GYPSUM LOWERS DRAWBAR POWER IN NORTHERN GREAT PLAINS SUBSURFACE-DRAINED SODIC SOILS

A. W. Wamono, D. D. Steele, T. DeSutter, Z. Lin, X. Jia, D. Clay

ABSTRACT. *The saline/sodic soils of the U.S. Northern Great Plains often have very low yields due to poor germination, become exceptionally hard when the soil dries, and can be a sediment source following rainfall events. In addition, subsurface drainage can result in the conversion of saline/sodic soils to sodic soils. Calcium-based surface amendments (Ca amendments) may help preserve or improve soil structure, thereby improving drainage and trafficability. The objective of this study was to determine the impact of selected subsurface drainage practices and Ca amendments on tillage power requirements. The research was conducted in a sodic soil near Wyndmere, North Dakota. The experiment used a completely random design with a split-plot arrangement in which whole plots consisted of free-outflow subsurface drainage (FD) and no subsurface drainage (ND), while split plots consisted of Ca amendments of 11.2 and 22.4 Mg ha*$^{-1}$ *gypsum (GL and GH), 22.4 Mg ha*$^{-1}$ *spent lime (SL), and check (CK) with no Ca amendments. A drawbar dynamometer measured draft on a chisel plow that was pulled across the plots by a tractor equipped with an auto-guidance system and instrumentation interfaced to its controller area network. No significant differences were observed in the mean drawbar power (*P_d*) of drainage treatments (53.6 kW for FD and 53.4 kW for ND). Compared with CK (54.8 kW), gypsum lowered the mean *P_d *(50.4 kW for GH and 51.2 kW for GL), while SL increased the mean *P_d *(57.6 kW). The *P_d *for GL was similar to that of GH. For the combined effects of drainage and surface treatments, the *P_d *of NDGH (48.9 kW) was significantly lower than that of FDGL, FDGH, and FDCK (51.7, 51.8, and 53.1 kW, respectively), which shows that drainage may have reduced soil moisture Ca activity. Twenty-three months after subsurface drainage installation, the *P_d *was lower (53.1 kW) in FDCK than in NDCK (56.4 kW). These findings suggest that subsurface drainage lowered drawbar power compared to no subsurface drainage when no amendments were applied. For low-productivity soils, NDGH had the lowest *P_d*, which may be a less costly approach to reducing drawbar power requirements compared with drainage coupled with gypsum application.*

Keywords. *Calcium, Draft, Drawbar power, Sodic soil, Spent lime, Subsurface drainage.*

Managing salt-affected soils is a serious and growing problem for farmers and engineers. It is estimated that more than 930 million ha worldwide (Szabolcs, 1989) and over 10 million ha in the U.S. Northern Great Plains (NGP) (J. Brennan, USDA-NRCS North Dakota, personal communication, 2008) are salt-affected. The recent increased commodity price cycle led to expansion of subsurface drainage in the NGP, which resulted in subsurface drainage of sodium-affected soils that are interspersed with high-productivity soils (He et al., 2015; Hellerstein and Malcolm, 2011). Subsurface drainage reduces excess moisture during a period of time when farmers are struggling to cultivate and plant their fields. However, subsurface drainage of sodium-affected soils may increase clay dispersion and swelling as a result of increased percolation and selective leaching of high-charge ions (He et al., 2013, 2015; Qadir et al., 2001; Sumner, 1993). Dispersion of sodium-affected soils may result in hardsetting as well as reduced soil trafficability and hydraulic conductivity (Earl, 1997; Hopkins et al., 2012; Levy et al., 2005; Reading et al., 2012; So and Aylmore, 1993). The use of the term "hardsetting" is founded on the consequences of the soils forming a hard structureless mass upon drying and becoming cultivatable only upon wetting (Mullins et al., 1990). Kyei-Baffour (2004) reported that increased sodicity levels followed by leaching increased soil shear strength. Sodium-affected soils that are hardset are difficult to till, leading to higher fuel consumption and increased equipment maintenance.

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, 2006). Drawbar power, which is the product of draft and speed of travel, is affected by soil strength, soil moisture content, tillage depth, tool geometry (e.g., tine or disk), tractor setup, and farming practices (Harrigan and Rotz, 1995; Kocher et al., 2011; Upadhyaya et al., 1984).

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The authors are **Anthony W. Wamono, ASABE Member,** Former Graduate Student, **Dean D. Steele, ASABE Member,** Associate Professor, and **Zhulu Lin, ASABE Member,** Assistant Professor, Department of Agricultural and Biosystems Engineering, **Thomas. M. DeSutter,** Associate Professor, Department of Soil Science, and **Xinhua Jia, ASABE Member,** Associate Professor, Department of Agricultural and Biosystems Engineering, North Dakota State University, Fargo, North Dakota; **David Clay,** Professor, Department of Plant Sciences, South Dakota State University Brookings, South Dakota. **Corresponding author:** Dean D. Steele, P.O. Box 6050, North Dakota State University, Fargo, ND 58108-6050; phone: 701-231-7268; e-mail: dean.steele@ndsu.edu.

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Soil strength is dependent on many factors, including texture, bulk density, organic matter, and moisture state (Harrigan and Rotz, 1995; Kocher et al., 2011). Carter (1990) noted that soil strength decreased with increased soil water content, where the increased filled pore space decreased the frictional component of the shear strength; conversely, increased matric potential increased the frictional component of the shear strength. The effects of increased sodicity on aggregate stability have been reported to lead to less stable aggregates; however, soil aggregates remained stable in non-sodic soils (Bronick and Lal, 2005). Macroporosity, 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). Barzegar 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 sodium (Na) ions in Na-affected soils can be remediated by replacement with 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 of the sugar beet industry, is expected to improve the physical and hydraulic characteristics of soil (Cochrane and Aylmore, 1991; So and Aylmore, 1993). Bennett et al. (2014) reported long-term improvement in aggregate stability and hydraulic conductivity of an acidic sodic soil, classified as a Red Sodosol, that was treated with both lime and gypsum. Keiblinger et al. (2016) observed a rapid increase in aggregate stability of agricultural soils with application of quicklime, a compound whose use has been limited to geotechnical engineering. Dose et al. (2015) reported that Ca amendments impact soil microbial diversity, and He et al. (2013) suggested that 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 requires numerous parameters that are rarely measured. Ucgul et al. (2014) used three-dimensional discrete element modeling of tillage in a cohesionless soil to optimize draft force prediction. The performance of the Ucgul et al. (2014) model was 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).

Changes in soil strength can be reliably estimated with cone penetrometers; however, these measurements are not a good predictor of draft and drawbar power (Arvidsson et al., 2004). Draft is closely related to soil cohesion and varies 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 and 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 with clevis pin load cells. Advancement in computer and electronic systems integrated with global positioning systems (GPS) has improved the accuracy of field measurements (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 drainage practices and Ca amendments. An important advantage of draft measurements is that they represent a much larger area when compared with penetration resistance measurements. Moreover, draft and vehicle speed can be used to calculate drawbar power (Steinbruegge and 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 savings 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.

MATERIALS AND METHODS

SITE SELECTION AND CHARACTERIZATION

The field site was located near Wyndmere, North Dakota (97.26° W, 46.28° N, and 323 m elevation), 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). Although the NRCS threshold for sodic soils is a sodium adsorption ratio (SAR) of >13 (Richards, 1954), He et al. (2015) determined that a percent sodium value (%Na) of 5 or more is restrictive to water movement in North Dakota soils. DeSutter et al. (2015) found that %Na relates to SAR using the following equation: $\text{SAR} = 1.04 \times (\%\text{Na}) - 0.35$. Suarez et al. (2008) and Levy et al. (2005) reported deleterious effects of sodium as low as SAR of 2; thus, we use 5 to designate soils as sodic and not 13, which is used for NRCS soil classification purposes. At the site, visible "puddling" of soil indicated that the 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). The mean cation exchange capacity across the surface treatments plots was 28 $\text{cmol}_c\ \text{kg}^{-1}$, with a range of 16.3 to 40.5 $\text{cmol}_c\ \text{kg}^{-1}$. Additional soil chemical properties are summarized in table 1. The changes in SAR at the site before and after application of surface amendments were reported by Wamono et al. (2016).

Table 1. Percent sodium (%Na), electrical conductivity (EC), and pH averaged over surface amendments for 0-15 cm and 15-60 cm depths sampled in October 2014. Means in the same column followed by the same letter are not statistically different for either depth at p = 0.05.

Depth (cm)	Surface Amendment[a]	%Na[b]		EC_{1-1} (dS m^{-1})[c]		pH_{1-1}[c]	
		Mean	Range	Mean	Range	Mean	Range
0-15	Check	5.3 a	0.7 to 15	0.5 a	0.3 to 0.9	8.3 a	6.9 to 8.8
	Gypsum high	2.1 a	0.6 to 4.6	1.7 b	1.4 to 1.9	7.8 b	7.5 to 7.9
	Gypsum low	3.9 a	0.7 to 13	1.3 b	0.8 to 1.8	7.8 b	7.7 to 8.3
	Spent lime	3.9 a	1.0 to 14	0.5 a	0.4 to 0.8	8.3 a	7.7 to 8.9
15-60	Check	7.0 a	0.8 to 21	0.5 a	0.7 to 0.9	8.8 a	6.6 to 9.6
	Gypsum high	5.2 a	1.0 to 13	1.4 b	0.7 to 1.9	8.5 a	7.8 to 9.5
	Gypsum low	10 a	1.0 to 45	1.1 ab	0.7 to 1.8	8.7 a	8.0 to 9.6
	Spent lime	7.0 a	1.1 to 20	0.5 ab	0.2 to 0.9	8.7 a	7.6 to 9.3

[a] The surface amendments 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.

[b] %Na = Na/(Na + Mg + Ca+ K), where all ions are expressed in cmol kg^{-1}; %Na relates to sodium adsorption ratio (SAR) using the following equation: SAR = 1.04 × (%Na) – 0.35 (DeSutter et al., 2015).

[c] The 1-1 subscript indicates a 1:1 soil:water extract.

In the study area (Wyndmere, N.D.), the average May through October precipitation was 416 mm, and the Penman evapotranspiration was 882 mm (NDAWN, 2016). A phreatic surface may occur at 0.3 m or less from the soil surface (Baker and Paulson, 1967).

The experiment used a split-plot completely randomized design. The drainage treatments were the whole plots, which were split by Ca amendments (fig. 1). Each drainage treatment, 24.4 m wide (east-west) by 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), 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 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}.

EXPERIMENTAL DESIGN

The experiment used two Ca sources: gypsum ($CaSO_4{\cdot}2H_2O$) and spent lime (predominantly $CaCO_3$). 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 and Godsey, 2010). The gypsum and spent lime surface treatments were applied on 14 and 15 May 2013. The applications 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. The high application rate of gypsum (22.4 Mg ha^{-1}) was deter-

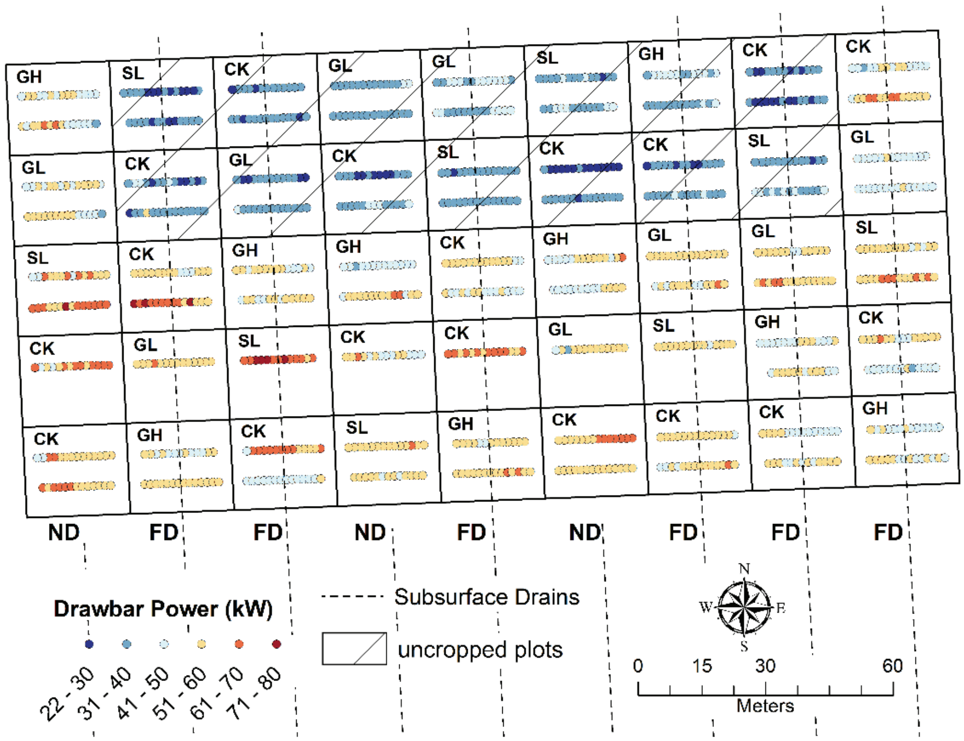

Figure 1. Drawbar power measurements across surface amendments and drainage treatments plots near Wyndmere, North Dakota. The surface amendments are gypsum at high rate (GH, 22.4 Mg ha^{-1}), gypsum at low rate (GL, 11.2 Mg ha^{-1}), sugar beet spent lime (SL, 22.4 Mg ha^{-1}), and check plots receiving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

mined using samples collected in fall 2012. The gypsum requirement (GR), as determined using equation 8.2 of Oster and Jayawardane (1998), ranged from about 4 to 20 Mg ha^{-1} for the 30 cm depth. Therefore, 22.4 Mg ha^{-1} was used for the GR, which was mixed into the top 10 cm of the soil immediately after application.

The site was under pasture/hay production for over 30 years prior to this field research in 2013. 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 (fig. 1). The corn was harvested on 25 October 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 RTK-GPS surveying equipment.

In an effort to provide covariate measurements to account for soil moisture and crop effects on the draft measurements, surface soil samples (0-15 cm) that were collected on 6 November 2014 were analyzed for gravimetric soil moisture (Dane and Topp, 2002).

DRAFT MEASUREMENTS

Draft was measured on 7 November 2014 with a drawbar dynamometer placed between a tractor and a chisel plow (fig. 2). The dynamometer consisted of a hydraulic cylinder (approx. 60 cm pin-to-pin length) equipped with a pressure transducer (model Z, DR range 34,470 kPa, Honeywell Sensing and Control, Golden Valley, Minn.). Hydraulic hose extensions (approx. 1.8 m long) were used to accommodate the additional length of the dynamometer to avoid damage and constrictions when turning. Prior to the field experiment, 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. Pressure measurements were read by a four-channel AD-Scan MiniModules classic signal conditioning module (CSM Products, Inc., Crystal Lake, Ill.), 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, personal communication, 2014).

The tractor was a Case IH Steiger Series Rowtrac 470 (CNH Industrial, Burr Ridge, Ill.) 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 (fig. 2). 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.

GEOGRAPHIC DATA ACQUISITION

The 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,

Figure 2. 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.

Burr Ridge, Ill.). The maximum accuracy (best or smallest distance) of RTX-GPS systems in this arrangement is 3.8 cm (M. Hawkins, CNH Industrial, personal communication, 2014). The tractor was driven over the top of the flags on the north border of the plots to establish a baseline, and then parallel lines were propagated for 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.

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, aiming for 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 ver. 10.2, ESRI, Redlands, Cal.) 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.

STATISTICAL ANALYSIS

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 a completely randomized design with split plots. The whole-plot factor was 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 (ver. 9.4, SAS Institute, Inc., Cary, N.C.) and considered to be significant at $p < 0.05$. Pairwise comparisons were made into tabular form using an application by Dallal (2015).

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 3. The average speed across the field was maintained constant at 1.34 m s^{-1} (fig. 3). 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 differences in draft 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 for collection of accurate data. The P_d values varied from 23 kW (blue) to 80 kW (red), as shown in figure 1. The P_d values were generally lower for the uncropped plots than for the cropped plots irrespective of the drainage treatment or surface amendment (fig. 1). The differences in P_d values between the cropped and uncropped plots could be attributed to seasonal evapotranspiration (ET). 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 uncropped plots (15.8%) than in the cropped plots (14.3%). These results were attributed to transpiration by the prior crop that reduced soil moisture. Klocke et al. (1985) observed that evaporation constituted approximately 30% of seasonal ET on fine sandy and loamy sandy soils in Nebraska.

The mean soil water content across the cropped plots was 14.3% and ranged from 11.4% to 18.6%. The standard deviation was 1.73%. The surface chemical amendments did not

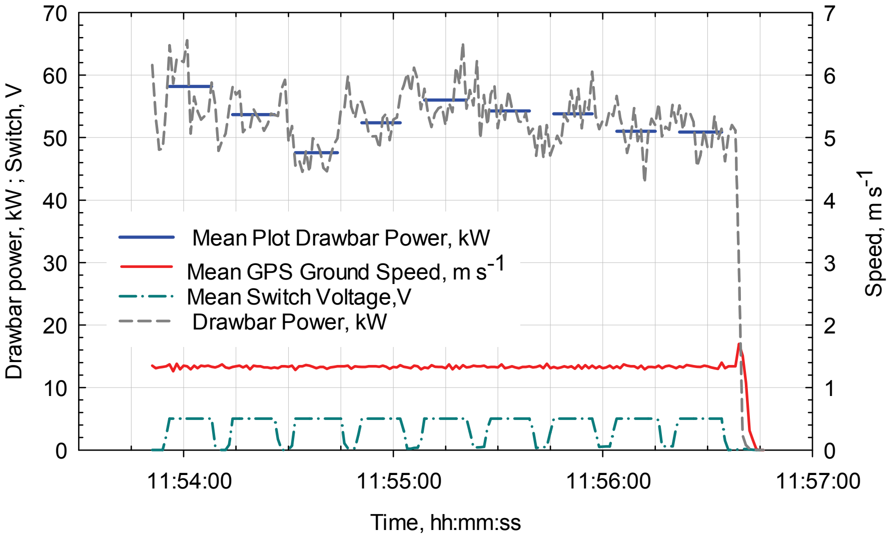

Figure 3. Drawbar power from pull meter draft and average ground speed and switch voltage measurement during tillage of the southernmost row of plots at the experimental field site near Wyndmere, North Dakota.

influence gravimetric soil water content. The results of ANOVA were p = 0.54 for drainage treatments, $p < 0.0001$ for surface treatments, and $p < 0.0001$ for drainage × surface treatment. The influence of soil water content on the P_d values as a covariate was statistically significant ($p < 0.0001$), and means were adjusted for the influence of soil water content.

Drawbar power was similar in the FD (53.6 kW) and ND (53.4 kW) plots. Because ET typically exceeds rainfall during the latter part of the growing season (fig. 4), especially in 2014, the near-surface soil water contents for both FD and ND were expected to be relatively low for all cropped plots, and thus the mean P_d values for FD and ND were not significantly different. An additional 7 mm of rain was measured at the experimental site for 1 through 7 November 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. In the short term, subsurface drainage affects 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 and Sharma (2004) also observed no significant differences in draft forces for a range of soil moisture contents, with the exception of higher values in very dry soil. Subsurface drainage in a high water table environment, such as the site in this study, may reduce the capillary rise of soil water to the root zone in addition to draining the gravitational water (Baker and Paulson, 1967). The long-term effects of subsurface drainage on soil structure in 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 effects of drainage on P_d near the soil surface.

The surface amendments had significant effects on the mean P_d requirements, as shown in table 2. Compared with no surface amendments, gypsum significantly lowered P_d, while spent lime significantly increased P_d. The P_d 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 and Aylmore, 1991; Sumner, 1993). The thickness of the diffuse double layer, which affects dispersion and swelling, is inversely related to the valence and ion strength (Essington, 2015; He et al., 2015). Gypsum amendments improved the soil physical properties 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 between soil particles, which decreased the friction component of the shear strength (Barzegar et al., 1994). Emami et al. (2014) observed a reduction in water-dispersible clay from 92.6% to 20.8% after gypsum powder application at a rate of 10 Mg ha^{-1} in a sodic loam with initial exchangeable sodium of 35.4% and pH of 9.1. Whereas gypsum and spent lime both contain Ca^{2+} ions, which facilitate flocculation of dispersed particles and thereby reduce the bulk density, improvement in soil aggregates with $CaCO_3$ use has been reported for low pH soils (Scott et al., 2003). An increase in the amounts of fine aggregates (<2 mm) and water-stable aggregates (>100 μm) has also been observed with lime application in sodic soils (So et al., 1978). 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 $CaCO_3$.

Table 2. Mean drawbar power for the surface treatments.

Symbol	Surface Amendments	Drawbar Power[a] (kW)
GH	Gypsum at 22.4 Mg ha^{-1}	50.4 a
GL	Gypsum at 11.2 Mg ha^{-1}	51.2 a
CK	Check	54.8 b
SL	Spent lime at 22.4 Mg ha^{-1}	57.6 c

[a] Means with the same letter are not statistically different at p = 0.05.

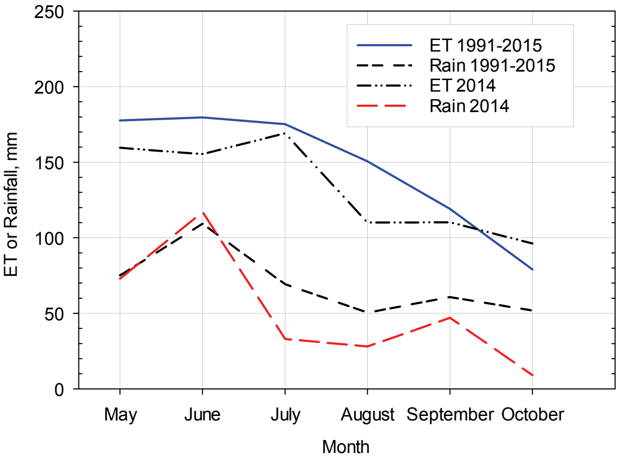

Figure 4. Monthly averages of Penman evapotranspiration and rainfall measured at the Wyndmere station of the North Dakota Agricultural Weather Network for the years 1991 through 2015.

$CaCO_3$ has been reported to facilitate bridging across soil particles, which reduces swelling and increases soil stability (Emerson, 1983; He et al., 2015; Keiblinger et al., 2016; Richards, 1954; Rimmer and 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 the 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 November 2014. Sodium in the soil increases the soil's 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 and Sharma, 2004). When lime is added beyond the limit needed for flocculation, pozzolannic reactions may occur, which increase the strength of the soil (Bell, 1996). Pozzolannic reactions often occur at pH near 12, where $Ca(OH)_2$ reacts with clays to form hydrated silicates and aluminates of calcium; this leads to increased soil strength and is applied in geotechnical engineering. However, Ghobadi et al. (2014) reported lime stabilization at pH of 9. Although a higher P_d value was observed with spent lime application, Keiblinger et al. (2016) suggested that the improvement from spent lime is delayed (long term) rather than instantaneous as with the more soluble options of Ca. Spent lime application boosts the soil microbial life, activities of which could also be observed in the long term (Castro and Logan, 1991; Dose et al., 2015).

There were also significant differences in P_d requirements for the combined effects of drainage and surface treatment, as shown in table 3. The mean P_d value of the NDGH plots was significantly lower than the mean P_d values of the FDGL, FDGH, and FDCK treatments, which suggests that drainage may have reduced the soil moisture content and hence limited the opportunity for soluble Ca to facilitate flocculation of the dispersed particles. Although NDGH resulted in the lowest drawbar power requirement, its adaptation is unlikely because drainage reduces soil moisture and enables trafficability and early planting in the spring. Bornstein and Hedstrom (1982) observed that drier conditions developed more rapidly in the soil profile of subsurface-drained silt loam following spring melt compared with a profile without subsurface drainage. Measurement of draft, slip, and trafficability in the spring would be helpful to further explore drawbar power responses to surface amendments and drainage practices. Future studies along these lines should also consider more closely matching the tractor power and chisel plow size so that slip and trafficability differences may be more easily detected across drainage and surface treatments.

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 tile drainage had lower P_d than no tile when amendments were not applied. While evaluating the effects of conservation tillage and no-till on drained and undrained soil in Ohio, Abid and 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 drawbar power was observed with 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 (DeSutter and Godsey, 2010; Windels et al., 2007). The increases in drawbar power need to be weighed against the benefits of spent lime application, especially for beet farmers. The P_d values may decrease proportionally with decreases in the application rate of spent lime. An economic analysis is recommended to investigate the cost-benefit ratio for applying the amendments and the energy saved from reducing P_d requirements for tillage, as well as other supporting management implications, such as trafficability, drainage from the field, and disease prevention. While the absolute changes in P_d were small in this study, in part due to the small width of the chisel plow, future comparisons should probably be carried out on a percentage basis. For example, GH saved about 8% on power compared with CK (table 2), while NDGH saved about 13% on power compared with NDCK (table 3).

Table 3. Mean drawbar power (kW) for combined effects of drainage and surface amendments.

Symbol	Drainage and Surface Treatment Combinations	Drawbar Power[a] (kW)
NDGH	No drainage, gypsum at 22.4 Mg ha^{-1}	48.9 a
NDGL	No drainage, gypsum at 11.2 Mg ha^{-1}	50.7 ab
FDGL	Free drainage, gypsum at 11.2 Mg ha^{-1}	51.7 b
FDGH	Free drainage, gypsum at 22.4 Mg ha^{-1}	51.8 b
FDCK	Free drainage, check	53.1 b
NDCK	No drainage, check	56.4 c
NDSL	No drainage, spent lime at 22.4 Mg ha^{-1}	57.4 c
FDSL	Free drainage, spent lime at 22.4 Mg ha^{-1}	57.9 c

[a] Means with the same letter are not statistically different at p = 0.05.

CONCLUSIONS

There were no differences in the drawbar power requirements between drained and undrained plots for tillage in fall 2014, which was 18 months after the application of surface amendments and 23 months after installation of subsurface 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 less than all other combined drainage and surface amendments except the 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 drawbar power requirements compared to no amendments. Under undrained conditions, both rates of gypsum application had lower drawbar power values compared to no amendments, while spent lime application did not decrease drawbar power requirements compared with no amendments. Our results indicate that spent lime did not decrease the drawbar power values under either drained or undrained conditions.

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