EFFECTS OF CALCIUM-BASED SURFACE AMENDMENTS ON THE PENETRATION RESISTANCE OF SUBSURFACE DRAINED SODIC SOILS

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

ABSTRACT. *In the saline/sodic and sodic soils of the northern Great Plains, 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 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 15 to 30 cm layers, respectively, were not significantly different. The PR value for the surface 15 cm was higher for GH (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), 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, NDGH had PR means (498 kPa) that were similar to all other treatments but higher than for FDSL (384 kPa). In the 15 to 30 cm layer, FDGL had PR means (1007 kPa) similar to FDGH (1074 kPa) and NDGH (1027 kPa), which showed that drainage coupled with a lower gypsum rate achieved similar results as the higher rate of gypsum application.*

Keywords. *Cone index, Drainage, Penetration resistance, Penetrometer, Sodic soils, Soil physical properties, Trafficability.*

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, NRCS North Dakota, personal communication, 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, 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 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 macroporosity (Ilyas et al., 1997), which in turn improves soil structure and load bearing capacity. Replacement of Na with Ca in the soil's exchange complex also reduces the water holding capacity of the soil because charged Na^{+} ions prefer to be hydrated while Ca^{2+} ions prefer to be bound to clay particles (He et al., 2015). Reduction in the water holding capacity and flocculation of dispersed soil aggregates should lead to better

Submitted for review in August 2015 as manuscript number NRES 11516; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in May 2016.

The authors are **Anthony W. Wamono, ASABE Member,** Graduate Student, **Dean D. Steele ASABE Member,** Associate Professor, and **Zhulu Lin, ASABE Member,** Assistant Professor, Department of Agricultural and Biosystems Engineering, North Dakota State University, Fargo, North Dakota; **Thomas. M. DeSutter,** Associate Professor, Department of Soil Science, North Dakota State University, Fargo, North Dakota; **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, Dept. 7620, P.O. Box 6050, North Dakota State University, Fargo, ND 58108-6050; phone: 701-231-7268; e-mail: dean.steele@ndsu.edu.

Transactions of the ASABE

Vol. 59(4): 869-877 © 2016 American Society of Agricultural and Biological Engineers ISSN 2151-0032 DOI 10.13031/trans.59.11516

trafficability in sodic soils treated with Ca. Gypsum application in the reclamation of sodic soils has been widely 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 the form 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 the effects of surface amendments and management practices on soil trafficability can be realized through analysis of changes in the soil's mechanical properties. Earl (1997) listed a range of properties (e.g., shear stress, bulk density, and plastic limit) that predict the mechanical state of the soil. Other properties, such as 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 and 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., 2013; Kandel et al., 2013; Mueller et al., 2003).

Mechanical soil properties pertaining to soil trafficability can be reliably estimated by cone penetrometers, which measure penetration resistance (ASABE, 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.

MATERIALS AND METHODS

SITE SELECTION AND CHARACTERIZATION

The experimental site (97.25° W, 46.2° N, 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 h^{-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, which was 25 months after the surface amendments (discussed below) were applied.

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 (fig. 1). The whole plots were 24.4 m × 107 m (80 ft × 350 ft), and the split plots were 24.4 m × 21.3 m (80 ft × 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}) of sugarbeet spent lime (SL), cover crops (CC), and check (CK) plots receiving no surface amendment. Corn was planted at the site, which left no time after harvest for growing cover crops; therefore, CC was treated as CK plots.

In the CD plots, manual flow control structures (Inline Water Level Control Structures, Agri Drain Corp., Adair, Iowa) were installed to manage the depth of the water table. In the FD plots, water flowed out of the plots with no restriction. No flow management was done in the CD plots 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, Iowa) were applied using a machine spreader wagon pulled by a tractor and by hand using shovels to deliver gypsum at desired rates for the GH plots. Known quantities of spent lime powder and gypsum were spread manually using shovels to deliver the desired application rate for the 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 application and prior to planting. The post-spreading tillage, the farmer's annual tillage each fall, and freeze-thaw

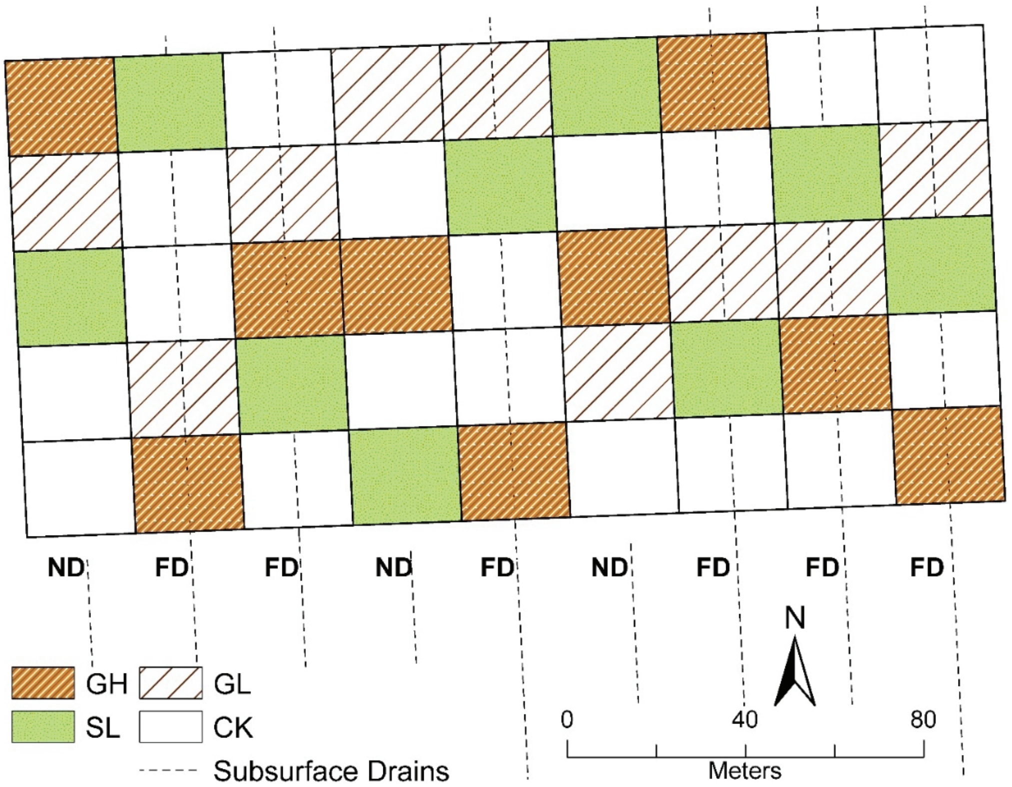

Figure 1. Field-plot layout of the Wyndmere site in Richland County, North Dakota. The surface amendments are: GH = gypsum at high rate (22.4 Mg ha^{-1}, 10 t ac^{-1}); GL = gypsum at low rate (11.2 Mg ha^{-1}, 5 t ac^{-1}); SL = sugarbeet spent lime (22.4 Mg ha^{-1}, 10 t ac^{-1}); and CK = check plots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

cycles over the two years after application were expected to have alleviated the compaction from wheel traffic and helped to spread the hand-applied spent lime and gypsum for GL. We avoided penetrometer sampling at all locations where wheel traffic was evident.

PENETROMETER

The cone index, which is a pressure measurement, was taken against depth in all plots using a hand-driven cone penetrometer (Field Scout SC 900, Spectrum Technologies, Inc., Plainfield, Ill.) with data logging capabilities synchronized with a GPS unit for spatial coordinates. The penetrometer has an inbuilt ultrasonic sensor at its base that measures the depth of penetration. The penetrometer was pushed into ground at a uniform rate of approximately 30 mm s^{-1} (ASABE, 2009). A cone 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, 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 × 9.1 m (4 ft × 30 ft) sampling area was monitored (shaded area in fig. 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 (fig. 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 confidence interval of 90% (Student's t-test) (Hillel, 1980; ASABE, 2009). That is, n = 10 penetration profiles were taken per split plot in subsequent measurements.

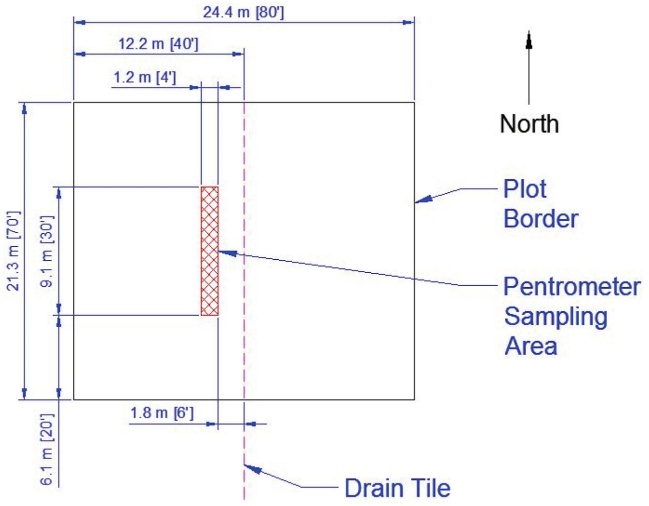

Figure 2. Layout and dimensions of the penetrometer sampling area in a split plot.

SOIL SAMPLING AND MOISTURE CONTENT

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 in., 6 to 12 in., and 12 to 18 in.) depths in each experimental plot where PR profiles were measured. A soil probe (Brown Moisture Probe, AMS, Inc., American Falls, Ida.), which had a modified auger tip to trap soil at the 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°C for a minimum of 24 h (Dane and Topp, 2002). Soil samples for chemical analysis were collected in 15 cm increments using a Giddings soil probe of 6 cm diameter (Blake and Hartge, 1986) and analyzed in the laboratory for K, Na, Ca, and Mg for calculation of the sodium adsorption ratio (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 × (%Na) − 0.35 (DeSutter et al., 2015).

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 separately for the 0 to 15 cm layer and the 15 to 30 cm layer, 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 such as subsoiling (Jorajuria and 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 the surface amendment in a completely randomized design (fig. 1). The mean PR values for the CK treatment were obtained from 18 split plots (nine CK and nine 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 for Windows (ver. 9.4, SAS Institute, Inc., Cary, N.C.) and considered significant at $p < 0.05$.

RESULTS AND DISCUSSION

The SAR values estimated from soil samples from 18 plots with surface treatments (nine GH plots and nine CK plots) taken before and after application of the surface amendments are summarized in table 1. 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 to 15 cm layer of the GH plots was the reduction significant. This decrease in SAR in the gypsum plots is attributed to Ca added through gypsum and 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).

Table 1. Soil sodium adsorption ratios, averaged over surface amendments for layers 0 to 15 cm and 15 to 30 cm.

		Sodium Adsorption Ratios[a]	
Depth (cm)	Year	Check Plots (No Ca amendments)	Gypsum High Rate Plots ($22.42\ Mg\ ha^{-1}$)
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

[a] Means within the same column for each depth followed by the same letter are not statistically different at p = 0.05 using Student's t-test between 2012 and 2015.

DRAINAGE TREATMENTS

The effect of moisture content on the PR values was significant in the 0 to 15 cm layer ($p = 0.0001$) and not significant in 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.

SURFACE TREATMENTS

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 in the deeper parts of the soil profile. 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). This increase in bulk density may also 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 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 in figure 5 for the 15 to

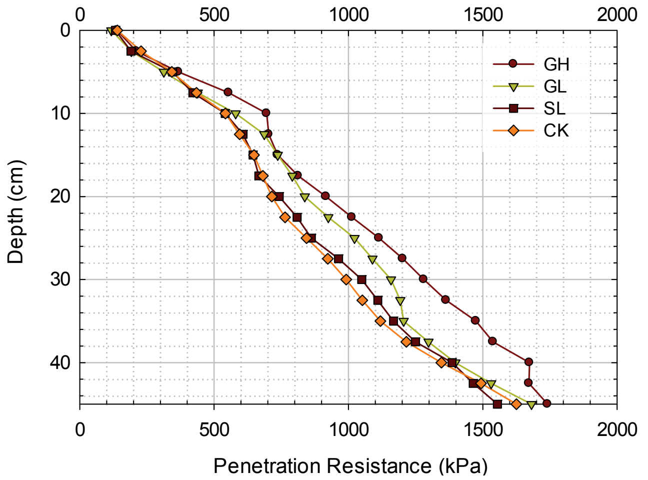

Figure 3. Mean values of penetration resistance (kPa) of all plots for various surface amendments at the Wyndmere site. These means were not adjusted for soil water content. The treatments are: GH = gypsum at high rate (22.4 Mg ha^{-1}), GL = gypsum at low rate (11.2 Mg ha^{-1}), SL = sugarbeet spent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

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 2 for the 0 to 15 cm and 15 to 30 cm layers. In the 0 to 15 cm layer, the PR values were significantly higher for the GH plots than for other surface treatments. In the 15 to 30 cm layer, the PR values were higher for the gypsum amendments than for the CK plots. The use of spent lime resulted in PR values that were similar to those of the CK plots.

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 and 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 a soil with no gypsum where the PR values returned to pre-cultivation levels.

Because of the weak structure as result of the 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 low Na soil samples. By reducing the Na in soil with Ca substitution, a reduction in the 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. The limited

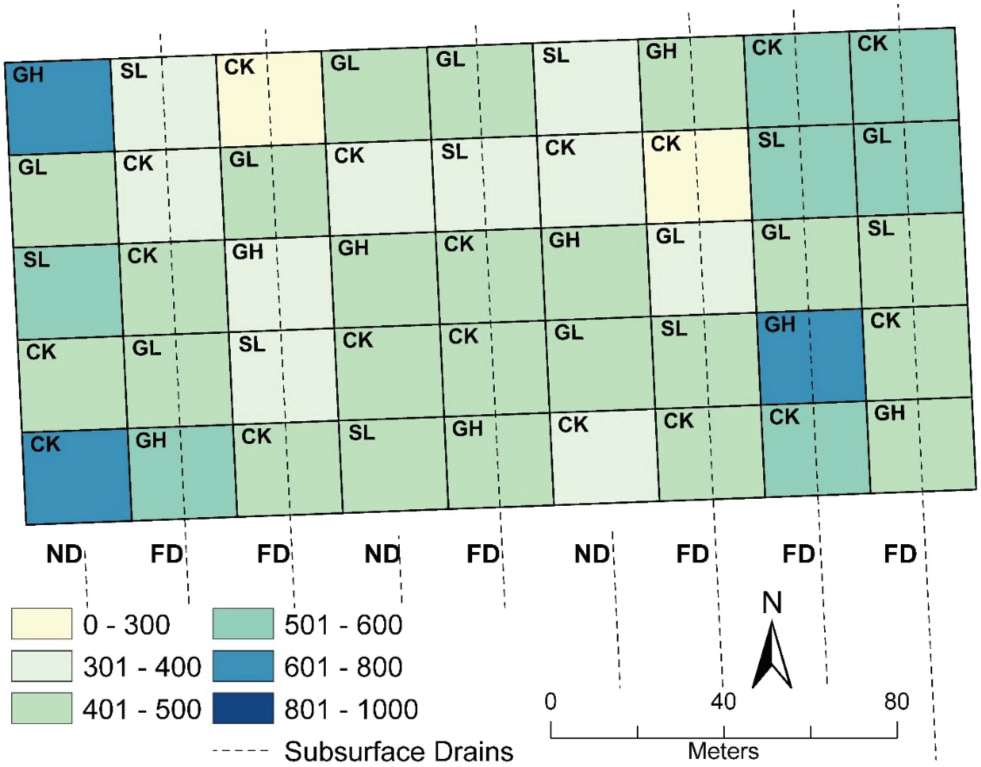

Figure 4. Mean values of penetration resistance (kPa) of all plots for various surface amendments for the 0 to 15 cm layer at the Wyndmere site. The treatments are: GH = gypsum at high rate (22.4 Mg ha^{-1}), GL = gypsum at low rate (11.2 Mg ha^{-1}), SL = sugarbeet spent lime at 22.4 Mg ha^{-1}, and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

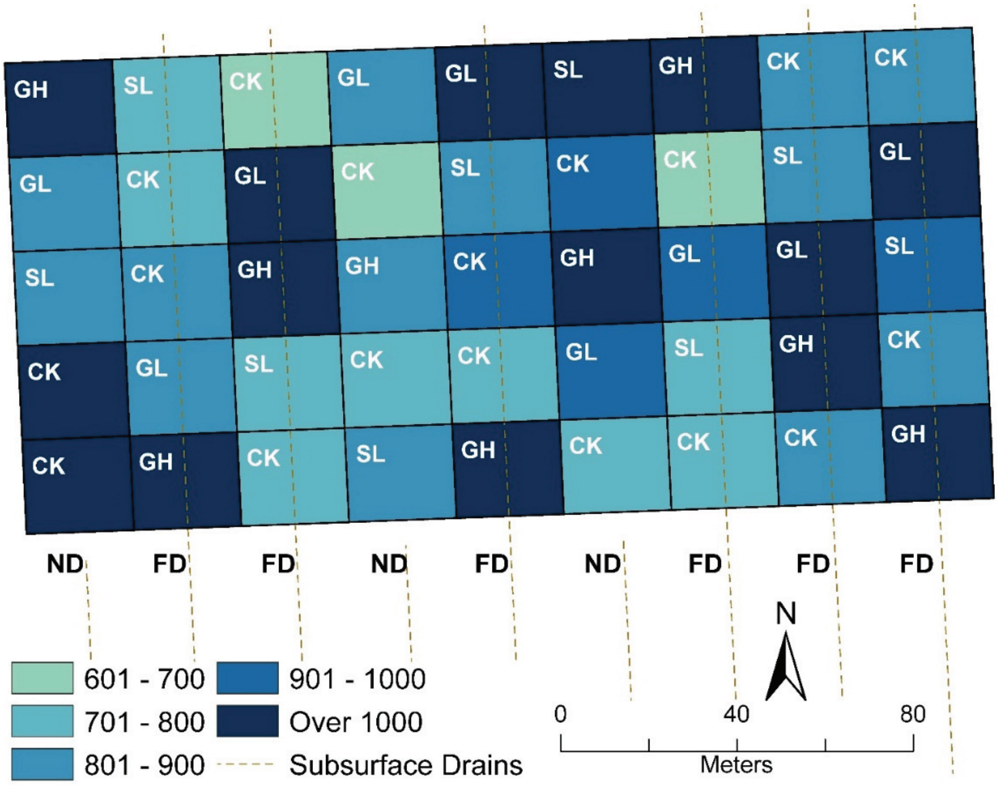

Figure 5. Mean values of penetration resistance (kPa) of all plots for various surface amendments from 15 to 30 cm layer at the Wyndmere site. The treatments are: GH = gypsum at high rate (22.4 Mg ha^{-1}), GL = gypsum at low rate (11.2 Mg ha^{-1}), SL = sugarbeet spent lime at 22.4 Mg ha^{-1}, and CK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

Table 2. Mean penetration resistance values measured in June 2015 for surface amendments applied in May 2013.

Depth (cm)	Symbol	Surface Amendment[a]	Mean Penetration Resistance[b] (kPa)	Standard Error (kPa)
0 to 15	GH	Gypsum high	485 a	15
	GL	Gypsum low	430 b	10
	CK	Check	426 b	5
	SL	Spent lime	420 b	14
15 to 30	GH	Gypsum high	1050 a	14
	GL	Gypsum low	954 b	14
	SL	Spent lime	866 c	14
	CK	Check	839 c	10

[a] Gypsum high = 22.4 Mg ha^{-1}, gypsum low = 11.2 Mg ha^{-1}, spent lime = 22.4 Mg ha^{-1}, and check = plots receiving no surface amendment.

[b] Penetration resistance values were adjusted for soil water content. Means followed by the same letter are not statistically different at p = 0.05 using the Tukey test for comparison of means for each depth.

solubility of the spent lime explains why the Ca in the SL plots did not produce similar results.

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 of drainage treatments and surface amendments are denoted with combined abbreviations, 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 the combined effects of drainage and surface amendments in the 0 to 15 cm and 15 to 30 cm layers are shown table 3.

Table 3. Mean penetration resistance values measured in June 2015 for combined effects of drainage installed in December 2012 and surface amendments applied in May 2013.

Symbol	Drainage and Surface Treatment Combination[a]	Mean Penetration Resistance[b] (kPa)	Standard Error (kPa)
Depth = 0 to 15 cm			
NDGH	No drainage, gypsum high	498 a	23
FDGH	Free drainage, gypsum high	471 a	18
NDSL	No drainage, spent lime	457 ab	23
NDGL	No drainage, gypsum low	433 ab	23
FDCK	Free drainage, check	432 ab	12
FDGL	Free drainage, gypsum low	426 ab	16
NDCK	No drainage, check	420 ab	16
FDSL	Free drainage, spent lime	384 b	16
Depth = 15 to 30 cm			
FDGH	Free drainage, gypsum high	1074 a	16
NDGH	No drainage, gypsum high	1027 a	23
FDGL	Free drainage, gypsum low	1007 a	16
NDSL	No drainage, spent lime	921 b	22
NDGL	No drainage, gypsum low	901 b	22
NDCK	No drainage, check	898 b	16
FDSL	Free drainage, spent lime	811 c	16
FDCK	Free drainage, check	779 c	11

[a] Gypsum high = 22.4 Mg ha^{-1}, gypsum low = 11.2 Mg ha^{-1}, spent lime = 22.4 Mg ha^{-1}, and check = plots receiving no surface amendment.

[b] Penetration resistance values were adjusted for soil water content. Means followed by the same letter are not statistically different at p = 0.05 using the Tukey test for comparison of means for each depth.

The PR means of the 0 to 15 cm layer are important for analysis of the effects of surface amendments and drainage treatments on trafficability and workability of agricultural soils, especially those with compositions of high silt and clay separates. The mean PR values of the NDGH and FDGH plots were significantly higher than that of the FDSL plots. The remaining treatments were not significantly different from each other. The 15 to 30 cm layer is important for trafficability when the predominant soil texture is clay or loam (Rab et al., 2005) and 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 the 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 the higher PR means in FDGH. The higher concentration of Ca in 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 and Horn (1991) explained that an increase in bulk density corresponds to an increase in strength when the influence of soil structure is ignored (e.g., in nonstructured or weakly aggregated soils). However, soil strength becomes more dependent on shear parameters (e.g., 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 Ca from the upper layers of the soil profile. The results of our study agree with Cochrane and Aylmore (1991), who noted an improvement in aggregate stability using the modulus of rupture for soils treated with gypsum as a surface amendment. We attribute this improvement in strength to an improvement in soil structure. Soils that are better structured because of aggregation have higher porosity and more micro- and macropores compared to dispersed soils with 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 PR means that were significantly lower than those of the FDGH, NDGH, and FDGL plots but significantly higher than those of the 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, the application of spent lime or gypsum at the low rate provided no benefit in 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) resulted in the lowest PR values.

Challenges in trafficability have been reported by Müller et al. (1990) in soils where the topsoil was dry and firm but the lower layers were below the critical PR of 300 kPa. For this study, a threshold PR value of 300 kPa was assumed to represent the value 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 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 the 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 values from penetrometers often overestimate the force encountered by the roots by up to a factor of three due to the higher friction encountered by the metal compared to the roots (Whalley et al., 2007).

CONCLUSIONS

At 25 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 were significantly higher for GH plots than for all other surface amendments in the 0 to 15 cm layer. In the 15 to 30 cm layer, the PR values were significantly higher for GH plots than for 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 those of NDSL, NDGL, and NDCK. Drainage complemented the lower rate of gypsum in the FDGL plots to produce results similar to the higher gypsum rate in the 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. The PR means for the FDSL and FDCK plots were significantly lower than those of 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 with no land modification (NDCK).

ACKNOWLEDGEMENTS

This research was supported by the USDA Natural Resources Conservation Service under the Conservation Innovation Grants program, under the project entitled “Reducing Sodification in High-Risk Northern Great Plains Soils” (Agreement No. 69-3A75-12-185). The North Dakota Water Resources Research Institute also provided support. The authors acknowledge Sheldon Tuscherer for help with field work and data collection. The authors also thank Calcium Products, Inc. (Ames, Iowa) for donating the gypsum used in this study. Use of trade names is for informational purposes, and no endorsement is implied by the authors or their respective institutions.

REFERENCES

Abro, I. P., Yadav, J. S., P., & Massoud, F. I. (1988). Reclamation and management salt-affected soils and their management. Rome, Italy: United Nations FAO.

Aksakal, E. L., Angin, I., & Oztas, T. (2013). Effects of diatomite on soil consistency limits and soil compactibility. *Catena, 101*, 157-163. http://dx.doi.org/10.1016/j.catena.2012.09.001

ASABE. (2009). EP542: Procedures for using and reporting data obtained with the soil cone penetrometer. St. Joseph, MI: ASABE.

Bachmann, J., Contreras, K., Hartge, K. H., & MacDonald, R. (2006). Comparison of soil strength data obtained *in situ* with penetrometer and with vane shear test. *Soil Tillage Res., 87*(1), 112-118. http://dx.doi.org/10.1016/j.still.2005.03.001

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In *Methods of soil analysis: Part 1. Physical and mineralogical methods* (pp. 377-382). Madison, WI: SSSA, ASA, CSSA.

Bower, C. A., Reitemeier, R. F., & Fireman, M. (1952). Exchangeable cation analysis of saline and alkali soils. *Soil Sci., 73*(4), 251-262. http://dx.doi.org/10.1097/00010694-195204000-00001

Buckley, M. E., & Wolkowski, R. P. (2014). In-season effect of flue gas desulfurization gypsum on soil physical properties. *J. Environ. Qual., 43*(1), 322-327. http://dx.doi.org/10.2134/jeq2012.0354

Bueno, J., Amiama, C., Hernanz, J. L., & Pereira, J. M. (2006). Penetration resistance, soil water content, and workability of grasslands soils under two tillage systems. *Trans. ASABE, 49*(4), 875-882. http://dx.doi.org/10.13031/2013.21727

Carter, M. R. (1990). Relationship of strength properties to bulk density and macroporosity in cultivated loamy sand to loam soils. *Soil Tillage Res., 15*(3), 257-268. http://dx.doi.org/10.1016/0167-1987(90)90082-O

Cochrane, H. R., & Aylmore, L. A. G. (1991). Assessing management-induced changes in the structural stability of hardsetting soils. *Soil Tillage Res., 20*(1), 123-132. http://dx.doi.org/10.1016/0167-1987(91)90130-P

Daigle, J. J., Hudnall, W. H., Gabriel, W. J., Mersiovsky, E., & Nielson, R. D. (2005). The National Soil Information System (NASIS): Designing soil interpretation classes for military land-use predictions. *J. Terramech., 42*(3-4), 305-320. http://dx.doi.org/10.1016/j.jterra.2004.12.002

Dane, H. J., & Topp, G. C. (2002). *Methods of soil analysis: Part 4. Physical methods*. Madison, WI: SSSA, ASA, CSSA.

DeSutter, T., Franzen, D., He, Y., Wick, A., Lee, J., Deutsch, B., & Clay, D. (2015). Relating sodium percentage to sodium adsorption ratio and its utility in the Northern Great Plains. *SSSA J., 79*(4), 1261-1264. http://dx.doi.org/10.2136/sssaj2015.01.0010n

Earl, R. (1997). Prediction of trafficability and workability from soil moisture deficit. *Soil Tillage Res., 40*(3-4), 155-168. http://dx.doi.org/10.1016/S0167-1987(96)01072-0

Ellington, A. (1986). Effects of deep ripping, direct drilling, gypsum and lime on soils, wheat growth, and yield. *Soil Tillage Res., 8*(1-4), 29-49. http://dx.doi.org/10.1016/0167-1987(86)90321-1

Gao, W., Watts, C. W., Ren, T., & Whalley, W. R. (2012). The effects of compaction and soil drying on penetrometer resistance. *Soil Tillage Res., 125*, 14-22. http://dx.doi.org/10.1016/j.still.2012.07.006

Greene, R. S. B., Eggleton, R. A., & Rengasamy, P. (2002). Relationships between clay mineralogy and the hardsetting properties of soils in the Carnarvon horticultural district of Western Australia. *Appl. Clay Sci., 20*(4), 211-223. http://dx.doi.org/10.1016/S0169-1317(01)00073-4

He, Y., DeSutter, T., Casey, F., Clay, D., Franzen, D., & Steele, D. (2015). Field capacity water as influenced by Na and EC: Implications for subsurface drainage. *Geoderma, 245-246*, 83-88. http://dx.doi.org/10.1016/j.geoderma.2015.01.020

Hillel, D. (1980). *Applications of soil physics*. New York, NY: Academic Press.

Hillel, D. (1998). *Environmental soil physics: Fundamentals, applications, and environmental considerations*. New York, NY: Academic press.

Ilyas, M., Qureshi, R. H., & Qadir, M. A. (1997). Chemical changes in a saline-sodic soil after gypsum application and cropping. *Soil Tech., 10*(3), 247-260. http://dx.doi.org/10.1016/S0933-3630(96)00121-3

Jonard, F., Mahmoudzadeh, M., Roisin, C., Weihermuller, L., Andre, F., Minet, J., ... Lambot, S. (2013). Characterization of tillage effects on the spatial variation of soil properties using ground-penetrating radar and electromagnetic induction. *Geoderma, 207-208*, 310-322. http://dx.doi.org/10.1016/j.geoderma.2013.05.024

Jorajuria, D., & Draghi, L. (1997). The distribution of soil compaction with depth and the response of a perennial forage crop. *J. Agric. Eng. Res., 66*(4), 261-265. http://dx.doi.org/10.1006/jaer.1996.0141

Kandel, H. J., Brodshaug, J. A., Steele, D. D., Ransom, J. K., DeSutter, T. M., & Sands, G. R. (2013). Subsurface drainage effects on soil penetration resistance and water table depth on a clay soil in the Red River of the North Valley. *Agric. Eng. Intl.: CIGR J., 15*(1), 1-10.

Lebert, M., & Horn, R. (1991). A method to predict the mechanical strength of agricultural soils. *Soil Tillage Res., 19*(2-3), 275-286. http://dx.doi.org/10.1016/0167-1987(91)90095-F

Mitchell, J. P., Shennan, C., Singer, M. J., Peters, D. W., Miller, R. O., Prichard, T., ... Munk, D. S. (2000). Impacts of gypsum and winter cover crops on soil physical properties and crop productivity when irrigated with saline water. *Agric. Water Mgmt., 45*(1), 55-71. http://dx.doi.org/10.1016/S0378-3774(99)00070-0

Motavalli, P. P., Anderson, S. H., Pengthamkeerati, P., & Gantzer, C. J. (2003). Use of soil cone penetrometers to detect the effects of compaction and organic amendments in claypan soils. *Soil Tillage Res., 74*(2), 103-114. http://dx.doi.org/10.1016/S0167-1987(03)00150-8

Mueller, L., Schindler, U., Fausey, N. R., & Lal, R. (2003). Comparison of methods for estimating maximum soil water content for optimum workability. *Soil Tillage Res., 72*(1), 9-20. http://dx.doi.org/10.1016/S0167-1987(03)00046-1

Müller, L., Tille, P., & Kretschmer, H. (1990). Trafficability and workability of alluvial clay soils in response to drainage status. *Soil Tillage Res., 16*(3), 273-287. http://dx.doi.org/10.1016/0167-1987(90)90101-I

NRCS. (2014). Web soil survey. Washington, DC: USDA Natural Resources Conservation Service. Retrieved from http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Rab, A., Bradshaw, J., Campbell, R., & Murphy, S. (2005). Review of factors affecting disturbance, compaction, and trafficability of soils with particular reference to timber harvesting in the forests of southwest Western Australia. SFM Technical Report No. 2. Kensington, Western Australia: Government of Westerna Australia, Department of Conservation and Land Management.

Sansom, J. J., Chanasyk, D. S., Naeth, M. A., & Bateman, J. C. (1998). *In situ* amelioration of sodic minespoil with chemical amendments and crop management: II. Soil physical properties, soil moisture, and plant growth. *Canadian J. Soil Sci., 78*(4), 667-674. http://dx.doi.org/10.4141/S97-018

Szabolcs, I. (1989). *Salt-affected soils*. Boca, Raton, FL: CRC Press.

Tejedor, M., Jimenez, C. C., & Diaz, F. (2003). Use of volcanic mulch to rehabilitate saline-sodic soils. *SSSA J., 67*(6), 1856-1861. http://dx.doi.org/10.2136/sssaj2003.1856

Tirado-Corbalá, R., Slater, B. K., Dick, W. A., Bigham, J., & McCoy, E. (2013). Hydrologic properties and leachate nutrient responses of soil columns collected from gypsum-treated fields. *Soil Tillage Res., 134*, 232-240. http://dx.doi.org/10.1016/j.still.2013.08.007

Vaz, C. M. P., Manieri, J. M., de Maria, I. C., & Tuller, M. (2011). Modeling and correction of soil penetration resistance for varying soil water content. *Geoderma, 166*(1), 92-101. http://dx.doi.org/10.1016/j.geoderma.2011.07.016

Weaich, K., Cass, A., & Bristow, K. L. (1992). Use of a penetration resistance characteristic to predict soil strength development during drying. *Soil Tillage Res., 25*(2), 149-166. http://dx.doi.org/10.1016/0167-1987(92)90108-N

Whalley, W. R., To, J., Kay, B. D., & Whitmore, A. P. (2007). Prediction of the penetrometer resistance of soils with models with few parameters. *Geoderma, 137*(3-4), 370-377. http://dx.doi.org/10.1016/j.geoderma.2006.08.029

Wheaton, A. D., McKenzie, B. M., & Tisdall, J. M. (2008). Management to increase the depth of soft soil improves soil conditions and grapevine performance in an irrigated vineyard. *Soil Tillage Res., 98*(1), 68-80. http://dx.doi.org/10.1016/j.still.2007.10.007

Wösten, J. H., & Bouma, J. (1985). Using simulation to define moisture availability and trafficability for a heavy clay soil in the Netherlands. *Geoderma, 35*(3), 187-196. http://dx.doi.org/10.1016/0016-7061(85)90036-9