks from shrink-swell processes while low sorptivity may also indicate the presence of surface crusts and reduction in the cracks from shrink-swell properties.

Table 7. Mean final infiltration rates and sorptivity for the combined effects of drainage and surface treatments for the Cornell sprinkle infiltrometer.

Drainage and Surface Treatment Combinations		Final Infiltration Rate* (cm day^{-1})	Sorptivity * (cm $day^{-1/2}$)
FDCK	Free drainage and check	86.6 [a] (13.8) †	281 [a] (74.8)†
NDSL	No drainage, Spent lime at 22.4Mg/ha	59.8 [a] (13.9) †	137[a] (75.0)†
NDGH	No drainage, Gypsum at 22.4Mg/ha	59.4 [a] (13.8) †	95.1[a] (74.9)†
FDSL	Free drainage, Spent lime at 22.4Mg/ha	51.6 [a] (14.2) †	103[a] (76.8)†
NDCK	No drainage and check	47.1 [a] (13.9) †	8.50[a] (75.1)†
FDGH	Free drainage, Spent lime at 22.4Mg/ha	45.3 [a] (14.1) †	109 [a] (76.4) †

* In each column, drainage and surface amendment combination means with the same letter are not statistically different at P=0.05 using the Tukey test for mean comparison.
† The values in parentheses represent the standard error.

3.5. Conclusions

At 14 months after the application of the surface amendments, gypsum at a high rate significantly increased the hydraulic conductivity at 2 cm tension through the matrix of a sodic soil compared to spent lime for tests conducted using the mini disk tension infiltrometer. In contrast, hydraulic conductivity at 2 cm tension for a high rate of gypsum application was not significantly higher than that for check plots where no amendments were applied. The final infiltration of water into the soil surface, including the matrix flow and flow through larger macro-pores, evaluated using Cornell sprinkle infiltrometer, was not affected by the surface treatments. The sorptivity of the soil was not affected by both the drainage treatments or surface treatments measured using either the mini disk tension infiltrometer or the Cornell sprinkle infiltrometer. There was no evidence that tile drainage of this sodic soil affected its final infiltration rates or hydraulic conductivities at 2 cm tension.

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4. GYPSUM LOWERS DRAWBAR POWER IN NORTHERN GREAT PLAINS SUBSURFACE DRAINED SODIC SOILS[3]

4.1. Abstract

Northern U.S. Great Plains' saline/sodic soils often have very low yields due to poor germination, become exceptionally hard when crop evapotranspiration dries out the soil, and can be a sediment source following rainfall events. Subsurface drainage can result in the conversion of saline/sodic soils to sodic (sodium-affected) soils. Calcium-based surface amendments may help preserve or improve soil structure, thereby improving drainage and trafficability. The objective of this study was to measure chisel plow draft in a sodic soil near Wyndmere, North Dakota, to determine whether selected subsurface drainage practices and calcium-based surface amendments affected tillage power requirements. Field plots were set up in a completely random design with a split-plot arrangement in which whole plots consisted of free-outflow subsurface drainage (FD) (installed Dec 2012) and no subsurface drainage (ND); split plots consisted of calcium-based surface amendment treatments (applied May 2013) of 11.2 and 22.4 Mg ha^{-1} gypsum (GL for gypsum low and GH for gypsum high), 22.4 Mg ha^{-1} spent lime (SL, a byproduct of the sugar beet processing industry), and check plots (CK) with no surface

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amendments. A drawbar dynamometer measured draft on a chisel plow (Nov 2014) as it was pulled across the plots by a tractor equipped with an auto-guidance system and instrumentation interfaced with the controller area network of the tractor. No significant differences were observed in the mean drawbar power (P_d) of drainage treatments, 53.6 kW for the FD plots and 53.4 kW for the ND plots. Compared with CK (P_d=54.8 kW), gypsum lowered the mean P_d (50.4 kW for GH and 51.2 kW for GL) while spent lime increased the mean P_d (57.6 kW). The mean P_d for GL was not significantly different from that for GH. For the combined effects of drainage and surface treatments, the mean P_d value of NDGH plots (48.9 kW) was significantly lower than mean P_d values (51.7, 51.8, and 53.1 kW) of FDGL, FDGH, and FDCK plots, respectively, which shows that drainage could have reduced the soil moisture content and hence decreased the activity of the Ca. At 23 months after installation of subsurface drainage, the mean P_d value (53.1 kW) of the FDCK plots was significantly lower than the mean P_d value (56.4 kW) of the NDCK plots, indicating that tile drainage lowered drawbar power compared to no tile drainage when no amendments were applied. For low productivity soils, the use of NDGH provided the lowest drawbar power requirement, which may be a less costly solution compared with drainage coupled with gypsum application

4.2. Introduction

Managing salt-affected soils is a serious and growing problem for farmers and engineers; it is estimated that more than 930 million hectares worldwide (Szabolcs, 1989) and over 10 million hectares on the Northern Great Plains (NGP) of the USA (J. Brennan, personal communication, NRCS North Dakota, 2008) are salt-affected. The recent increased commodity price cycle led to expansion of subsurface drainage on the NGP which resulted in subsurface drainage of sodium affected soils that are interspersed with high productivity soils (He et al., 2015; Hellerstein & Malcolm, 2011). Subsurface drainage reduces excess moisture in wet soils in spring when farmers are struggling to cultivate and plant the fields. However, subsurface drainage of sodium (Na) affected soils may increase clay dispersion and swelling as a result of increased percolation and selective leaching of high charge ions (He et al., 2015; He, DeSutter, & Clay, 2013; Qadir et al., 2001; Sumner, 1993). Dispersion of sodium affected soils may result in hardsetting as well as reduced soil trafficability and hydraulic conductivity of the soil (Earl, 1997; Hopkins et al., 2012; Reading et al., 2012; So & Aylmore, 1993). The use of hardsetting term is founded on the consequences of the soils forming a hard structureless mass upon drying and only cultivatable upon wetting (Mullins et al, 1990). Kyei-Baffour (2004) reported that increased sodicity levels followed by leaching increased soil shear strength. Hardsetting sodium affected soils are difficult to till, leading to higher fuel consumption and increased wear and tear of tillage implements.

In crop production, a significant portion of energy consumption is used for tillage, i.e., power developed at the wheels or tracks of the tractor and transmitted through the drawbar to pull implements through the ground or over the crop (ASABE Standards, 2006). Drawbar power, which is a product of draft and speed of travel, is affected by soil strength, soil moisture content, depth of tillage and the geometry of the tool (e.g., tine or disk), the tractor setup and farming practice (Harrigan & Rotz, 1995; Kocher et al., 2011; Upadhyaya et al., 1984). Soil strength is dependent on other soil properties such as texture, bulk density, organic matter and the moisture state (Harrigan & Rotz, 1995; Kocher et al., 2011). Carter (1990) noted that soil strength decreased with increased soil water content, where increased filled pore space decreased the frictional component of the shear strength; conversely, increased matric potential increased the frictional component of the shear strength. Effects of increased sodicity on aggregate stability has been reported to lead to less stable aggregates, however, soil aggregates remained stable in non-sodic soils (Bronick & Lal, 2005). Macro-porosity, which is linked to aggregates in the soil and to bulk density, has been reported to account for 66% of the shear strength in fine sand dominant soils (Carter, 1990). Barzegal et. al (1994) also reported reduced tensile strength in soil samples with larger aggregates and increasing porosity. Lowering the drawbar power requirements in sodium affected soils can result in monetary savings for farmers due to less fuel consumption (Schaefer et al., 1989).

The deleterious effects of Na ions in Na-affected soils can be remediated by replacement of calcium (Ca) ions on the soil's exchange sites (Ilyas et al., 1997). Application of Ca-surface amendments, such as gypsum or spent lime, a by-product from the sugar beet industry, are expected to improve physical and hydraulic characteristics of the soil (Cochrane & Aylmore, 1991; So & Aylmore, 1993). Dose et al. (2015) reported that Ca amendments impact soil microbial diversity and He et al. (2013) suggested Ca helps build soil aggregate stability. Schaefer et al. (1989) observed a reduction in the draft requirement for tillage on a sodium-affected silt loam (Beotia series, Mollisols) in South Dakota after it was treated with gypsum (source unspecified), which reduced its exchangeable sodium percentage.

Mathematical models have been developed to estimate the draft and drawbar power for various soil types and implements. Godwin et al. (2007) developed a force prediction model based on the soil characteristics, however, the model needs many parameters for its adoption. Ucgul et al.(2014) used three-dimensional discrete element modelling of tillage in a cohesionless soil to optimize draft force prediction. The performance of the Ucgul et al.(2014) model was greatly improved in a sandy loam when adhesion forces were incorporated (Ucgul et al., 2015).

Models are very adept for optimizing tillage implement design under different conditions; however, repeatable results are difficult to obtain (Grisso et al., 1996).

The changes in soil physical properties such as soil strength that affect trafficability can reliably be estimated with cone penetrometers, however, the cone index from penetrometers is not a good predictor of draft and drawbar power (Arvidsson et al., 2004). Draft is closely related to soil cohesion and will vary with the type of implement used (Arvidsson et al., 2004). Al-Kheer et al. (2011) observed that soil cohesion had the largest effect on draft (both vertical and horizontal forces) compared with other tillage parameters. Using an instrumented tractor, Wiedemann & Cross (1994) measured the drawbar power needs for chain-diking implements. Doppler radar was used to measure the ground speed while the draft was measured by clevis pin load cells. The advancement in computer and electronic systems integrated with global positioning systems (GPS) on the tractor has made it possible to measure more accurately several performance metrics pertaining to tractor-implement interaction under field conditions (Yahya et al., 2009). Relationships between fuel consumption and drawbar power have been developed for tractors with various tillage implements under different conditions (Grisso et al., 2004), which may provide insight into the changes in soil strength as a result of the amendments.

Measurements of draft provide a key data set that will help us understand the physical response of the soil to the drainage practices and Ca amendments. An important advantage of draft measurements is that they represent a much larger area in each plot compared with other measurements such as penetration resistance where very few points are sampled in the field. Moreover, draft and vehicle speed can be used to calculate drawbar power (Larsen, 1966), thereby providing a farmer-friendly means of comparing and contrasting various drainage and surface treatments.

In addition to the improvement in hydraulic properties of Na-affected soils treated with Ca amendments, the potential saving in fuel consumption as a result of reduced drawbar requirements due to Ca-amendments provides another incentive to farmers. The objective of this study was to determine the effects of Ca-based surface amendments and subsurface drainage conditions on the drawbar power requirements for a sodium-affected soil.

4.3. Materials and methods

The field site was located near Wyndmere, North Dakota (97.26° W, 46.28° N and elevation 323 m) and the soil was Exline loam (Fine, smectitic, frigid Leptic Natrudolls) with some inclusions of Stirum-Arveson complex (Stirum: Coarse-loamy, mixed, superactive, frigid Typic Natraquolls; Arveson: Coarse-loamy mixed, superactive, frigid Typic Calciaquolls). At the site, visible “puddling” of soil indicates that surface structure was not defined and led to field observed hardsetting .These are low productivity soils with a crop productivity index of 25 and SAR values as high as 20 (NRCS, 2015). For 1991 through 2015, May through October precipitation and Penman evapotranspiration averaged 416 and 882 mm, respectively, at the Wyndmere station of the North Dakota Agricultural Weather Network (NDAWN; North Dakota Agricultural Weather Network Center, 2016). A phreatic surface may occur at 0.3 m or less from the soil surface is common (Baker and Paulson, 1967).The mean and the range for selected chemical properties across the surface treatments are summarized in Table 8. He et al. (2015) reported a cation exchange capacity of 12.0 cmol kg^{-1} for the soils at the site.

A completely randomized design with split-plots was used, where drainage treatments were the whole plots and split plots consisted of surface applications of Ca-amendments (Figure 7). Each drainage treatment, 24.4 m wide (east-west) and 107 m long (north-south), was overlaid with five surface treatment plots, each of which was 24.4 m wide (east-west) by 21.3 m long (north-south). The drainage treatments were no drainage (ND), controlled drainage (CD) with control structures (Agri-Drain inline water level control structures, Adair, Iowa, USA), and free-outflow drainage (FD). During 2014 the CD plots had little or no outflow and thus behaved as FD plots; the CD and FD plots were combined and labeled FD in for this study. The north-south subsurface drains, installed in December 2012, were spaced at 24.4 m with a depth of approximately 1.2 m and a drainage coefficient of 9.5 mm d^{-1}.

Table 8. Percent sodium (%Na), electrical conductivity (EC), and pH averaged over surface amendments for layers 0 to 15 cm and 15 to 60 cm sampled October 2014.

Depth (cm)	Surface Amendment*	%Na		EC_{1-1}†		pH_{1-1}	
		Mean	Range	Mean	Range	Mean	Range
0-15	Check	2.8	9.0 –0.4	0.7	4.2 –0.3	8.3	8.8 –6.9
	Gypsum High	1.3	3.3 –0.3	1.9	2.1 –1.7	7.8	7.9 –7.5
	Gypsum Low	2.3	9.1– 0.4	1.5	1.8– 1.1	7.8	8.3– 7.7
	Spent Lime	2.1	7.5 –0.9	0.5	0.7 –0.4	8.3	8.9 –7.7
15-60	Check	3.39	12– 0.4	0.6	1.2– 0.3	8.8	9.6 –6.6
	Gypsum High	2.82	6.7– 0.3	1.2	6.5– 0.6	8.5	9.5 –7.8
	Gypsum Low	5.91	35– 0.4	0.9	1.5–.6	8.7	9.6 –8.0
	Spent Lime	3.52	12–0.5	0.6	2.3–0.3	8.7	9.3 –7.6

*The surface amendments designated in the legend are: gypsum at high rate (22.4 Mg ha-1), gypsum at low rate (11.2 Mg ha-1), sugar beet spent lime (22.4 Mg ha-1), and check plots receiving no surface amendment.

† The 1-1 footnote indicates a 1:1 soil: water extract.

It is important to recognize the differences in Ca sources used as surface amendments in this project: gypsum is $CaSO_4{\cdot}2H_2O$, while spent lime is $CaCO_3$.The gypsum used in this study was mined (Calcium Products, Inc., Ames, Iowa) and the spent lime was obtained locally and is a low cost by-product of processing sugar beets (DeSutter & Godsey, 2010). The gypsum and spent lime surface treatments were applied on 14 and 15 May 2013. The application rates consisted of high (22.4 Mg ha^{-1}) and low (11.2 Mg ha^{-1}) rates of gypsum (designated GH and

GL, respectively), a high rate of spent lime (22.4 Mg ha^{-1}; designated SL) and check plots (CK) with no amendment.

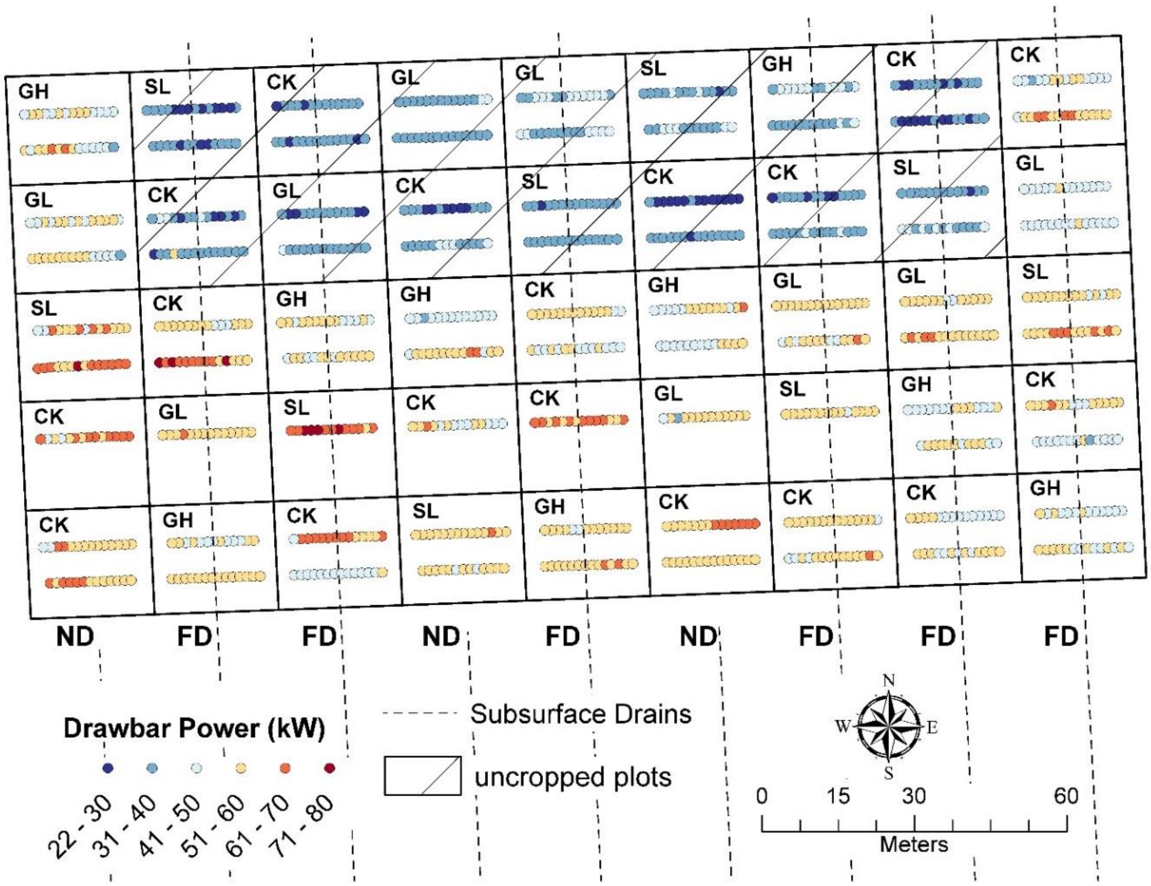

Figure 7. Drawbar power measurements across the surface amendments and drainage treatments plots near Wyndmere, North Dakota. The surface amendments designated in the legend are: gypsum at high rate (GH, 22.4 Mg ha^{-1}), gypsum at low rate (GL, 11.2 Mg ha^{-1}), sugar beet spent lime (SL, 22.4 Mg ha^{-1}), and check plots receiving no surface amendment (CK). The drainage treatments are: FD (free drainage) and ND (no drainage).

This site was under pasture/hay production for over 30 years prior to commencement of this field research in the 2013 growing season. Corn (Zea mays) was grown on the field in 2013 and 2014. Due to wet field conditions in the spring, some plots were not planted in 2014 (see Figure 1). The corn was harvested on 25 Oct 2014 and the combine was equipped with a stalk chopper, which minimized the interference of crop residue with the tillage experiment. The corners of all plots were flagged after the corn harvest and prior to the tillage experiment with real-time kinematic geographic positioning system (RTK-GPS) surveying equipment.

In an effort to provide covariate measurements to account for soil moisture and crop effects on the draft measurements, soil samples were taken in each plot on 6 Nov 2014. Soil samples were taken at two locations within each plot from the top 15 cm of the profile for gravimetric moisture content determination (Dane & Topp, 2002).

Draft was measured on 7 Nov 2014 with a drawbar dynamometer placed between a tractor and a chisel plow (Figure 8). The dynamometer consisted of a hydraulic cylinder [approximately 60 cm pin-to-pin length] equipped with a pressure transducer [Model Z, DR range (34,470 kPa) Honeywell Sensing and Control, Golden Valley, Minnesota]. Hydraulic hose extensions [approximately 1.8 m long] were used to accommodate the additional length of the dynamometer, i.e., to avoid damage and constrictions when turning. The dynamometer was calibrated ($r^2 = 0.999$) by lifting dead weights [0.1 to 66.9 kN] on an overhead crane at the CNH Industrial Engineering Test Center in Fargo, North Dakota, prior to the field experiment. Pressure measurements were read by a four-channel AD-Scan MiniModules classic signal conditioning module (CSM Products, Inc., Crystal Lake, Illinois), which was interfaced with a CANalyzer software tool (Vector Informatik GmbH, Stuttgart, Germany) and the controller area network bus on the tractor. The resolution of the pull meter and data logging system was 4.9 N, ascertained by finding the closest two points in a data file from the field testing (L. Salfer, CNH Industrial, 2014 personal correspondence).

The tractor was a Case IH Steiger Series Rowtrac™ 470 (CNH Industrial, Burr Ridge, Illinois, USA) equipped with 45.7-cm wide tracks. The chisel plow was an International model 55 with the outer wings removed, leaving a working width of 3.81 m, (Figure 8). Although the tractor could have pulled a much wider chisel plow, a small chisel plow was used to allow multiple passes per plot. The chisel plow had 13 shanks with curved, flat-faced points each 39.4 cm long (along the curve) by 5 cm wide. A tillage depth of 15 cm was used to match the estimated depth of Ca incorporation. The depth control hydraulic cylinder and the hitch of the chisel plow were adjusted by making trial tillage runs until the depths of the chisel points at the four corners of the plow averaged 15.7 cm below the soil surface, with a standard deviation of 1.9 cm. Cylinder stroke control segments (shaft collars) were used to maintain this working depth on the depth control hydraulic cylinder throughout the tillage experiment. A tillage depth of 15 cm was targeted geographic position of the tractor was logged via an RTX-GPS system interfaced with an Advanced Farming System Pro 700 Auto Guidance System (CNH Industrial, Burr Ridge, Illinois, USA). The maximum accuracy (best or smallest distance) of RTX GPS systems in this arrangement is 3.8 cm (M. Hawkins, CNH Industrial, 2014 personal correspondence).

The tractor was driven over the top of the flags on the north border of the plots to establish a baseline, then parallel lines were propagated one-third (7.10 m) of the north-south dimension of the plots to generate parallel travel lines in each of the plots. The experiment was conducted by lowering the chisel plow into the soil and pulling it along the interior two paths through each plot. Each 220-m run through the field consisted of pulling the chisel plow through nine plots along east-west travel lines. Two equally-spaced, non-overlapping runs were made over each plot, one in each direction. Borders 3.05 m long on each end of each plot were flagged to identify transition zones between adjacent plots with differing treatments.

Figure 8. Tractor, pull meter, and chisel plow used to measure draft during tillage at an experimental field site near Wyndmere, North Dakota. The insert shows the pull meter used to measure draft on the chisel plow.

The geographic position of the chisel shanks was logged using a 10.9-m GPS offset from the front axle of the tractor to the center of rotation of the lift linkage on the chisel plow. Position data were taken at approximately 1 Hz, which yielded approximately 13 draft measurements per plot, per pass, at the target travel speed of 1.34 m s-1 on the 18.3-m long working area within each plot. The data logger sampled draft at approximately 140 Hz and average draft values for each 1-Hz interval were synchronized with the time stamps on the position data. Geographic information system software (ArcMap version 10.2, ESRI, Redlands, CA) was used to assign the GPS positions of the chisel shanks and the corresponding draft, speed, and other parameters from the data logging system to individual field plots after buffering inward 3.05 m from each plot border.

The average values of draft, speed, drawbar power, and other measurements from each plot were obtained. Drawbar power across the plots was compared and contrasted using analysis of variance techniques. The cropped and uncropped plots were analyzed separately using a two-way factorial in completely randomized design with split plot. The whole plot factor was the drainage type and the split plot (or subplot) factor was surface amendment. We report results for only the cropped plots. The gravimetric moisture content was included in a generalized linear model as a covariate. The statistical model and Tukey tests for means comparisons were implemented using PROC GLM in SAS 9.4 (SAS Institute Inc., 2014) and considered to be significant at $P<0.05$. Pairwise comparisons were made into tabular form using an application by (Dallal, 2015).

4.4. Results and discussion

The drawbar power (P_d) and average speed for one of the tractor runs (the southernmost row of plots) is shown in Figure 9. The average speed across the field was maintained constant (1.34 m s^{-1}; see Figure 9), slip averaged approximately 0.3% when the chisel plow was engaged in the soil (data not shown), and the variations in drawbar power were attributed to the difference in draft experienced as the chisel plow was pulled across the field. Naderloo et al. (2009) observed that draft and forward speed have a relationship that varies from linear to quadratic, therefore maintaining a constant speed was paramount in reducing the impact of speed variations on draft, and hence drawbar power. The P_d values varied from 23 kW (blue) to 80 kW (red) as shown in Figure 7. The P_d of the uncropped plots were generally lower than cropped plots irrespective of the drainage treatments or surface amendments that had been applied (Figure 7).

The differences in P_d values between the cropped and unplanted plots could be attributed to the effects of seasonal evapotranspiration. An analysis of the gravimetric water contents of the cropped and uncropped plots showed that the mean soil water content was significantly higher (P = 0.014) in the non-cropped plots (15.8%) than in cropped plots (14.3%). The cropped plots were drier because transpiration from the corn crop during the season provided an additional process to remove soil water compared with the uncropped plots where soil water was lost through evaporation only. Klocke et al. (1985) observed that evaporation constituted approximately 30% of seasonal ET on fine sandy and loamy sandy soils in Nebraska.

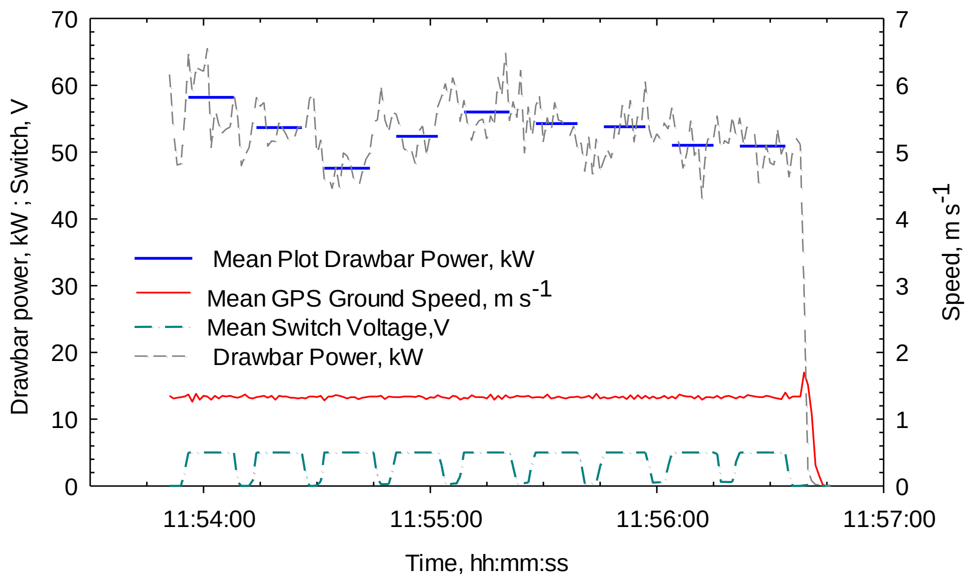

Figure 9. Drawbar power from pull meter draft and average speed, speed, and switch voltage measurement during tillage of the southernmost row of plots at the experimental field site near Wyndmere, North Dakota.

The mean soil water content across the cropped plots was 14.3% with a range from 11.4% to 18.6% and standard deviation of 1.73%. The mean gravimetric soil water content was not statistically significant across the different surface amendments. However, the influence of soil water content as a covariate was statistically significant (P < 0.0001) and means presented were adjusted for the influence of soil water content.

Drawbar power averaged 53.6 kW for the FD plots and 53.4 kW for the ND plots and these values were not significantly different from each other. The similarities in drawbar power may be attributed to fact that the P_d values for the FD and ND plots were attributed to equilibration of the soil water contents near the soil surface during the latter part of the growing season in which ET typically exceeds rainfall (Figure 10). An additional 7 mm of rain was measured at the experimental site for 1 through 7 Nov 2014, but this was assumed to have negligible effect on the draft measurements; soil moisture contents were not statistically different (P=0.95) for the cropped ND and FD plots.

The changes in the moisture regime as a result of drainage are expected to be more pronounced in spring when near saturation conditions in the soil profile prevail. The effects of subsurface drainage in the short term affect the moisture regime in the soil profile and the difference in drawbar power requirements would be predominantly a result of the difference in the soil moisture content. Raper & Sharma (2004) also observed no significant differences in draft forces for a range of soil moisture contents with the exception of higher values in the very dry soil. Subsurface drainage in a high water table environment such as the site in this study (Baker and Paulson, 1967) may reduce the capillary rise of soil water to the root zone in addition to draining the gravitational water. The long-term effects of subsurface drainage on soil structure studied on non-sodic soils include the development of larger pores (Müller et al., 1990); but these changes in structure develop first in the lower layers of the soil profile and more time is needed to see the contribution of drainage.

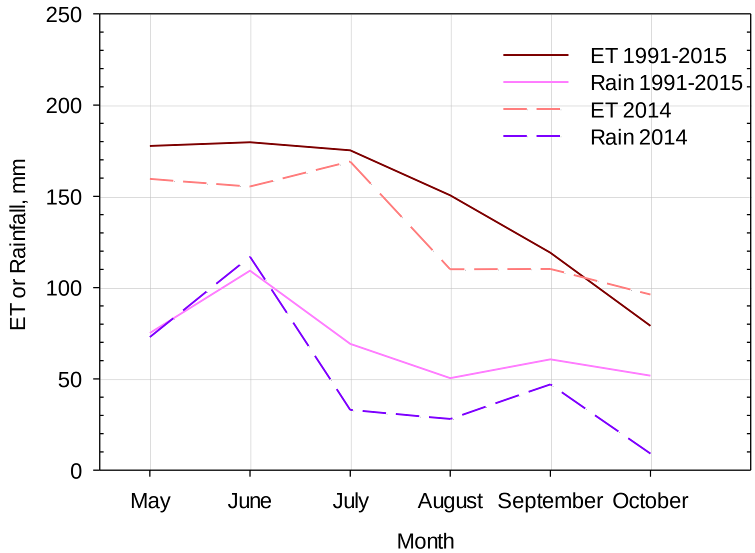

Figure 10. Monthly averages of Penman evapotranspiration and rainfall measured at the Wyndmere station of the North Dakota Agricultural Weather Network for the years 1991 through 2015.

The surface amendments had significant effects on the mean Pd requirements as shown in Table 9. Compared with no surface amendments, gypsum significantly lowered Pd while spent lime significantly increased Pd. The Pd values for GL plots were not significantly different from those for GH plots. The mechanisms behind the lower draft or reduced soil strength in sodic soils treated with gypsum have been documented (Cochrane & Aylmore, 1991; Sumner, 1993). The thickness of the diffuse double layer, which affect dispersion and swelling, are inversely related to the valency and ion strength (Essington, 2015; He et al., 2015). Gypsum amendments improve the physical properties of the soil by replacing Na with Ca at the exchange sites; Ca fosters flocculation of aggregates as opposed to Na which leads to dispersion (Choudhary et al., 2011; Emami et al., 2014). Barzegar et al. (1994) found that larger aggregates and increasing porosity corresponded to decreasing tensile strength. The reduction in tensile strength as a result of larger aggregates was attributed to fewer contact points, which decreased the friction component of the shear strength (Rahman Barzegar et al., 1994).

Table 9. Mean drawbar power for the surface treatments

Symbol	Surface amendments	Drawbar power* (kW)	Standard error (kW)
GH	Gypsum at 22.4 Mg ha^{-1}	50.4[a]	0.39
GL	Gypsum at 11.2 Mg ha^{-1}	51.2[a]	0.52
CK	Check	54.8[b]	0.36
SL	Spent lime at 22.4 Mg ha^{-1}	57.6[c]	0.53

* Means with the same letter are not statistically different at P=0.05.

Emami et al. (2014) observed a reduction in water dispersible clay from 92.6% to 20.8% after gypsum powder application at rate of 10 Mg ha^{-1} in a sodic loam with initial exchangeable sodium percent 35.4 and pH 9.1. Whereas gypsum and spent lime both contain Ca^{2+} ions which facilitate flocculation of dispersed particles thereby reducing the bulk density, improvement in soil aggregates with $CaCO_3$ use have been reported in low pH soils (Scott et al., 2003). An increase in the amount of fine aggregates (<2 mm), and the water stable aggregates (>100 μm) has also been observed with lime appplication in acidic soils (Chan et al., 2007).The higher mean P_d values for SL at the Wyndmere site could be attributed to the high pH which limits the solubility of the $CaCO_3$.

$CaCO_3$ has been reported to facilitate bridging across soil particles which reduces swelling and increases soil stability (Emerson, 1983; He et al., 2015; Richards, 1954; Rimmer & Greenland, 1976) but also increases the shear strength and stiffness of the soil (Cheng et al., 2013). The bridging effect may help explain why the SL plots had higher P_d requirements compared with gypsum and check plots. $CaCO_3$ may help with trafficability when soils are wet and soft, but it may be counterproductive because it does not reduce P_d requirements once the soil dries out, such as during the relatively dry conditions when the draft measurements were made on 7 Nov 2014. Sodium in the soil increases the water holding capacity (He et al., 2013); gypsum-soluble salt interactions reduce the ability of the soil to hold water unlike spent lime due to its limited solubility. Whereas a higher moisture content may reduce the chisel plow's metal-to-soil friction (Carter, 1990), a higher moisture content may also increase the ability of the soil to adhere to the implement thereby increasing the draft and drawbar power (Raper & Sharma, 2004).

There were also significant differences in P_d requirements for the combined effects of drainage and surface treatments as shown in Table 10. The mean P_d value of NDGH plots was significantly lower than mean P_d values of FDGL, FDGH, and FDCK plots, which suggests that drainage could have reduced the soil moisture content and hence limited the contact time for the soluble Ca to interact with soil and facilitate flocculation of the dispersed particles. Bornstein & Hedstrom (1982) observed that drier conditions developed more rapidly in the soil profile of subsurface drained silt loam following spring melt compared one without subsurface drainage.

Table 10. Mean drawbar power (kW) for combined effects of drainage and surface amendments

Symbol	Drainage and Surface treatment Combinations	Drawbar power* (kW)	Standard error (kW)
NDGH	No drainage, Gypsum at 22.4 Mg ha^{-1}	48.9^{a}	0.62
NDGL	No drainage, Gypsum at 11.2 Mg ha^{-1}	50.7^{ab}	0.87
FDGL	Free drainage, Gypsum at 11.2 Mg ha^{-1}	51.7^{b}	0.58
FDGH	Free drainage, Gypsum at 22.4 Mg ha^{-1}	51.8^{b}	0.48
FDCK	Free drainage, Check	53.1^{b}	0.39
NDCK	No drainage, Check	56.4^{c}	0.61
NDSL	No drainage, Spent lime at 22.4 Mg ha^{-1}	57.4^{c}	0.75
FDSL	Free drainage, Spent lime at 22.4 Mg ha^{-1}	57.9^{c}	0.75

* Means with the same letter are not statistically different at P=0.05.

Although NDGH resulted in the lowest drawbar power requirement, its adaptation is unlikely due to the fact that drainage reduces soil moisture and enables trafficability and early planting in the spring. Measurement of draft, slip, and trafficability in the spring would be helpful to further explore this topic.

The mean P_d value of the FDCK plots was significantly lower than the mean P_d value of the NDCK plots which showed that where no amendments were applied there was benefit of tile drainage compared to no tile. While evaluating the effects of conservation tillage and no till on drained and undrained soil in Ohio, Abid & Lal (2009) observed that drainage lowered the tensile strength of aggregates.

In our study, under conditions of no drainage, gypsum amendments significantly decreased P_d values. For plots with the SL surface treatment, mean P_d values did not differ for drained plots compared to undrained plots. The application of spent lime on drained and undrained plots offered no reduction in drawbar power requirement in comparison to the check plots with no treatments. Although an increase in the drawbar power was observed with a high rate of spent lime application on the soils in this study, spent lime has been reported to control *Aphanomyces cochlioides*, a pathogen that causes root-rotting in sugar beets in the Red River Valley, across a range of application rates (Windels, 2007).

The increases in drawbar power need to be weighed against the benefits for spent lime application especially for beet farmers. The P_d values may decrease proportionally with decreases in application rates of spent lime. An economic analysis is recommended to investigate cost-benefit ratio for applying the amendments and energy saved from reduce P_d requirements for tillage, as well as other supporting management implications such as trafficability, drainage of water from the field, and disease prevention. While the absolute changes in P_d are small in this study, in part due to the small width of the chisel plow employed, future comparisons should probably be carried out on a percentage basis. Thus, for example, GH saved about 8% on power compared with CK (Table 9), while NDGH saved about 13% on power compared with NDCK (Table 10).

4.5. Conclusions

There were no differences in the drawbar requirements between drained and undrained plots carried out in the fall 2014, which was 18 months after the application of the surface amendments and 23 months after installation of tile drainage. However, results could be different if the tillage experiment was done in the spring instead of the fall. The application of gypsum at both high and low rates reduced the drawbar power requirements of a sodic soil whereas spent lime application increased the drawbar power requirements compared to plots with no amendments. The 22.4 Mg ha^{-1} gypsum rate with no drainage had the lowest mean drawbar power value, which was significantly lower than all the other combined drainage and surface amendments except 11.2 Mg ha^{-1} gypsum rate with no drainage. Under drained conditions, gypsum application did not reduce drawbar power requirements compared to no amendments while spent lime increased the drawbar power requirements compared to no amendments. Under undrained conditions, both rates of gypsum application had lower drawbar power values compared to no surface amendments, while spent lime application did not decrease drawbar power requirements compared with no surface amendments. Our results indicate spent lime did not lower the drawbar power values under either drained and undrained conditions.

4.6. Acknowledgements

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5. GENERAL CONCLUSIONS

The experiments showed that gypsum application increased the penetration resistance of the soil during the wet conditions, improved the movement of the water through the soil matrix and reduced the drawbar power requirements comparison to spent lime.

The penetration resistance (PR) values were significantly higher in the plots with gypsum compared to the check plots and those with spent lime; higher PR values indicate better trafficability in the spring where higher soil water contents exist. It would be important to investigate the effects of both drainage and surface amendments on the hardsetting properties of the soil using a penetrometer. This should be done late in the summer when the soil is dry and using a penetrometer capable of handling higher PR values than the hand held penetrometer used in this study. The penetration resistance measurements could be expanded to cover a larger section of the plots although this may involve more personnel and time.

The improvement in infiltration was limited to the soil matrix with water at 2 cm tension. The final infiltration including the matrix flow and flow through macro-pores, evaluated using Cornell sprinkle infiltrometer, was not affected by the surface treatments. There were no significant differences in the drainage treatments (undrained and drained plots), however, the effects of the drainage were evident in the combined effects of drainage and surface amendments, where drainage was observed to augment the impact of surface amendments. *In situ* hydraulic properties determined by both the Cornell sprinkler infiltrometer and the mini-disk tension infiltrometer were highly variable; to maintain a confidence interval of 95% for comparison between surface and drainage treatments, the number of samples taken needs to be greatly increased for each plot. It is also important to explore using a normal sized tension infiltrometer instead of the mini disk tension infiltrometer although time saved with the mini disk tension infiltrometer use will be sacrificed.

The drawbar power measurements were carried out in the fall when the soil was fairly dry using a tractor that was oversized compared with the chisel plow's requirement. The contribution to power loss through slip is worth investigating using a more closely matched tractor to the chisel plow power requirements. Furthermore, it's important to investigate the drawbar power requirements in the spring when near saturation conditions exist and when a good number of the farmers do some tillage operations.

An economic analysis of the cost-benefit of ameliorant and cultivation energy is recommended. This may necessitate collecting data over multiple growing seasons. Lowering draft as a result of gypsum application is an added incentive which also needs to be captured in a cost-benefit analysis and the present study provides a useful starting point for such analyses. Although application of spent lime did not reduce the drawbar power nor improve water flow through the soil matrix, the protective value of spent line applications for deterring pathogen growth while growing sugarbeets needs to be considered when making management decisions.

The increase in P_d values after spent lime application needs to be accounted for as an additional cost and weighed against its benefits. Even though spent lime may increase drawbar power, it may have a net positive effect if its protective disease-prevention value outweighs the increased fuel costs especially if lower application rates are adopted.

For many farmers, drainage enables early planting and the adding of ameliorants will safeguard against further sodification of their fields.