Soil Drying Effects on Soil Strength and Depth of Hardpan Layers as Determined from Cone Index Data

Mehari Z. Tekeste [1], Randy L. Raper[2], and Eric B. Schwab[2]
[1] Former PhD student, Department of Biological and Agricultural Engineering, University of Georgia, Athens, GA, 30602. Current Address: John Deere Technology Center, Moline, IL. TekesteMehari@JohnDeere.com

[2] USDA-ARS-Nation Soil Dynamics Laboratory, 411 Donahue Drive, Auburn, AL, 36830.

ABSTRACT

Site-specific detection of a soil hardpan is an important step in precision farming. Different methods have been developed including the ASABE standard soil cone penetrometer to detect presence of hardpan layers. Most of the newly developed methods use results obtained by a soil cone penetrometer as a reference to validate their potential. Soil factors, mainly soil moisture and bulk density, may influence the cone index measurement and the prediction of the relative strength and depth of the hardpan layer. The effects of soil drying on hardpan characterizing attributes of peak cone index, depth to the peak cone index and depth to the top of the hardpan layer were studied for three compaction levels on a Norfolk sandy loam soil in a soil bin. The soil in the bin was wetted to near saturation and then subjected to four levels of soil drying. A multiple-probe soil cone penetrometer (MPSCP) was used to measure soil cone index. The results showed that soil drying had a significant effect on peak cone index for the single pass compaction (1.78 Mg m^{-3} within hardpan) and the double pass compaction (1.83 Mg m^{-3} within hardpan). The peak cone index increased two-fold and 1.3 times due to soil drying from 'day-1' to 'day-4' for the single pass compaction and for the double compaction, respectively. The depths to the top of the hardpan determined from the depth to the peak cone index and the depth to the top of the hardpan showed a statistically significant decreasing trend for the single pass compaction. The differences, however, were too small (< 2 cm) to justify varying prescription tillage depth due to soil drying.

Keywords: Precision tillage, soil hardpan, soil drying, soil cone index, sandy loam soil, USA.

1. INTRODUCTION

In the southeastern USA, the Coastal Plain soils typically have a highly compacted subsoil layer commonly called a hardpan that occurs at an approximate depth range of 15 to 35 cm (Campbell et al., 1974; Radcliffe et al., 1989; Busscher et al., 2005; Raper et al., 2005c). The causes for its formation are associated with both the inherent soil properties of being relatively low in organic matter, weak in soil structure and soil particle size variability (Spivey et al., 1986 and Radcliffe et al., 1988) and also to the anthropogenic forces mainly from wheel traffic and tillage practices in the region (Busscher et al., 2002; Raper et al., 2005a).

The excessively compacted hardpans impede root growth below the plow depth thereby resulting in crop yield reduction especially during drought periods when soil moisture and nutrient reserves in the lower soil strata are critical for crop growth (Taylor and Gardner, 1963; Camp and Lund, 1968, Busscher and Bauer, 2003; Raper et al., 2005a). Taylor and Gardner (1963) found 2 MPa as root limiting soil strength value on southeastern Coastal Plain soils.

Isaac et al. (2002) reported that corn yield variability within a field strip (323 m x 1.6 m size) was negatively correlated to the mean soil cone index (r = -83) and maximum cone index values (r=-0.71). The presence of soil hardpan layers also reduces soil water infiltration, which can accelerate erosion and runoff of nutrients. Farmers in the region typically apply uniform depth subsoiling either annually or biennially to mechanically disrupt the hardpan layers and improve the rooting environment for optimal crop growth (Busscher and Bauer, 2003; Raper et al., 2005a). The application of this energy-intensive subsoiling operation is based on the assumption that the compacted layers are located at a constant depth across the field. The relative strength and depth to the hardpans, however, vary from field to field and within fields (Fulton et al., 1996; Clark, 1999; Goodson et al., 2000; Isaac et al., 2002; Raper et al., 2005c). With uniform depth subsoiling, tillage may be applied in areas of the field where there is no soil compaction problem or at depths that do not necessarily correspond to the hardpan depth. This may incur unnecessary fuel consumption or the desired soil conditions may not be attained. Site-specific/precision tillage that takes into account the depth variability of the soil hardpan could be an alternative subsoiling practice in southeastern region. It also has the potential to reduce tillage energy and fuel consumption as compared to uniform depth tillage (Fulton et al., 1996; Gorucu et al., 2001; Raper et al., 2005b).

Accurate sensing of the soil strength and the location of hardpan is an important step for the success of precision tillage. Technologies using either stop-and-go or on-the-go soil strength measurement are being developed to identify the hardpan layer to assist with the objective of site-specific tillage. The soil cone penetrometer, a device that measures force required to push a metal cone vertically down into the soil, is a tool for relatively quick and easy measurement of soil compaction (ASABE 2008a, b). The results are reported as cone index (penetration force / cone base area) as a function of depth (ASABE, 2008b). The soil cone penetrometer apparatus has been automated and modified to improve the data acquisition rate and evaluated to produce soil strength maps (Clark, 1999; Raper et al., 1999; Price, 2002).

Research and development of real-time (on-the-go) and non-destructive soil compaction measurement technologies have potential for precision tillage management (Raper et al., 1990; Liu et al., 1993; Sudduth et al., 1998; Andrade et al., 2004; Hall and Raper, 2005; Grift et al., 2005). Raper et al. (1990) were able to detect a soil hardpan with ground penetrating radar (GPR) that showed good agreement with cone penetrometer prediction of the depth of hardpan for Norfolk sandy loam and Decatur clay loam soil bins at the USDA-ARS National Soil Dynamics

Laboratory. According to Raper et al. (1990) the amount and distribution of soil moisture along the profile ought to be uniform for accurate GPR detection of a soil hardpan. Under field conditions it is often unlikely to obtain uniform soil moisture profiles. Sudduth et al. (1998) successfully sensed the topsoil depth on claypan soils of central Missouri from soil electrical conductivity measurement by a non-contact, electromagnetic induction-based sensor (EM38 electromagnetic induction instrument (Geonics Ltd., Mississauga, Ontario, Canada)) and a coulter-based sensor (Veris 3100, Salina, KS, USA). Hall and Raper (2005) developed an on-the-fly mechanical impedance sensor to measure horizontal soil wedge penetration resistance. They reported similar results between the "wedge index" and cone index with the "wedge index" being less sensitive to soil moisture. Grift et al. (2005) studied the potential of an acoustic method to detect the depth of a soil hardpan. Their results showed good agreement with cone penetrometer detection of the soil hardpan layer. Even though these new soil compaction detection methods have potential for being incorporated into real-time precision agricultural management, they are still in development and are not as standardized as the soil cone penetrometer.

The influences of soil parameters, mainly soil moisture and bulk density, on cone index may affect the interpretation of cone penetrometer data in predicting hardpan locations. Many studies (Mulqueen et al., 1997, Ayers and Perumpral, 1982; Rajaram and Erbach, 1998; Utset and Greco, 2001; Raper et al., 2005c) have addressed the effect of soil moisture and bulk density on cone index in laboratory and field-scale studies. Ayers and Perumpral (1982) studied soil moisture-bulk density-cone index relationships on artificial soils obtained by mixing different quantities of zircon, sand and clay. According to their report, the cone index decreased with increasing soil moisture content. The effect of bulk density varied with soil moisture such that at low soil moisture content, the influence of soil bulk density on cone index was high and at high soil moisture content, cone index was less dependent on bulk density. Raper et al. (2005c) determined the depth of the hardpan and its spatial variability in upland soils of Northern Mississippi, USA. The authors found a good correlation between the depth of hardpan and soil moisture in the depth ranges of 0-15 cm and 0-30 cm for trafficked and non-trafficked soils, respectively. However, the average depth to the trafficked hardpan (21 cm) was not within the soil moisture sampling depth range (0-15 cm) making their conclusion on the relationship between the predicted hardpan depth and soil moisture less strong. Rajaram and Erbach (1998) studied the effect of drying stress induced by a wetting and drying cycle on soil physical properties of a clay loam soil. It was observed that cone penetration resistance measured at 50, 100, and 150 mm depths increased with increased drying stress. The study was conducted in a uniform soil density profile, which may not be representative of many field soil conditions.

Most of the previous studies emphasized the relationship between soil parameters and the magnitude of soil compaction (cone index values). Limited information is available on the effects of soil moisture and bulk density on the cone index interpretation to ascertain whether the predicted depth of the hardpan (hardpan location) remains the same or is shifted upward or downward due to soil moisture variations in layered soils. In precision tillage, accurate hardpan detection under field soil conditions is important because errors of a few centimeters could cause variations in precision tillage depth recommendations. Real-time soil strength sensing methods that have potential of being used in precision agriculture are also intended to detect hardpans at soil moisture conditions similar to the tillage operation, which often is expected under dry soil moisture conditions for maximum performance (Al-Adawi and Reeder (1996) and Raper and Sharma (2004). Appropriate evaluation of real-time (on-the-go) soil strength sensing methods with the cone index measurement in predicting soil hardpan depth would require a study of the influences of soil drying and layering on cone index.

Examining the soil moisture-bulk density-cone index relationships in a stratified soil strength profile is important in enhancing the understanding of using cone index measurements as a tool for site-specific determination of hardpan depths. One important area that needs further studies could be the site-specific soil moisture variation and its effect on the prediction of the soil strength and relative position of hardpan layers. Measuring soil moisture over short depth increments may provide a better understanding of the soil moisture-cone index relationship.

Thus, the objectives of this study were: 1) to investigate the effect of soil drying on peak cone index; 2) to investigate the effect of soil drying on the depth to the peak cone index; and 3) to investigate the effect of soil drying on the depth to the top of the hardpan.

2. MATERIALS AND METHODS

2.1 Soil Preparation and Experimental Design

The experiment was conducted in 2004 in a Norfolk sandy loam (Typic Paleudults) soil bin at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Ala. The soil bin is 6-m wide, 58-m long and 1.5-m deep. The soil in the bin was from the A-horizon of Norfolk sandy loam (*Fine-loamy, kaolinitic, thermic Typic Kandiudults*) and consists of 72 % sand, 17 % silt and 11 % clay (Batchelor, 1984). For the soil hardpan creation, the soil was first wetted to workable soil moisture content and then tilled using a rotary tiller to a depth of 40 cm. Soil hardpan layers with three different soil strength levels were created by varying the number of passes of a cylindrical rigid compression wheel. One cycle of forward and backward movements of the rigid compression wheel created a single-pass compaction treatment. Two cycles of the movement of the rigid compression wheel created the double pass compaction treatment. No hardpan was installed for the no-pass compaction treatment that was used as a control treatment. The soil surface was leveled using a scraper blade and the surface soil was compacted using a 6-m wide roller. The entire surface of the soil bin was then wetted using a mobile sprinkler vehicle until the soil profile was nearly saturated.

A split plot experimental design with a randomized complete block design at the whole plot level was used to conduct the experiment. The soil bin was divided into four blocks (replicates). Each block consisted of three whole plot experimental units where the three compaction treatments (No pass, Single and Double passes) were randomly applied. Each whole plot experimental unit was further divided into four sub-plot experimental units. Within each sub-plot, cone index data were collected at a 25Hz sampling rate using a Multiple-Probe-Soil-Cone-Penetrometer (MPSCP) (Raper et al., 1999) mounted on a soil bin vehicle. The MPSCP consists of five

ASABE standardized (ASABE 2008a) probes that has a 30^o cone with a cone base diameter of 12.83 mm and a shaft diameter of 9.53 mm; and inserted vertically into the soil at a uniform rate of 30 mm/ sec. Cone penetration measurements were taken at four horizontal positions (20 cm apart) to a depth of 45 cm for four measurement days (‘day-1’, ‘day-2’, ‘day-3’and ‘day-4’). Cone index measurement on ‘day-1’ was 24-hrs after the soil profile was saturated. On ‘day-1’ no ponding was observed on the soil bin. The soil surface was exposed to the atmosphere to enhance drying. Sufficient days had passed between sampling dates that would allow the soil bin to dry. The four measurement days were considered as four levels of the subplot treatment factor (soil moisture). A total of 320 cone index measurements (1 compaction x 4 horizontal positions x 5 probes per horizontal position x 4 days x 4 replicates) were obtained for each compaction treatment.

Soil core samples in four replicates were taken immediately after cone index measurement for soil moisture determination up to 40 cm depth at an increment of 2.5 cm. Soil moisture (dry basis) was determined after oven drying the samples at 105 ^oC for 72 hrs. Cylindrical soil cores samples (70.2 mm in diameter and 40.6 mm in height) were collected for bulk density determination from three vertical positions in the soil profile: above within, and below the hardpan. For the above hardpan bulk density measurement, core sampler was inserted from soil surface to 40.6 mm depth. Soil above the hardpan layers was carefully removed and core sampled for determination of within hardpan bulk density. Soil sample for bulk density measurement of below hardpan was taken at depth approximately below the rotary tiller depth. The soil cores were oven-dried at 105 ^oC for 72 hrs. Within each single and double pass compaction subplots in the soil bin, the loose soil above the hardpan was carefully removed after cone index measurement to measure the actual depth to the top of the soil hardpan using a portable tillage profiler (Raper et al., 2004).

2.2 Cone Index Analysis

The digitally-obtained cone penetrometer data averaged for each position (five MSCP probes) were analyzed using script written in Matlab to extract the hardpan parameters, namely peak cone index, the depth to the peak cone index, and the depth to the top of the hardpan layer. The peak cone index value was assumed as the numerically greatest value of cone index in the soil profile (0-40 cm). Mean value of cone index reading taken as probes were moved in the air, which could be considered as instrumental noise, was calculated and subtracted from the cone penetrometer acquired data. Depth with cone index changing from zero (standard deviation of 2 kPa) to cone index value as the probes were inserted into the soil was considered as the elevation of the soil surface. The depth from the soil surface to the depth of the maximum cone index in the soil profile (0-40 cm) was considered as to the depth to the peak cone index. Cone index values at depths deeper than 40 cm depth were not considered in the analysis as they may have been created by the previous compaction history of the soil in the bin.

Abrupt changes in cone index data was observed at the interface between loose soil above the hardpan and the hardpan. The hardpan was assumed to start where the cone index increased rapidly with the change in slope which is cone index from zero to positive values for a unit increase in soil depth. The corresponding cone index value at the top of the hardpan was also determined. The method used to determine the hardpan parameters are shown graphically in Figure. 1.

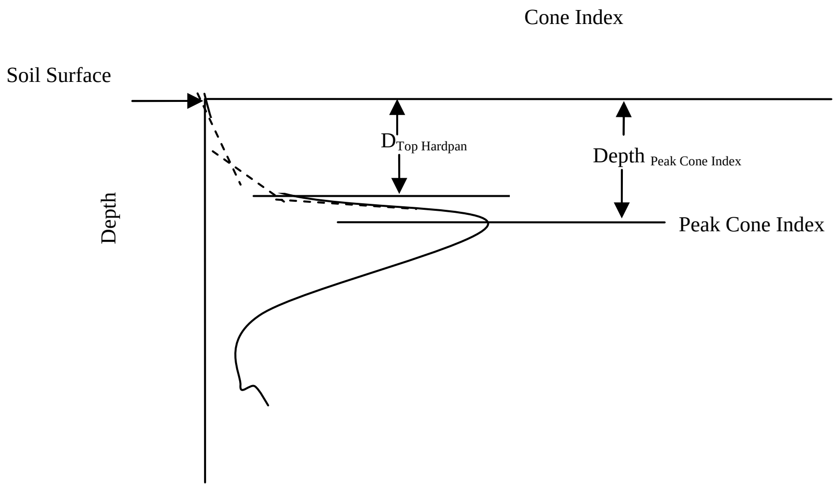

Figure 1. Cone index vs. depth to determine the depth to the peak cone index ($D_{Top\ Hardpan}$) and the depth to the top of the hardpan layer ($D_{Hardpan}$). The instantaneous slope values are shown as straight dashed lines that are tangent to the curve.

The effects of the four levels of soil drying and three compaction levels on peak cone index, the depth to the peak cone index and the depth to the top of the hardpan were analyzed using the PROC GLM procedure in SAS for a split plot experimental design (SAS, 2001).

3. RESULTS AND DISCUSSION

The soil bulk densities for the three layer positions: above hardpan, within and below hardpan created by the three compaction treatments are shown in Table 1. For the single and double pass compaction, the highest and smallest bulk density values were created at the within hardpan and above hardpan locations. Having within hardpan bulk density value smaller than above hardpan for the no pass compaction indicated no hardpan was created. The bulk density values among the three vertical positions for the no-pass compaction indicated that hardpan was not created. Within the hardpan, soil bulk density values of the three compaction treatments were significantly different (Fig. 2, $P \leq 0.0001$). The single pass and double pass compaction resulted in a 23% and 26% increase in soil bulk density (within hardpan) as compared to the within hardpan bulk density of no pass compaction, respectively. Above hardpan bulk density values for the single and double pass compactions did not vary significantly.

Table 1. Soil dry bulk density ($\mathrm{Mg\ m^{-3}}$) above, within, and below hardpan layer positions for no pass, single pass and double pass compaction for Norfolk sandy loam soil.

Compaction Level	Above Hardpan		Within Hardpan		Below Hardpan	
	Mean -$\mathrm{Mg\ m^{-3}}$-	Std. Dev. -$\mathrm{Mg\ m^{-3}}$-	Mean -$\mathrm{Mg\ m^{-3}}$-	Std. Dev. -$\mathrm{Mg\ m^{-3}}$-	Mean -$\mathrm{Mg\ m^{-3}}$-	Std. Dev. -$\mathrm{Mg\ m^{-3}}$-
No pass compaction	1.50 (a) (A)[a]	0.04	1.45 (c) (B)	0.08	1.39 (c) (C)	0.06
Single pass compaction	1.46 (b) (C)	0.05	1.78(b) (A)	0.06	1.65(b) (B)	0.06
Double pass compaction	1.45(b) (C)	0.05	1.83(a) (A)	0.06	1.69(a) (B)	0.08

[a] For the Above, Within and Below hardpan layer positions, means followed by the same letter were not significantly different ($\mathrm{LSD}_{\alpha=0.1}$). Lower case letters indicate statistical comparisons among the soil compaction levels within each soil layer, i.e. within each column. Upper case letters indicate statistical comparisons among soil layer positions within each soil compaction treatment, i.e. within each row.

3.1 Soil Moisture Distribution

The soil moisture profile distributions over the sampling days are shown in Figure 2. There were significant interaction effects ($P \leq 0.01$) of compaction and days on the soil moisture content over the sampling depth (0 - 40 cm). The soil moisture contents decreased as the days passed for each compaction level. Within the hardpan, the soil moisture variations during the first four sampling periods were small for the double pass compaction (1.83 $\mathrm{Mg\ m^{-3}}$, within hardpan). Soil compaction and depth showed statistically insignificant interaction effects ($P \leq 0.07$) on the soil moisture profile distribution implying the soil profile dried significantly in each of the compaction treatments. The variation in soil moisture profile varied by the degree of compaction from the no-pass to the single pass compaction was high for the successive sampling periods.

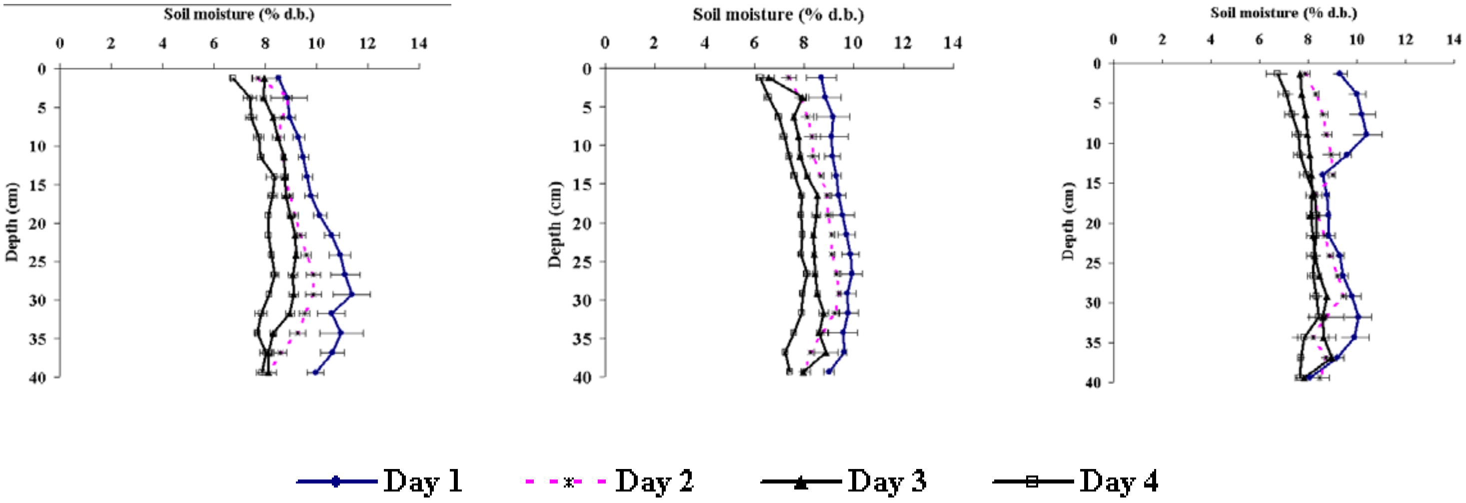

Figure 2. Soil moisture content distribution throughout soil profile of the four measurement days for (A) No pass compaction, (B) Single pass compaction and (C) Double pass compaction. Horizontal bars indicate one standard deviation.

The magnitude of soil dryness was quantified by computing soil drying index in absolute values (Eq. 1) that compares the average soil moisture content of each sampling day with the soil moisture content of 'day-1' (wet soil moisture).

$$Soil\,Drying\,Index(\%) = \left|\frac{Soil\,moisture_{day-i} - Soil\,moisture_{day-1}}{Soil\,moisture_{day-1}}\right| * 100 \qquad \text{Eq. 1}$$

where: i = day index 1, 2, 3 and 4 that shows the four sampling days.

The soil drying index was affected both by the number of days passed and the amount of soil compaction. It was observed that the soil drying index values increased with measurement days passed and the values of drying index for the double pass compaction were slightly smaller than for the other two soil compaction treatments (Fig. 3).

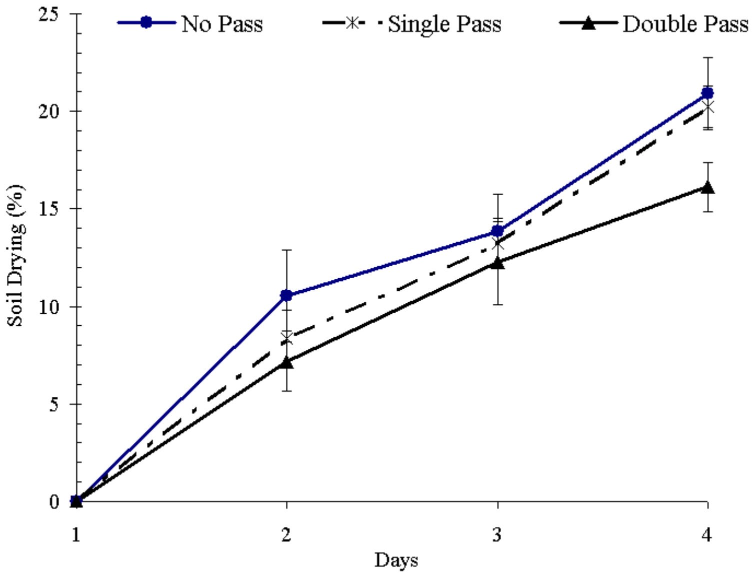

Figure 3. Mean soil drying index vs. measurement days for No pass, Single pass and Double pass compaction. Vertical bars indicate standard deviations.

The cone index profile of the experimental units of the no-pass compaction showed that there was no hardpan (Fig. 4) but for the single and double pass compaction treatments the hardpan creation is clearly observed from the cone index profile. The effects of soil drying on the hardpan parameters (peak cone index, the depth to the peak cone index, and the depth to the top of the hardpan layer) were, therefore, analyzed only for the single and double pass compaction treatments.

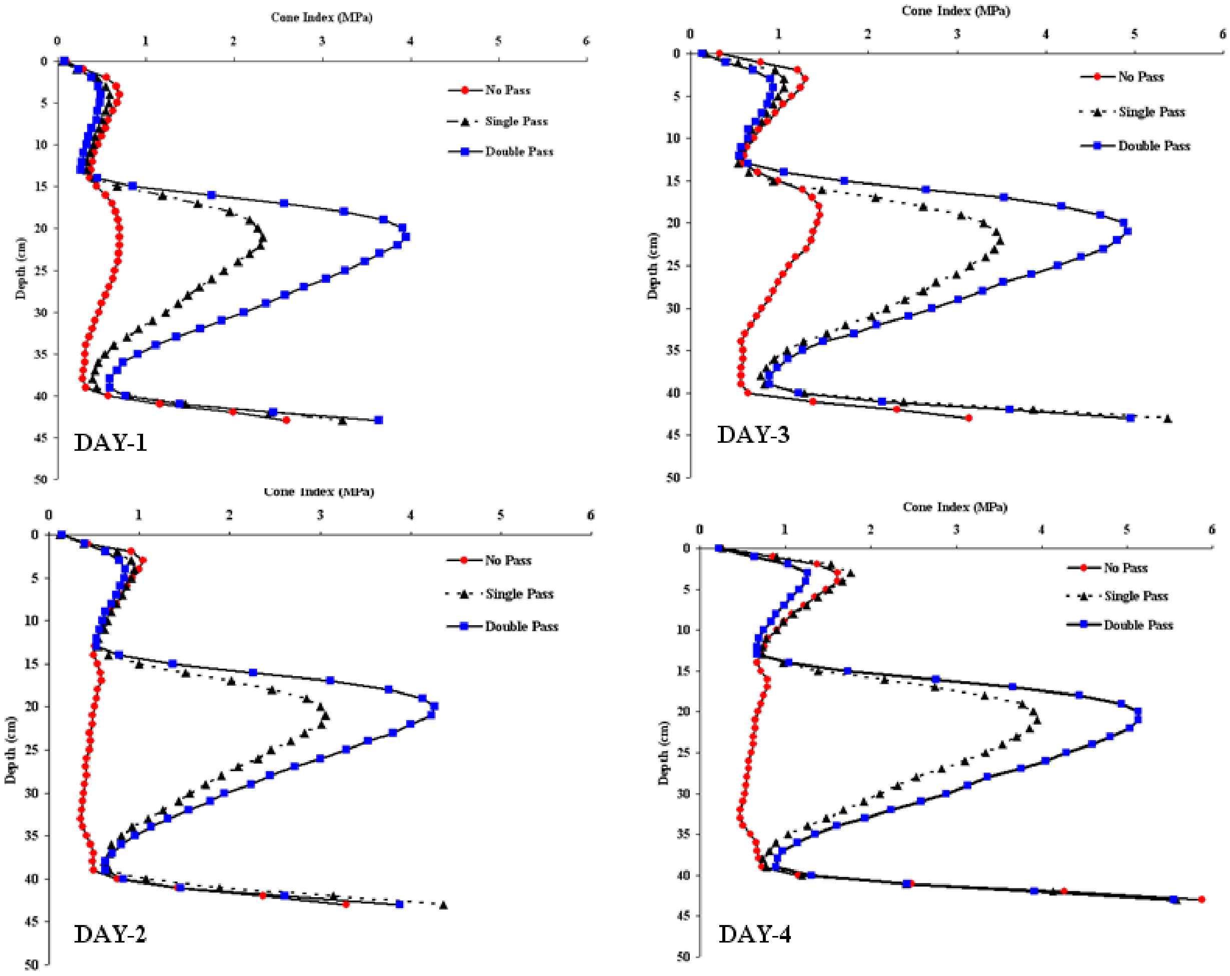

Figure 4. Cone index profile for No-Pass, Single Pass; and Double Pass compactions for the four measurement days.

Soil compaction and soil moisture content affected peak cone index significantly (Fig.5 (A) and (B); $P \leq 0.01$). The interaction effects of soil compaction and soil moisture content were not statistically significant ($P = 0.09$). The peak cone index values increased for the single and double pass compaction treatments as the soil dried. Maximum peak cone index values of 4.02 MPa and 5.34 MPa occurred on ‘day-4’, respectively, for the single and double pass compaction treatments. For the single pass compaction, the soil drying from ‘day-1’ to ‘day-4’ (drying index value of 18.44 %) caused the peak cone index to increase two-fold. The peak cone index on the double pass compacted soils on ‘day-4’ was 1.3 times the value observed at ‘day-1’ (drying index value of 12.10%). The smaller differences in the peak cone index values during the drying periods for the double pass treatment could be due to the reduced variation in soil moisture at the hardpan location (Fig. 2).

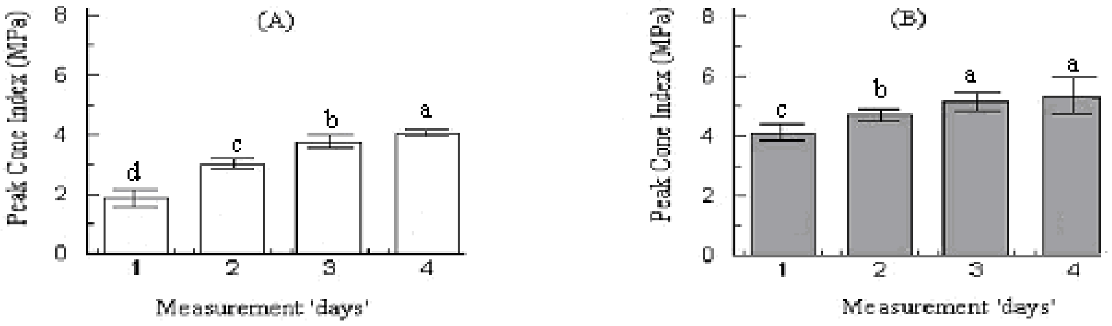

Figure 5. Mean of peak cone index vs. the four measurement days for (A) Single pass compaction and (B) Double pass compaction. For each compaction level, means with the same letter are not significantly different at LSD $_{\alpha=0.05}$. Each vertical bar indicates one standard deviation.

The strength of relationship between the hardpan attributes and soil moisture content were determined using the Pearson's correlation coefficients for the single pass and double pass compaction treatments (Table 2). The peak cone index and the cone index at the top of the hardpan were each related negatively to the soil moisture variation with a statistically significant Pearson's correlation coefficient close to –1.0, at the 5% significance level (Table 2). The depth of hardpan parameters (depth to the peak cone index and the depth to the top of the hardpan) exhibit low correlation with the soil moisture variations, moreover, these correlation tests showed high *p*-values (Table 2).

Table 2. Pearson's correlation coefficients between hardpan attributes and soil moisture content for single and double pass compaction for Norfolk sandy loam soil. Values in the parentheses indicate the p-values.

Hardpan parameters	Single pass compaction	Double pass compaction
	----- Soil moisture content (%, b.d.) ------	
Peak cone index (MPa)	-0.94 (0.06)	-1.0 (0.004)
Depth to the peak cone index (cm)	-0.65 (0.35)	-0.24 (0.76)
Cone index at the top of the hardpan (MPa)	-0.99 (0.01)	-0.99 (0.01)
Depth to the top of the hardpan (cm)	0.65 (0.35)	0.92 (0.08)

There were statistically significant interaction effects of soil compaction and soil moisture content on the depth to the peak cone index ($P \leq 0.0001$). The soil drying caused a significant decrease in the predicted depth to the peak cone index for the single pass compaction (Fig. 6); however, for the double pass compaction the soil drying did not cause a significant variation in the predicted depth to the peak cone index.

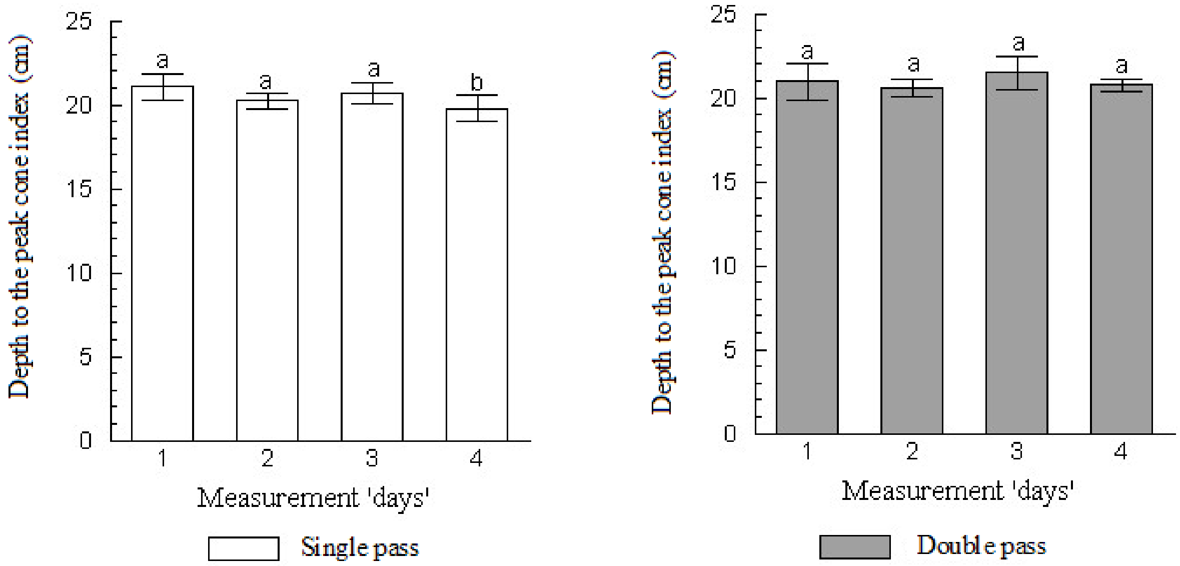

Figure 6. Mean depth to the peak cone index (cm) vs. the four measurement days for the Single pass compaction and the Double pass compaction. For each compaction level, means with the same letter are not significantly different, LSD $_{\alpha = 0.05}$. Each vertical bar indicates one standard deviation.

There were interaction effects of soil compaction and soil moisture content for the depth to the top of the hardpan (*P* = 0.03), with the depths to the top of the hardpan ranging from 13.04 cm to 13.79 cm for the single pass and 12.91 cm to 12.99 cm for the double pass compaction (Fig. 7).

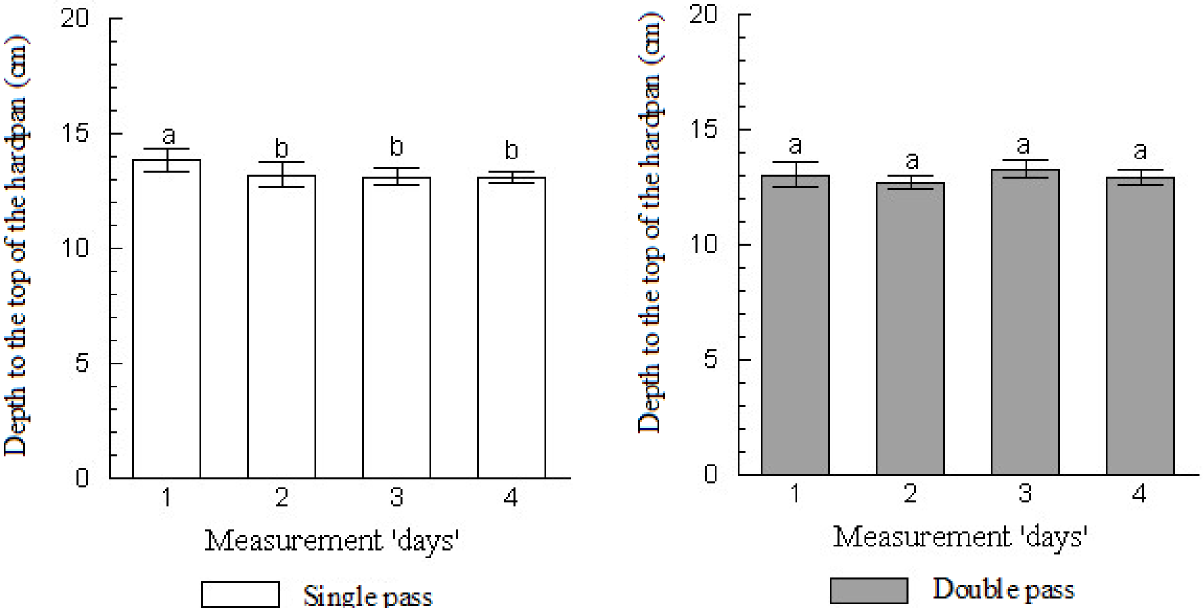

Figure 7. Mean depth to the top of the hardpan (cm) vs. the four measurement days for the Single pass compaction and the Double pass compaction. For each compaction level, means with the same letter are not significantly different, LSD $_{\alpha=0.05}$. Each vertical bar indicates one standard deviation.

The depth measured using the profile meter was compared with the top hardpan depth determined from the cone index profile. The depth of the top of the hardpan as measured from the profile meter was 14.95 cm (CV= 0.05) for the single pass and 14.26 cm (CV = 0.09) for the double pass compaction. The differences in the depth as measured by the tillage profile meter were not statistically significant ($P \leq 0.12$) by compaction treatments. The depths to the top of the hardpan determined from the cone index data averaged over the whole drying period were 13.26 cm (CV = 0.03) for single pass, and 12.95 cm (CV = 0.02) for double pass, respectively. The depths to the top of hardpan from cone index data were slightly smaller than the tillage profiler-measured depths both for the single and double pass compaction. The results also indicated that hardpan depth determination from the cone index profile was better estimated using the tip of the cone as depth reference.

The soil strength at magnitude of the hardpan as indicated by the peak cone index was highly affected by soil drying suggesting interpretation of soil cone index for determining the hardpan should be done with caution. The depth to the hardpan (the depths to the peak cone index and the top of the hardpan) determine from the cone index measurement appeared to be predicted at shallower depths as the soil dried; however, the differences caused by soil drying was too small (< 3 cm) to cause sizable variations in prescribing tillage depth. The results of the study appear to be in consistent with the mechanics of soil-cone interaction observed by (Gill, 1968; Sanglerat, 1972; Koolen and Kuipers, 1983; Lunne et al., 1997) that cone penetration readings are influenced by soil layering and soil behaviors in the zones of influence. According to Lunne et. al. (1997), the distance over which the cone starts to sense the layer depends on material stiffness and thickness of the stiff layer; in soft soil the diameter of the zone of soil influenced could be two to three times the cone diameter.

4. CONCLUSIONS

The following conclusions were drawn from the experiment: a) the effects of soil drying on the hardpan parameters in the Norfolk sandy loam soil bin were dependent both on the magnitude of soil drying and the bulk density of the hardpan. The peak cone index value for the single pass compaction (within hardpan bulk density of 1.78 Mg m^{-3}) doubled as the soil dried over the sampling depth (0-40 cm) from ‘day-1’ (9.61% d.b.) to ‘day-4’ (7.74% d.b.) measurement days. For the double pass compaction (within hardpan bulk density of 1.83 Mg m^{-3}), the increase in peak cone index as the soil dried was 1.3 times; b) the depth to the peak cone index and the top of the hardpan were determined at shallower depth as the soil dried; however, the differences caused by soil drying appeared to be too small to cause sizable variations in prescribing tillage depth; c) as the soil dried, the top of the hardpan layer determined from the cone index data was shallower in depth by differences of 2d and d [d = 12.8 mm ASABE standard cone base diameter] for the single and double pass compaction, respectively, than the depth measured using tillage profile meter in an excavated trench up to the artificially installed hardpan layer; and d) further study on the soil drying effects on hardpan characterization is important under field soil conditions.

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