Subsurface drainage effects on soil penetration resistance and water table depth on a clay soil in the Red River of the North Valley, USA

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Abstract: Since 1993, the Red River of the North Valley in North Dakota (ND) and Minnesota (MN), in the USA has experienced increased annual rainfall which has caused localized seasonal soil waterlogging and inhibited crop yield potential in the unique, high water table clay soils of the region. Subsurface (tile) drainage has been increasingly considered by farmers to help reduce excess water in the crop root zone. Producers desire to manage the water table for optimizing yield and trafficability of the field. The objective of this research was to evaluate differences in soil penetration resistance and water table depth between subsurface (drained) and non-subsurface drained treatments (undrained), using water control structures, in fallow, and cropped soybean (*Glycine max* L. Merr.) and wheat (*Triticum aestivum* L. emend. Thell.) cultivars on a Fargo-Ryan silty clay soil near Fargo, ND, USA in 2009 and 2010. The experimental design was a randomized complete block in a split-plot arrangement with four replicates. The whole plot treatments were drained and undrained (control structures opened and closed, respectively). Soil penetrometer readings and water table depth were measured weekly. Yields of each crop were not different comparing drained and undrained treatments in 2009 and 2010. The depth averaged drained penetration resistance was 1,211 kPa compared with 1,097 kPa for undrained treatment, averaged across 2009 and 2010. The depth-averaged drained penetration resistance values for fallow, soybean, and wheat were 1,077, 1,137, and 1,420 kPa, respectively. The undrained values for fallow, soybean and wheat were 1,001, 1,021, and 1,267 kPa, respectively, all significantly lower than the drained treatments, indicating that the drained soil is capable of a higher load carrying capacity compared to the undrained soil. The average depth to the water table was greater on drained soil compared to the undrained soil both early and late in the growing season. Forty two percent of the variation in the penetration resistance can be explained by the level of the water table below the surface. Water control structures can be used to manage the water table level and soil penetrations resistance. The ability for land managers to enter drained fields with farm equipment earlier will likely extend the length of the growing season and potentially increase crop yields in this region.

Keywords: subsurface water management, penetration resistance, controlled drainage, water table depth, trafficability, USA

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1 Introduction

Since 1993, the Red River of the North Valley in North Dakota and Minnesota has seen increased annual rainfall (NDAWN, 2012) which has caused localized seasonal soil waterlogging inhibiting crop yield potential in the unique, high water table clay soils of the region. Subsurface (tile) drainage, a relatively new technology for the region, has increasingly been considered by farmers to help reduce excess water in the crop root zone.

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Being able to work in the field and early planting due to warmer soil temperature in the spring (Jin et al., 2008) are generally considered as the largest benefits of subsurface drainage. Early planting provides a longer growing season which may increase yield potential (Wiersma et al., 2010). Tile drainage can allow soils to drain more quickly, reduce crop waterlogging stress, and increase the load bearing capacity of the soil so that heavy equipment can access the field for crop management and harvest in a timely manner (Chieng et al., 1987). Bornstein and Hedstrom (1982) in a three year study, concluded that trafficability (the capability of the soil to bear mechanized traffic) occurred earlier in the spring with tile drainage, regardless of the tile drain spacings they tested.

Trafficability impacts the efficiency of a farming operation. When the soil can support the weight of farm equipment and the timing of required farming operations is appropriate for the stage of crop development, profitability might be improved. Soil penetration resistance, which can be used as an indicator for trafficability, is quantified by a pressure measurement (Bradford, 1986). Penetration resistance is greatly affected by soil water content, and also influenced by bulk density, soil compressibility, soil strength parameters, and soil structure (Bradford, 1986).

The strength of soil can affect soil's load-bearing capacity, compaction, and root penetration and is related to soil's bulk density and water content (Marshall and Holmes, 1988; Kornecki and Fouss, 2001). Soil penetration resistance has a strong inverse relation to soil water content. Marshall and Holmes (1988) concluded that the bonds that hold the soil particles together in structural units are weakened as more water is adsorbed in the clay layers' inter phase, decreasing soil strength. Penetrometers are commonly used in agricultural settings to find hardpans and compaction zones and to measure the physical status of the soil. Penetrometers and their use are described by ASAE (2009a, 2009b). Jin et al. (2008) reported a lower water table in subsurface drained soil, but they did not evaluate the level of the water table below the surface with penetration resistance measurements. Tile drainage is relatively new to this region and no research has been done here to better understand the relationship between penetration resistance and the potential to manage the water table on artificially drained soils. This research evaluated the relationship of the water table and penetrometer resistance readings with subsurface drainage. No such research has previously been reported for the northern regions of the USA.

The long term objective for tiling in this region is to manage the water table in production fields to optimize crop yields and allow timely field operations with agricultural machinery. Water control structures, new to the area, were used to influence the water table level. The objectives for this study were to quantify the effects of subsurface drainage (water control structure open and closed) on soil penetration resistance and water table depth for fallow and cropped soybean and wheat conditions for a Fargo-Ryan silty clay soil type and Fargo, ND.

2 Materials and methods

2.1 Site characterization

The experimental field site was located at 46.932 °N and 96.858 °W, near Fargo, ND, USA (Figure 1). The field area is 2.5 ha and has surface drainage achieved through land-leveling equipment. The soil type of the area is classified as a Fargo-Ryan silty clay. The Fargo series (fine, smectic, frigid Typic Epiaquerts) consists of deep, poorly drained, slowly permeable, lacustrine soils. This soil generally has a slope of 0 to 1%. The Ryan series (fine, smectic, frigid, Typic Natraquerts) is very similar to the Fargo series (USDA-NRCS, 2012).

The 2.5 ha experimental area was divided into eight units of 61 m (E-W) by 54 m (N-S), each of which has seven lateral subsurface drainage tiles lines (E-W), installed in 2008, at a depth of 100 cm and a spacing of 7.6 m. The subsurface drainage tiles are perforated, corrugated polyethylene, and 10 cm in diameter. The design drainage coefficient, based on the soil type, drain tile depth, slope, and the spacing is 7.5 mm per 24 h. Each of the eight units has a water table control structure (Agri Drain Corp, Adair, IA). The control structures on four of the units remained open to create a subsurface drained treatment and were closed on the remaining four units to create a non-subsurface drained treatment (which we will call undrained).

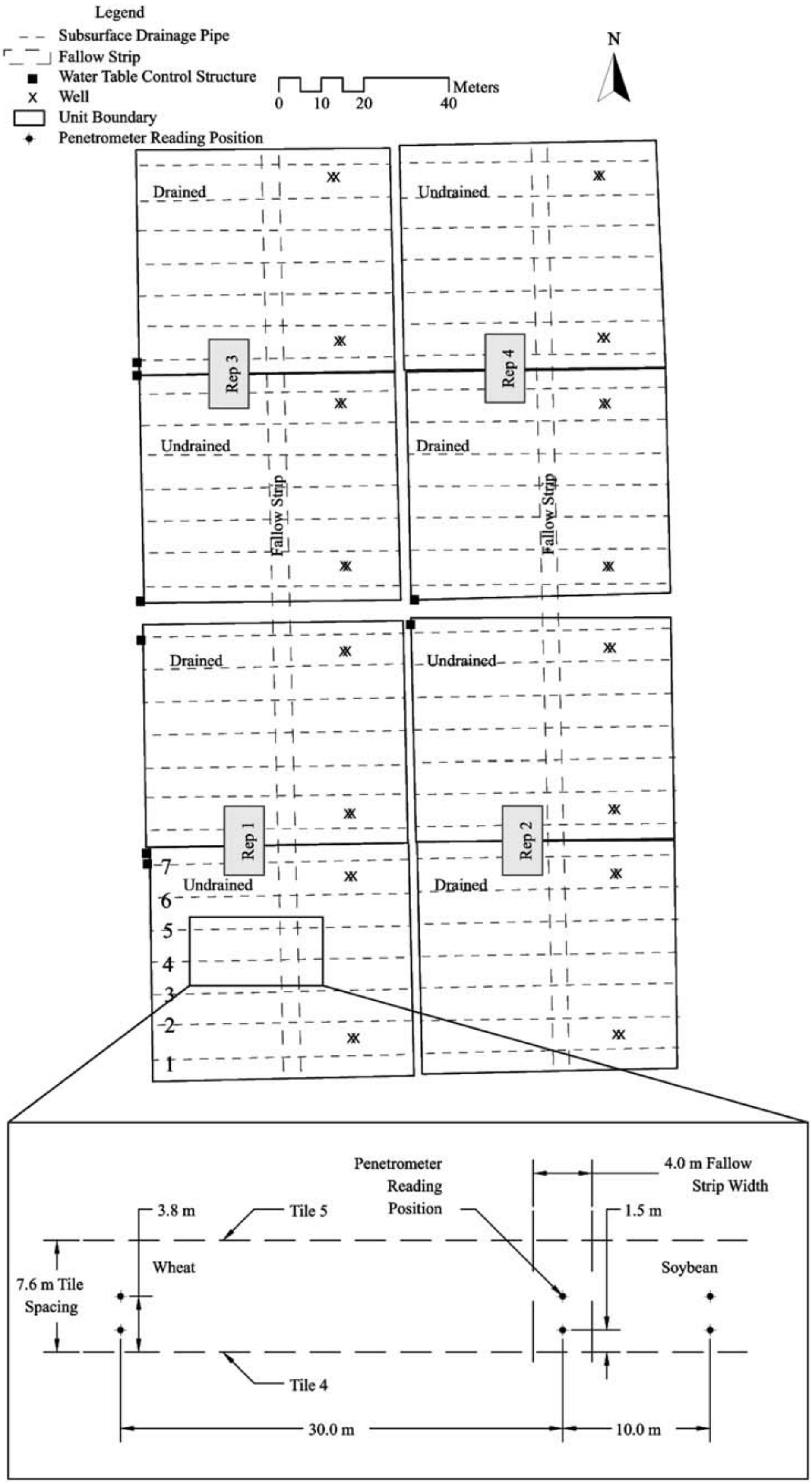

Figure 1 GPS based layout of experimental area with location of fallow, soybean and wheat in 2010, near Fargo, ND

2.2 Field experiment

Twenty five soybean cultivars were planted on May 19 and 21, and harvested on November 5 and October 6, in 2009 and 2010, respectively. Five wheat cultivars were planted on May 11 and April 12, and harvested on August 24 and 5, in 2009 and 2010, respectively. The layout for 2010 is depicted in Figure 1. Wheat and soybean were rotated from 2009 to 2010. The fallow strip remained in the same location.

A cone penetrometer (Field Scout SC 900, Spectrum Technologies, Inc., Plainfield, IL) was used to measure soil penetration resistance in kPa. The penetrometer cone had a 12.8 mm diameter base and meets specifications in ASAE (2009b). Weekly penetrometer resistance readings were recorded every 2.5 cm from a soil depth of 8 to 46 cm. The top 8 cm of depth were excluded from measurement due to irregularities in the top-soil layer such as surface crusting after rainfall events. Penetrometer measurements were obtained at two locations in the fallow, soybean, and wheat: one measurement at the midpoint between subsurface drainage tile lines four and five (3.8 m from each tile line), and the other at 1.5 m from subsurface drainage tile line four.

These two locations, 3.8 and 1.5 m from tile 4, are referred to as ‘position’ in the statistical analysis. The average penetrometer measurement of the two positions is considered the average field condition for fallow, soybean, and wheat and is discussed in this paper. The measurements in the wheat plots were continued in the wheat stubble after the August harvest.

Water table depth measurements were taken manually each week in two wells located in each unit on the same day as the penetrometer measurements, using a water level meter (Model 101, Solinst, Georgetown, ON, Canada). The wells in each unit were located between tile line one and two, and between tile line 6 and 7 and 15 m from the east edge of each unit. The wells were installed in May of 2009 using a soil probe. Each well was constructed from polyvinyl chloride pipe (5.1 cm in diameter) screened from 1.2 to 2.1 m below the land surface with 0.23 mm of slot size and inserted into the hole created by the soil probe. Sand was filled in around the pipe and a bentonite seal was added at the soil surface.

A rain gauge with a 10 cm opening and 25 cm capacity was placed at the north end of the experimental area and rainfall was recorded on a weekly basis. Rainfall reported herein represents the accumulated precipitation since the last reading. Rain gauge observations were verified and compared with long-term averages (1971-2000) using the Fargo location of the North Dakota Agricultural Weather Network data (NDAWN, 2012).

2.3 Data analysis

The experiment utilized a randomized complete block design with a split-split plot arrangement. Drained or undrained treatments were the main plot, the positions of the observations were considered the sub-plot factor, and depth of penetrometer resistance measurement was considered the sub-sub-plot factor.

Each day of measurement was considered to be a random, independent ‘date’ with a unique set of soil penetration resistance and water table depth values. A total of 41 separate dates occurred over the two study years. Soil penetrometer readings were subjected to analysis of variance (PROC ANOVA) of SAS 9.2 (SAS Institute, Cary, NC) combined across dates after testing for homogeneity of variance. Fallow, soybean, and wheat, were analyzed separately since they were not randomly distributed across the field. Drainage practice (drained and undrained), position (distance from tile line), and depth were considered fixed effects while replication and dates were considered random effects in the statistical analysis. Means were separated using Fisher’s protected LSD at $\alpha \leq 0.05$ level of significance. A linear regression of depth of the water table on the soil penetration resistance was performed and a regression equation computed using Excel 2010 (Microsoft Corporation). The water table and penetration resistance data were averaged across all observations for drained and undained treatments for 11 dates in 2009 and 21 dates in 2010. There are fewer observations in 2009 because the water observation wells were installed in May and more late fall observations were made in 2010. Soybean and wheat yields were analyzed for each year as a split plot with drain and undrained treatments the main plot and cultivars the sub-plot. Means were separated using Fisher’s protected LSD at $\alpha \leq 0.05$ level of significance.

3 Results and discussion

3.1 Weather conditions

The 2009 growing season generally was lower in precipitation than normal years (Table 1), except for excess rainfall in October.

Table 1 Monthly rainfall totals during the growing season for 2009 and 2010 at the research site, and the 30-year long term average for the Fargo NDAWN weather station

	Rainfall / mm		
Month	Fargo	Research site	
	Average[a]	2009	2010
April	35	0	40
May	66	51	61
June	89	70	155
July	73	35	104
August	64	72	69
September	55	41	142
October	50	114	69
Total	432	383	640

Note: a30-year average (1971-2000), (NDAWN, 2012).

Two large rainfall events flooded the entire plot area in 2010 and caused waterlogging. During one event in June 2010, more than 100 mm of rainfall occurred in less than one hour. Most of the drainage from this event occurred via runoff. Nearly three times the long term average precipitation fell in September 2010. The 2009 and 2010 seasons had 89% and 148% of long term average seasonal precipitation, respectively.

3.2 Crop yield

The average soybean yield on the drained treatments was 1,930 and 3,202 kg ha^{-1} in 2009 and 2010, respectively. The yield for the undrained treatment was 1,925 and 3,107 kg ha^{-1} in 2009 and 2010, respectively. The soybean yields for drainage treatments were not significantly different in each of the years.

The average wheat yield on the drained treatments was 4,394 and 4,267 kg ha^{-1} in 2009 and 2010, respectively. The yield for the undrained treatment was 4,623 and 4,193 kg ha^{-1} in 2009 and 2010, respectively. The wheat yields for drainage treatments were not significantly different in each of the years.

3.3 Soil penetration resistance

The drained treatment (D in Table 2) in fallow, soybean, and wheat, across all observation dates and years had significantly higher penetration resistance values compared with the undrained treatment.

Table 2 Levels of significance for the soil penetration resistance combined ANOVA for date measurements averaged across 2009 and 2010, near Fargo, ND

Source of variation	df[a]	Fallow	Soybean	Wheat
Date (Dt)	40			
Replicates [Dt]	123			
Drainage (D)	1	*	**	**
Dt × D	40	ns	ns	ns
Error (a)	123			
Position (P)	1	**	**	ns
Dt × P	40	ns	**	**
D × P	1	ns	ns	ns
Dt × D × P	40	ns	*	ns
Error (b)	123			
Depth (De)	15	**	**	**
Dt × De	600	**	**	**
D × De	15	**	**	**
Dt × D × De	600	ns	ns	ns
P × De	15	**	**	**
Dt × P × De	600	ns	ns	ns
D × P × De	15	ns	ns	ns
Dt × D × P × De	600	ns	ns	ns
Error (c)	7,503			
CV /%		27.6	28.4	27.3

Note: [a]df = degrees of freedom. ns, *, ** = not significant, significant at ($P \le 0.05$) and ($P \le 0.01$), respectively.

The average resistance over all observations for the tile drained treatments was 1,211 kPa, compared with the undrained average of 1,097 kPa (Figure 2).

3.4 Drainge

Soil penetration resistance was significantly higher in the drained units for all three sites, fallow, soybean, and wheat compared with the undrained units (Table 3). Precipitation was above normal in October 2009. During harvest on November 5, 2009 the undrained soil was wet and the plot combine had wheel slippage, while the drained soil was dry and the combine had no difficulties harvesting the crop.

Table 3 Means of soil penetration resistance for fallow, soybean and wheat and two drainage treatments averaged across 41 observation dates during 2009 and 2010, near Fargo, ND

Drain Treatment	Fallow	Soybean	Wheat
Drained/kPa	1,077	1,137	1,420
Undrained/kPa	1,001	1,021	1,267
LSD (0.05)	58	50	78

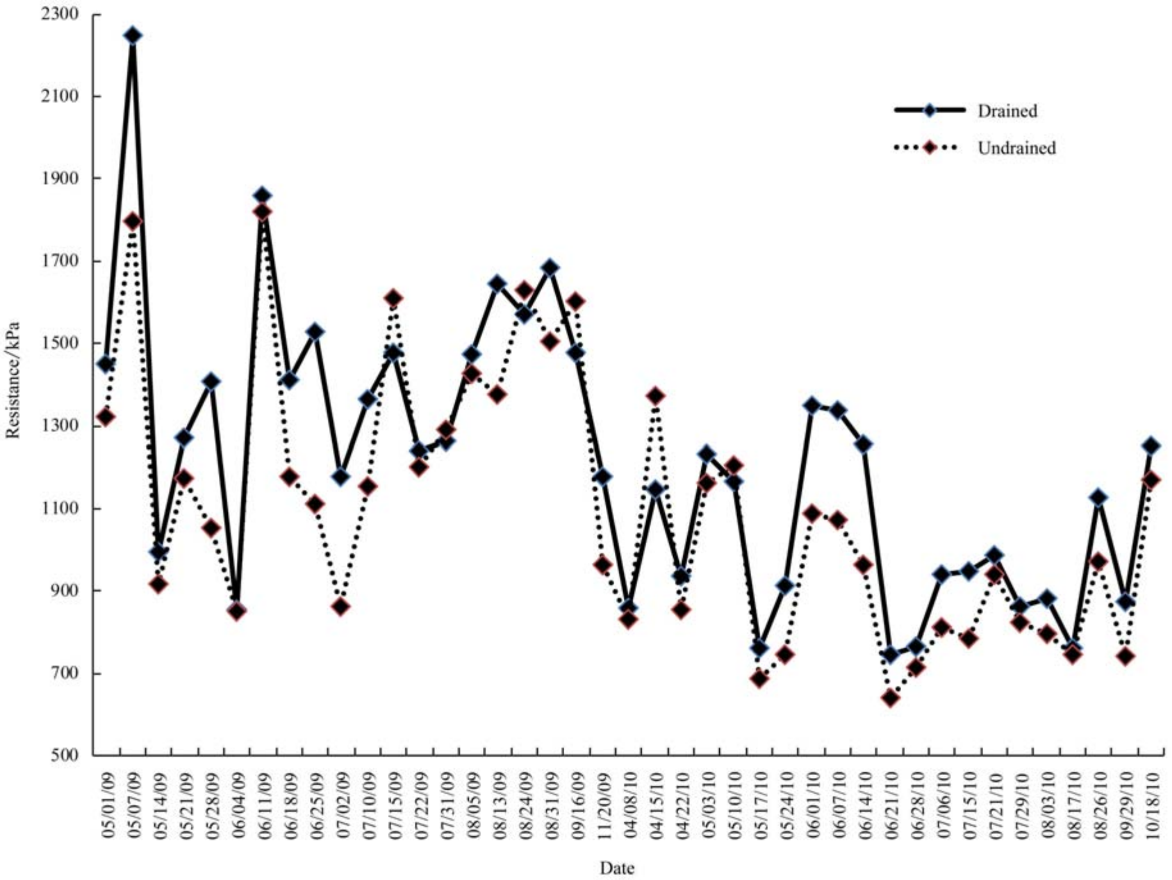

Figure 2 Mean soil penetration resistance (kPa) averaged over all observations on each date for drained and undrained treatments during 2009 and 2010, near Fargo, ND

3.5 Year

The precipitation distribution each year may have played a role in variability of soil penetration resistance. There was 383 mm of rainfall in the growing season of 2009, while in 2010 there was 640 mm of rainfall. When there was more rainfall in a given year, the soil penetration resistance value was lower. For observations in fallow the mean penetration value for 2009 was 1,201 kPa compared with 885 kPa in 2010. No statistics could be calculated for this comparison as ‘year’ is not a true replication. The soil appeared to be drier at the wheat sites compared with the soil appearance at the other sites just before wheat harvest and there were visible soil cracks in the wheat plots and none for fallow or soybean plots.

3.6 Depth

Penetrometer readings varied significantly with depth for the fallow, for the soybean, and for the wheat (Table 2). Figure 3 depicts the resistance values from a depth of 8 to 46 cm, for fallow, soybean, and wheat, averaged across drainage treatments, positions, and all dates. Soil in wheat had the highest resistance level. Estimated crop evapotranspiration (ET) for wheat from emergence to harvest was 319 and 379 mm in 2009 and 2010, respectively. The ET for soybean, from emergence to the date of the wheat harvest, was 272 and 224 mm in 2009 and 2010, respectively (NDAWN, 2012). The higher average resistance values in wheat were attributed to wheat’s higher ET early in the season compared with no plant growth (fallow) or the later planted and slower developing soybean.

3.7 Drain x Depth

The significant interaction drainage x depth (Table 2) is displayed in Figure 4. The difference in penetrometer resistance between drained and undrained conditions in wheat increased with depth from approximately 77 kPa at 8 cm (near the surface) to 153 kPa at a 46-cm depth (closer to the tile line). The soybean and fallow sites exhibited similar responses (data not presented).

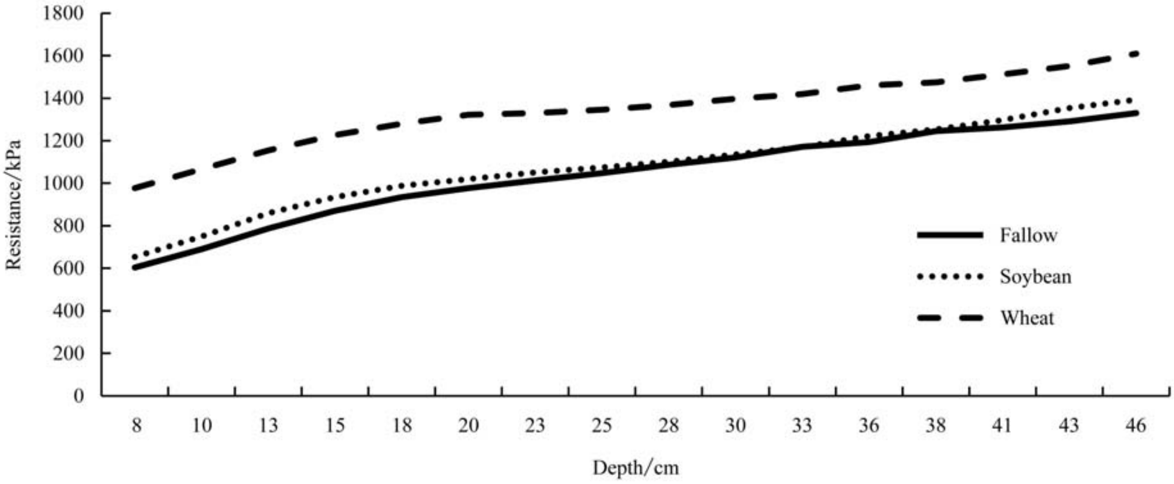

Figure 3 Mean soil penetration resistance at various depths for fallow, soybean, and wheat averaged across two drainage levels and two positions during 2009 and 2010, near Fargo, ND

For comparing readings at different depths: wheat LSD (0.05) = 105 kPa; soybean LSD (0.05) = 86 kPa; fallow LSD (0.05) = 84 kPa

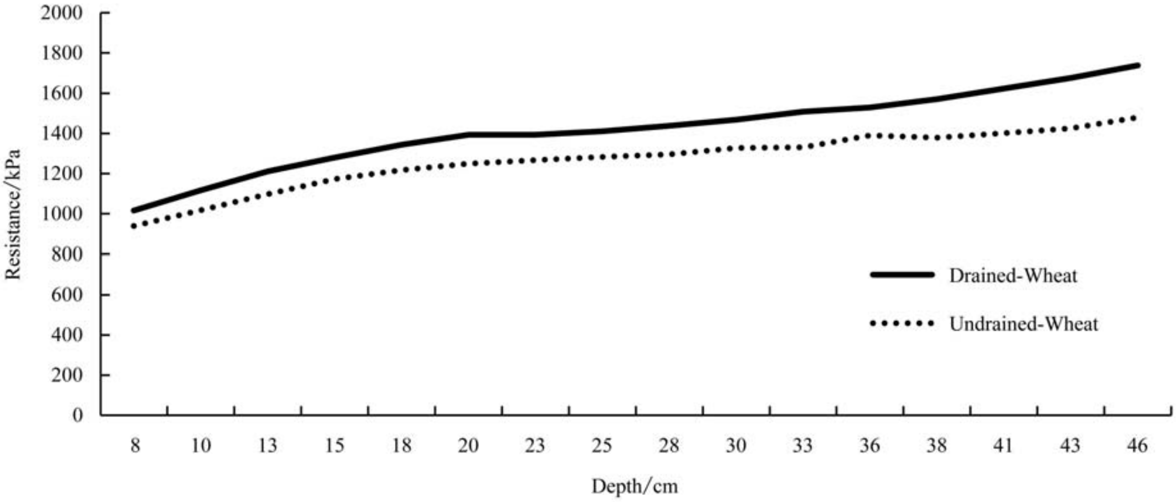

Figure 4 Mean soil penetration resistance values for depths 8 to 46 cm under wheat, on drained and undrained treatments, averaged over positions and dates, in 2009 and 2010, near Fargo, ND.

For comparing readings at different depths: LSD (0.05) = 153 kPa

3.8 Water table

The measured water table depths below the surface for 2009 and 2010 are depicted in Figure 5 and Figure 6. The water table data points in the graphs are averaged across all observation points for that date for the drained treatment wells or undrained treatment wells. In 2009 the water table in both drainage treatments was below the 100 cm drain tile depth from May through October 26, except for the reading on July 10. However, for most of the season, the water table for the undrained treatment was closer to the surface compared with the water table for the drained treatment. In 2009, differences in the water table depths were small due to lower precipitation than normal. Greater differences between drained and undrained water table depths were observed in May, mid-June, and September in 2010 (Figure 6) which were attributed to higher rainfall than in 2009 and compared with long term average precipitation (Table 1). Regression of penetration resistance versus water table depth is provided in Figure 7. The resistance values increased as the water table was lower below the surface. Approximately 42% of the variation in the penetration resistance measurement can be explained by the water table measurement.

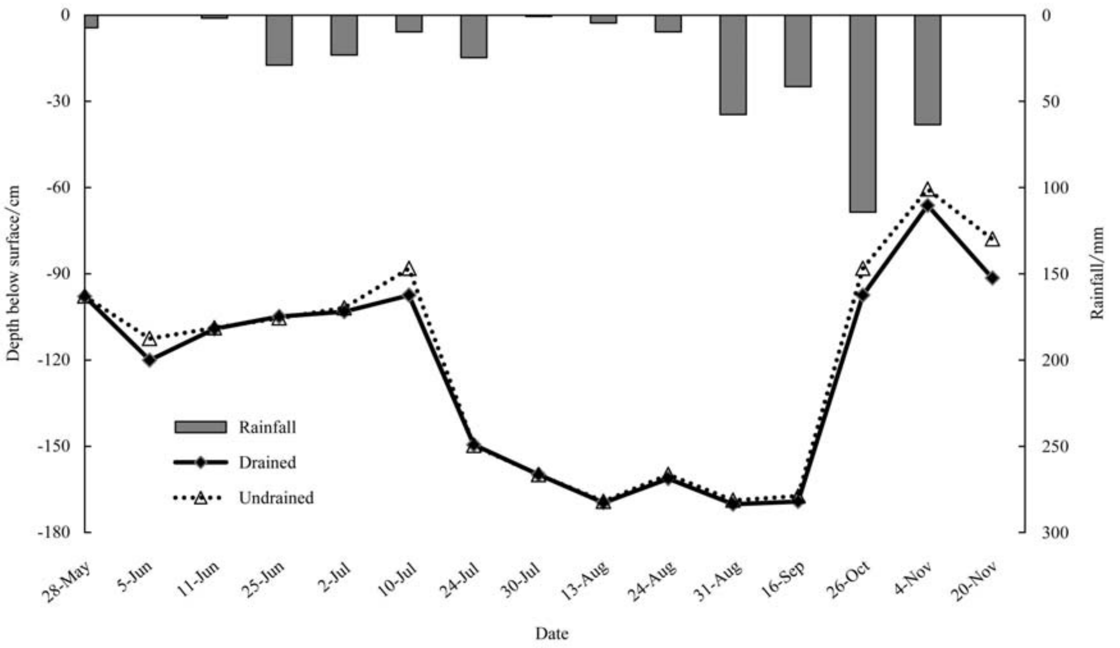

Figure 5 Water table depth for drained and undrained treatments and weekly rainfall amounts for 2009, near Fargo, ND

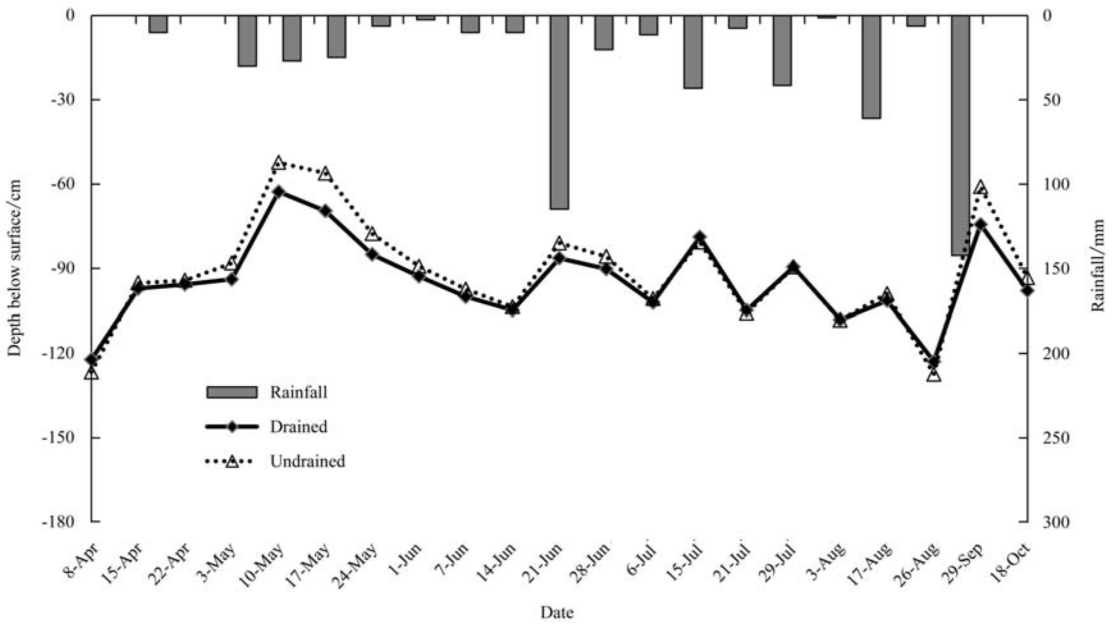

Figure 6 Water table depth for drained and undrained treatments and weekly rainfall amounts for 2010, near Fargo, ND

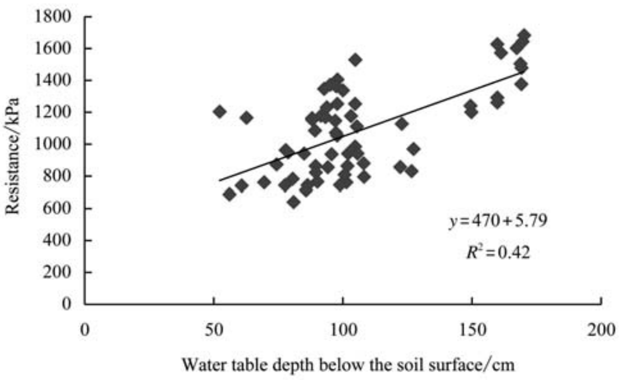

Figure 7 Linear regression line of water table depth on soil penetration resistance for observation dates in 2009 and 2010

4 Discussion

In this study, soil penetration resistance was significantly higher on the drained treatments for fallow, soybean, and wheat, which is similar to other studies that have been conducted using penetrometer readings as a means to quantify trafficability (Kornecki and Fouss, 2001; Bornstein and Hedstrom, 1982). Soil penetration resistance increased as depth increased due to the increasing overburden weight with the increasing depth (Bornstein and Hedstrom, 1982). The difference in soil penetration resistance between drainage treatments increased with depth. This implies that the tile drainage not only dries out the surface faster, but also impacts the soil moisture deeper in the profile.

Increased soil penetration resistance can be assumed to increase trafficability. This is an important aspect and allowed the soybeans in 2009 to be harvested normally on the drained portion of the field while on the undrained portion of the experiment; soil had to be cleaned regularly from the combine tires to prevent wheel slippage and getting stuck.

The soil penetration resistance was affected by the amount of rainfall and how that rainfall, combined with the crops' ability to utilize water, affected the water table depth. The water table depth was lower on the drained units for the majority of time that measurements were taken. This was also found in other water table studies (Mejia et al., 2000; Wiersma et al., 2010).

After rainfall, the water table rose and the drained and undrained treatments exhibited similar penetration resistances for a period of time. Several days following a rainfall event, the water table for the drained units would fall below the water table of the undrained units. Water moves slowly in these soils and takes some time to reach the drain tile. Pang et al. (2006) found in a study conducted in the Red River of the North Valley that water reached the lift station pumps in the drain tile systems as soon as two to three hours after a heavy rainfall event, but in other cases it took over six hours for the pumps to start.

Overall, increased soil penetration resistance makes subsurface drainage desirable for farmers because it allows for timelier field applications and harvesting, and possibly increasing the carry capacity of the soil allowing access for heavier equipment. The soil penetration resistance is affected by the amount of rainfall and the water table depth. One way to manage the water table would be with a water table control structure (Evans and Skaggs, 1996). Water management may increase yield potential of crops (Mejia, 2000). In this study we used the closed control structure to simulate undrained conditions. The data from this study indicates that there is a relationship between the water table depth and the soil penetration resistance. The tile line is 100 cm below the soil surface. Based on the regression equation we would expect the depth-averaged penetration resistance with a water table at the tile level to be 1,049 kPa. If a producer would manage the water table with a control structure at 90 cm below the surface we would expect the soil penetration resistance to be 991 kPa. In 2009 the wheat yields for the drained and undrained treatments were not significantly different, however the wheat yield for the drained treatment (n=80) was 4,394 kg ha^{-1} and the undrained treatment (n=80) 4,623 kg ha^{-1}. We did not expect the drained treatment to be lower. The 2009 season was drier and only on July 10 was the water table above the tile line (Figure 5) for the undrained treatment. We speculate that this water that was kept by the control structure may have given the undrained wheat some extra water to reach a numerical higher yield.

5 Conclusion

We used the closed control structures to produce undrained conditions as no water left the field from the drain tile. There was a difference in the water table depths between the drained and undrained treatments indicating that a control structure can influence the water table (Figure 5 and Figure 6). We propose that by managing the water table (by setting the control structure at the desired water table level) producers can supply the crop with soil moisture at the appropriate growth stage, and lower the water table to operate machinery in the field as needed. The higher soil penetration resistance found in wheat due to higher early season ET, indicates that this crop may be a candidate to manage and efficiently utilize soil moisture during the early summer when most of the seasonal precipitation occurs.

The main findings of this research are:

1) The depth-averaged drained penetration resistance was 1,211 kPa and 1,097 kPa for the undrained treatment.

2) Forty –two percent of the variation in penetration resistance could be explained by the level of the water table below the surface.

3) Drained penetration resistance in fallow, soybean, and wheat were higher compared with undrained treatments.

4) Soybean or wheat yields were similar in drained and undrained treatments in 2009 and 2010.

5) Water control structures can be used to manage the water table level and soil penetration resistance.

Future studies should look at the appropriate water table level during the season for crop yield and for trafficability. The ability for field equipment to enter drained fields earlier in this region will likely extend the length of the growing season and potentially increase crop yields.

The water table depth is useful in interpreting the soil penetration resistance, but soil water content might be a better predictor of penetration resistance.

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