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Soil compaction varies by crop management system over a claypan soil landscape

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ABSTRACT

While the effects of landscape position (LP) and management practices on soil compaction have been documented as individual factors, limited understanding exists of their interactions. Such understanding is needed to prevent site-specific compaction and to better optimize soil management practices using precision agriculture principles and technologies. The objective of this investigation was to quantify, for a typical claypan soil [Epiaqualfs (USDA); Stagnic Luvisols (WRB)], the impacts and interactions of crop management system and LP on soil compaction as quantified by cone index (CI) and CI-related variables. Cone penetrometer measurements were collected in 2004 at three claypan soil LP (summit, backslope, and footslope) for four different cropping systems [CS; mulch tillage corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] (MTCS), no-tillage corn–soybean (NTCS), no-tillage corn–soybean–wheat (*Triticum aestivum* L.) (NTCSW), and conservation reserve program (CRP)] that had been in place for more than a decade. Soils were sampled at the same time for soil water content (WC) and soil bulk density (BD) measurements. Mean differences for response variables were examined using *F*-protected ($P \leq 0.05$) LSD values. Cone index averaged over soil depth differed by CS and LP. At the footslope position, CI for the NTCSW CS measured ~2.0 MPa in the upper 25 cm of soil, and was notably greater than the other management systems. This outcome was attributed to the footslope staying wetter for a longer period during the spring and early summer because of un-removed cover crop plant residues. Wetter soils resulted in vulnerability to compaction during planting and spraying operations. Compaction on CRP was predictably less than the grain CS at all LP because farm machinery traffic only occurred on this system with bi-annual weed mowing during the mid-summer. These findings help bring to light where in claypan soil landscapes certain types of grain crop management will cause significant compaction. These areas could be targeted for further soil strength testing and then, when necessary, appropriate compaction remediation actions.

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1. Introduction

Soil compaction is a concern in crop production and environmental management (Soane and Van Ouwerkerk, 1994; Hamza and Anderson, 2005). When soil is compacted, pore space is reduced and other soil physical and chemical properties (e.g., water content, air or water permeability, strength) are affected so that root development and crop growth are negatively impacted. These other properties have been described as "behavioral properties" of soil compaction and more often are used to serve as indicators of compaction (Johnson and Bailey, 2002). An increase in soil compaction results in higher soil bulk density (BD) which can slow plant growth by restricting root penetration and decreasing water infiltration and air movement (Allmaras et al., 1988). This in turn causes nutrient stress and poor emergence of seeds (Braunack, 1986; Stepniewski et al., 1994). Commensurately, crop yields are reduced (Soane and Van Ouwerkerk, 1994). Furthermore, when crops are stunted by compaction, unused fertilizer and manure nutrients become more vulnerable to off-field movement into ground and surface waters (Soane and Van Ouwerkerk, 1995; Hamza and Anderson, 2005).

Soil water content (WC) is usually the most important factor influencing soil compaction processes (Soane and Van Ouwerkerk, 1994; Hamza and Anderson, 2005). Yet, the degree of compaction created by tillage and heavy machinery traffic is often also a function of soil texture (sand, silt and clay particle proportions),

Abbreviations: BD, bulk density; CI, cone index; CRP, conservation reserve program system; CS, cropping system; LP, landscape position; LSD, least significant difference; MTCS, mulch tillage with a corn–soybean rotation; NTCS, no-till with a corn–soybean; NTCSW, no-till with a corn–soybean–wheat rotation; RDW CI, root distribution weighted cone index; WC, soil water content.

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initial soil density, soil structure, organic matter content, and other weather conditions (e.g. temperature) (Cassel, 1982; Raper et al., 1998; Mosaddeghi et al., 2000). Generally, the depth of compaction varies widely from 10 to 60 cm (Flowers and Lal, 1998), but the effect on crop growth is usually more pronounced when found in the topsoil (∼15 cm).

Because quantifying soil compaction often requires disruptive sampling, direct measurement is often judged impractical. Soil strength is a commonly used surrogate measurement (Canarache, 1991), with a cone penetrometer employed as a standard instrument for quantifying soil strength (Mulqueen et al., 1977; Bengough and Mullins, 1990). The index of soil strength measured by a cone penetrometer, cone index (CI), is defined as the force per unit cone base area required to push the penetrometer through a specified small increment of depth (ASABE, 2008a). Numerous researchers (Canarache, 1991; Lowery and Schuler, 1994; Ngunjuri and Siemens, 1995) have documented the increases in CI that occur with increases in compaction and BD. In addition to compaction, the major factors affecting CI include WC and clay content of the soil (Elbanna and Witney, 1987). For example, CI has been found to increase with decreasing soil water potential (Lipiec et al., 2002). Thus, variation in soil texture and other physical properties among locations or soil horizons may complicate interpretation of CI as an indicator of soil compaction (Mulqueen et al., 1977).

Studies have determined root-growth-limiting values of CI. Taylor and Gardner (1963) showed that CI readings above 2 MPa could significantly impede root growth and reduce crop yields, providing a convenient way to relate CI to the need for tillage or other compaction amelioration. While this value has been often used as a benchmark for the point at which plants are negatively affected (Hamza and Anderson, 2005), others have documented exceptions. Ehlers et al. (1983) found that the growth-limiting soil penetration value was 2–3 MPa for oat (*Avena sativa*). Lutz et al. (1986) studied the relationship between citrus root growth and soil physical conditions, such as hardpans and claypans, and documented that 1.5 MPa was the maximum soil strength before root growth was restricted.

The claypan soils in north-central and northeastern Missouri and southern Illinois [Epiaqualfs (USDA); Stagnic Luvisols (WRB)] have a restrictive high-clay subsoil layer (the "claypan"). These soils are weathered loess over glacial till, and characterized by extensive leaching of bases (therefore they are moderately acidic) and subsoil illuviated clays. Claypan soils are usually classified as somewhat poorly to poorly drained and have slow to very slow permeability. With slow permeability through the claypan, soils saturate quickly creating a high probability of runoff, even in field areas with low slopes (Blanco-Canqui et al., 2002). Annual average surface runoff is about 30% of annual precipitation, which averages 900–1100 mm. On an event basis, the runoff percentage can be much higher, especially in the spring and early summer when soils are near or at saturation (Lerch et al., 2007).

Claypan soil properties such as BD, cation exchange capactity, OM, WC, and porosity can be extremely variable across the landscape and within the soil profile (Jung et al., 2006, 2008; Jiang et al., 2007a). Summit soils in claypan landscapes have a depth to the claypan horizon of around 30–40 cm, decreasing to as little as 5–15 cm on eroded backslopes and increasing to as deep as 100 cm on depositional footslope areas. Surface soil textures are silty clay loam to silty clay (Young and Geller, 1995). Below the A horizon an eluviated zone occurs and an albic (E) horizon, or transitional BE horizon, frequently overlays the claypan (Bt1/Btg1). The clay content of the claypan horizon is approximately 50–60% smectitic (high shrink–swell characteristics) clay minerals which can be alternately swollen or fissured depending on their water content (Bray, 1935; Soil Survey Staff, 1981; Baer and Anderson, 1997). These variations of claypan profile properties over the landscape greatly influence profile water holding capacity (Jiang et al., 2007b), hydraulic conductivity (Thompson et al., 1991; Yang et al., 2003; Jiang et al., 2007a), and plant root development (Wang et al., 2002; Myers et al., 2007). Some of these same properties are, as discussed earlier, properties that determine a soil's vulnerability to compaction.

Claypan soils can be particularly susceptible to surface compaction. Anderson and Cassel (1984) found that shallower surface horizons overlying a subsoil clay horizon (such as in an eroded area) had relatively higher soil strength. In other studies, the relatively low saturated hydraulic conductivity of the claypan (4–10 mm h^{-1}; Jiang et al., 2007a) perched water in the surface horizon (Blanco-Canqui et al., 2002) creating a higher susceptibility to surface compaction in this part of the profile during spring field operations. Motavalli et al. (2003) found that surface compaction on a Missouri claypan soil reduced corn (*Zea mays* L.) yields by 20–47%. However, a claypan soil study in Southeast Kansas found that compaction only reduced grain sorghum [*Sorghum bicolor* (L.) Moench.] and soybean [*Glycine max* (L.) Merr.] yields in some years, and only when compaction in excess of that expected in normal farming operations occurred (Sweeney et al., 2006).

While the effects of landscape properties and management practices on soil compaction have been documented individually, understanding of the interactions of these factors is generally limited. Such understanding is needed to better optimize soil management practices using site-specific principles and technologies.

2. Objective

The objective of the study was to quantify the impacts and interactions of crop management system (CS) and landscape position (LP) on the soil compaction of a typical claypan soil as quantified by CI and CI-related variables.

3. Materials and methods

3.1. Study site and experimental design

The study was conducted on a 12-ha site 2 km from Centralia, Missouri (39°13N, 92°07W) in Major Land Resource Area (MLRA) 113, the Central Claypan Region (USDA-NRCS, 2000). Average annual precipitation at this site is 970 mm. The site encompasses three LP: summit, backslope and footslope (Fig. 1). Soils were delineated on the basis of an order-one soil survey conducted in 1991. The summit LP was mapped as Adco (fine, smectitic, mesic Vertic Albaqualf) silt loam with 0–1% slopes; the backslope position was mapped as Mexico (fine, smectitic, mesic Aeric Vertic Epiaqualfs) clay loam with 1–3% slopes; and the footslope LP was mapped as Mexico silt loam with 1–2% slopes and somewhat poorly drained (Fig. 1). These three soils are very similar and differ only by subtle differences in diagnostic features. The landscape was linear to slightly convex at the summit position and linear to slightly concave in the backslope and footslope LP. The difference in elevation between summit and footslope positions was about 2–3 m. The subsoil argillic horizon, typical of claypan soils, was characterized by abrupt occurrence of silty-clay loam, silty clay, or clay at varying depths.

Soil profile samples were taken in 1991 by LP just prior to initiation of the management systems. Forty-eight cores over the study site were taken to a 1.2-m depth, described, and subsampled by soil horizon increment for further laboratory analysis. Selected soil properties are provided by LP in Table 1.

Cropping systems were established in 1991 to investigate the effects of tillage, rotation, and other management practices on crop production and soil and water quality. The experimental design was a randomized complete block with three blocks (i.e., replications) where all rotation phases of each CS were present

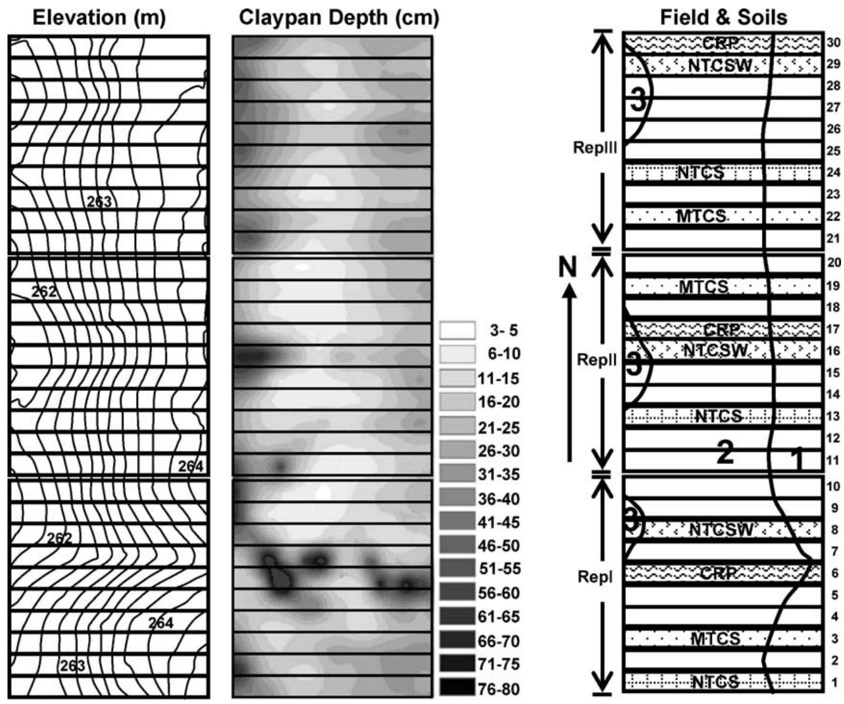

Fig. 1. Elevation, depth to the claypan horizon, and mapped soils for the research site near Centralia, Missouri. Mapped soils include 1: Adco silt loam, 0–1% slope; 2: Mexico silty clay loam, 1–3%, eroded; 3: Mexico silt loam, 1–2% slope. Plots used for this study are labeled with the cropping system treatment: MTCS: mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system.

each year. Each of the 30 plots measured 18 m × 189 m (0.35 ha) running east–west parallel to the slope direction (Fig. 1) and thus each LP was included within each plot. Four of the six CS were selected for investigation in this study: mulch tillage corn–soybean (MTCS); no-tillage corn–soybean (NTCS); no-tillage corn–soybean–wheat (*Triticum aestivum*) (NTCSW); and conservation reserve program (CRP). Descriptions of these management systems are given in Table 2, and additional information about the experimental area can be found in Ghidey et al. (2005). Equipment used for farming operations was typical of small to mid-sized farms (<200 ha) in the area. Approximate loads imposed by the farm equipment used for each management system are also provided in Table 2.

3.2. Penetrometer data collection and processing

Penetrometer measurements were collected using standardized methodology (ASABE, 2008b) on April 15, 2004 from each of the four CS discussed above and at three LP (summit, backslope, and footslope) for a total of 12 treatments. All three replications were included. The grain CS were entering the soybean year of the rotation. At each sampling location, penetrometer data were collected at a defined position from the north side of the plots to represent area that had received "normal" wheel traffic during the 13 years that the CS had been in place. With 18-m wide plots, traffic patterns were somewhat constrained over the years of the plot experiment. A number of types and sizes of equipment were used for field operations during those years, including both 4-row and 6-row width planters and various width tillage, chemical application, and harvesting equipment. Analysis of our management notes showed that certain locations received relatively more traffic over the years while others received less traffic. We concluded that the more trafficked areas had significantly more wheel traffic than would be found in larger production fields. We determined that the location between crop rows 6 and 7 from the north side of the plots experienced a level of traffic most like that

Table 1
Mean and standard deviation (in parentheses) of selected soil physical properties of the research site near Centralia, Missouri. The site is composed primarily of Mexico silt loam and Adco silt loam soils.

Landscape position	Horizon	Depth to horizon middle (cm)	Particle size distribution			Cation exchange capacity ($cmol_c\,kg^{-1}$)	Organic carbon ($g\,kg^{-1}$)
			Clay ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Sand ($g\,kg^{-1}$)		
Summit	Ap/AE	16 (6)	220 (60)	700 (70)	80 (20)	18.9 (2.8)	37 (1)
	Bt1	30 (12)	530 (50)	440 (40)	30 (20)	38.4 (3.3)	12 (1)
	Bt2	54 (14)	450 (90)	530 (90)	10 (10)	36.0 (5.4)	3 (1)
	Other	94 (19)	330 (40)	640 (30)	30 (10)	28.2 (4.5)	6 (3)
Backslope	Ap/AE	7 (4)	250 (60)	650 (60)	100 (20)	22.8 (4.2)	40 (9)
	Bt1	24 (9)	450 (110)	510 (100)	40 (30)	34.6 (7.9)	12 (8)
	Bt2	48 (14)	400 (50)	570 (50)	30 (10)	33.6 (4.4)	7 (5)
	Other	86 (21)	330 (40)	600 (40)	70 (40)	26.1 (5.2)	11 (7)
Footslope	Ap/AE	26 (19)	250 (80)	670 (80)	80 (10)	21.7 (4.7)	29 (9)
	Bt1	54 (20)	480 (80)	480 (40)	40 (40)	35.6 (6.9)	9 (7)
	Bt2	72 (12)	380 (50)	590 (50)	30 (30)	32.8 (4.4)	6 (7)
	Other	98 (12)	310 (40)	590 (40)	100 (50)	22.9 (3.1)	16 (10)

Table 2
Description of the four management systems used in the study.

Cropping system	Description	Fertilizer input	Yield goal	Major equipment used and mass
MTCS	Mulch tillage[a] with a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation	N: 190 kg ha^{-1} for corn; Lime, P, and K: by soil test	10.1 Mg ha^{-1} for corn and 2.5 Mg ha^{-1} for soybean	Tillage tractor (6200 kg); planting tractor (4800 kg); self-propelled sprayer (5200 kg); combine (10,800 kg empty; 14,400 kg full of grain)
NTCS	No-till with a corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation	N: 151 kg ha^{-1} for corn. Lime, P, and K: by soil test	7.5 Mg ha^{-1} for corn and 2.5 Mg ha^{-1} for soybean	Planting tractor (4800 kg); self-propelled sprayer (5200 kg); combine (10,800 kg empty; 14,400 kg full of grain)
NTCSW	Mulch tillage (1991–1995) then no-till (1996–2004) with a corn–soybean–wheat (*Triticum aestivum* L.) rotation, with either hairy vetch [*Vicia villosa* Roth] (1994–1995) or red clover (*Trifolium pretense* L.) (1996–2002) cover crop following wheat	N: 150 kg ha^{-1} for corn. 101 kg ha^{-1} for wheat. Lime, P, and K: by soil test	8.7 Mg ha^{-1} for corn, 2.5 Mg ha^{-1} for soybean, and 4.0 Mg ha^{-1} for wheat	Planting tractor (4800 kg); self-propelled sprayer (5200 kg); combine (10,800 kg empty; 14,400 kg full of grain)
CRP	Initiated as a mixture of grasses (i.e. orchard [*Dactylis glomerata* L.], smooth brome [*Bromus inermis* Leyss.], timothy [*Phleum pratense* L.], and tall fescue [*Festuca arundinacea* Schreb.]) and a legume (i.e. alfalfa [*Medicago sativa* L.]) drilled in the spring of 1991. In March of 1992 additional legumes (i.e. hairy vetch, red clover, lespedeza [*Lespedeza striata* (Thunb.) Hook. & Arn.], and birdsfoot trefoil [*Lotus corniculatus* L.]) were over-seeded	None	None	Mowing tractor (4800 kg)

[a] Tillage system that targets maximum retention of crop residues (30% or more) on the soil surface.

found in production fields. For the CRP plots where no crop rows were present, penetrometer readings were collected at a corresponding distance from the edge of the plot.

At each sampling location (CS $\times$ LP), CI profiles were obtained using five recording ASAE-standard large-cone penetrometers (ASABE, 2008a) mounted to a single hydraulically driven frame similar to the device described by Raper et al. (1999). The in-line series of penetrometers was oriented perpendicular to the row direction so that one reading was obtained over each of rows 6 and 7, one reading from the row middle between rows 6 and 7, and two readings from midway between the row middle and the rows. A second set of measurements was taken within 10 m of the first set, providing a total of 10 profiles (or penetrometer insertions) for each CS $\times$ LP sampling location.

Several steps were required to process raw CI data for further analysis. The 10 CI profiles obtained at a location were averaged to a single profile for that location. The raw CI data obtained on finer depth increments were transformed to a standard 0.5-cm depth increment by calculating the mean of all data falling within the increment. So that CI analysis could be conducted in parallel with BD and WC analyses, the CI data were further averaged to the same 10-cm depth sampling increments used for those parameters, as described in the next section. This procedure eliminated CI data from the surface to 5 cm depth; however, we judged this to not affect the overall information content of the analysis dataset. In our previous work on similar soils (Chung et al., 2006), as well as in other published reports characterizing variability in CI profiles (Grunwald et al., 2001; Gorucu et al., 2006) CI from 0 to 5 cm was consistently well-represented as a linearly increasing function of depth and contained no information regarding compacted layers.

3.3. Soil sampling

Soil core samples were collected for BD and WC analyses at the same time as penetrometer data collection. A single 4-cm diameter soil core sample was taken at each treatment location, in the interrow between rows 5 and 6 from the north side of the plots. The cores were segmented into 5 layers: 5–15 cm, 15–25 cm, 25–35 cm, 35–45 cm, and 45–55 cm. Sampling for BD and WC was conducted on these 10-cm increments so data could also be used for a separate study evaluating an on-the-go sensor (Chung et al., 2006). The core segments were each sealed separately in a plastic bag on site. Samples were oven-dried at 105 °C for 24 h to determine WC. Bulk density was calculated using field-sampled soil mass, water content, and sample volume.

3.4. Data analysis

Data were analyzed in a split–plot treatment arrangement with CS as the main plot and LP as the split–plot. Because LP was not randomized, a repeated-measures analysis (Littell et al., 2002) was used to assess the response variables of CI, BD, and WC using PROC MIXED in SAS (SAS Institute Inc., 2005). Mean separations using least significant difference (LSD) were determined for treatment effects when *F*-tests were significant at *P* values $\leq$0.05, unless otherwise noted. Significant CS $\times$ LP interaction effects were analyzed using the SLICE option within the LSMEANS procedure. The SLICE option partitions the interaction of two factors so each factor can be tested at different levels of the other factor (Schabenberger and Pierce, 2002; SAS Institute Inc., 2005). Analyses evaluated the effects of CS and LP on profile-mean CI, BD, and WC. Then, independent analyses were conducted for each of the five depth intervals.

For further analysis five profile-level response variables were calculated for the 5–55 cm profile. These included maximum CI (Max CI), depth to maximum CI, depth to 2 MPa, and the thickness of the layer with CI greater than 2 MPa. The two 2 MPa measures were included because this is often given as a threshold level above which root growth is significantly inhibited (e.g., Taylor and Gardner, 1963). In addition, we calculated another whole-profile CI index that incorporated both CI magnitude and depth. Based on the premise that compaction near the surface affects root growth more than deep compaction, CI values within a profile were weighted by an ideal root distribution function (Kiniry et al., 1983). This new measurement we called the root distribution weighted CI (RDW CI). The index was calculated as the weighted average over the CI measurement depth. This approach is similar to the procedure used by Scrivner et al. (1985) when generating a depth weighted soil productivity index.

Statistical analysis for these five profile variables, including mean separation and identification of interaction differences, proceeded as described above. For some plots CI readings never reached 2 MPa and therefore values for the response measurements of depth to 2 MPa and thickness of 2 MPa were missing. Compared to the total 9 plots per CS, these measurements were available in only 3, 2, 8, and 2 plots for MTCS, NTCS, NTCSW, and CRP, respectively. Compared to the total 12 plots per LP, the measurements were available in only 4, 5, and 6 plots for footslope, backslope, and summit, respectively. With this level of missing data, the analysis of variance and mean separation could not be performed. For these variables, means are provided to give the level of differences for this particular study location, with no inference to other locations implied.

4. Results and discussion

4.1. Compaction by soil depth

Analysis of variance results for the response variables of CI, BD, and WC are presented in Table 3. Main effect means by CS and LP are provided along with mean separation indicators when significance was found. Significant two-way interactions of the treatment factors on these three profile-mean response variables are presented in Figs. 2–4.

Profile-average CI differed by CS at the footslope LP (Fig. 2), with CI for the NTCSW CS significantly greater than the others. Runoff downslope and lateral flow seepage causes this LP to stay wetter for longer periods during the spring and early summer. Such conditions would increase vulnerability to compaction during this time when planting and spraying operations are done. Yet these results indicate that only the NTCSW CS caused significant

Table 3
Analysis of variance and main effect means for mean cone index, mean bulk density, and mean soil water content over the soil profile.

Source of variation	df	ANOVA $P > F$		
		CI	BD	WC
Block	2	–	–	–
Cropping system (CS)	3	<0.01	0.12	0.52
Landscape position (LP)	2	0.17	<0.01	<0.01
CS × LP	6	0.13	0.23	0.53
Main effect means		MPa	g/cm^3	%
Cropping system				
MTCS		1.44 bc	1.40 a	40.4 a
NTCS		1.25 ab	1.37 a	39.8 a
NTCSW		1.60 c	1.41 a	39.6 a
CRP		1.18 a	1.41 a	40.5 a
Landscape position				
Summit		1.40 b	1.36 a	39.2 a
Backslope		1.27 a	1.42 b	41.4 b
Footslope		1.43 b	1.41 b	39.6 a

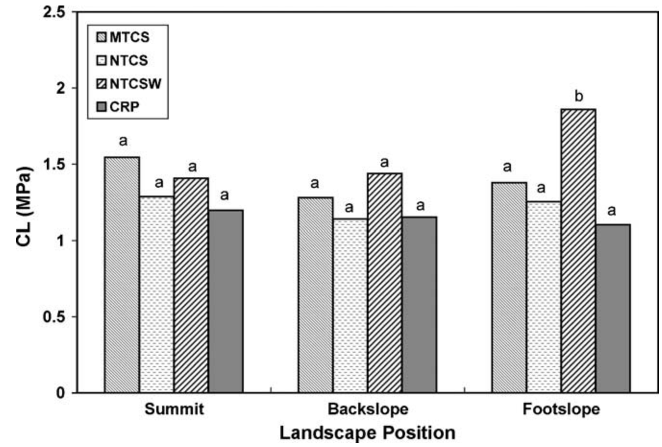

Fig. 2. Average cone index from 5 to 55 cm depth as affected by cropping system and landscape position. MTCS: Mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system. Within a landscape position, bars followed by the same letter are not significantly different.

footslope compaction. For this system the winter cover crop was usually killed by herbicides two to three weeks before corn planting, which resulted in a heavy mat of plant residues blanketing the soil and creating a barrier from the drying influences of wind and solar energy. Relative to the other grain CS, the NTCSW system remained wetter longer, especially in the lower parts of landscape (M.R. Volkmann, field technician, personal communication). These conditions were present for many years, requiring corn planting in wet soils that resulted in uneven corn stands (unpublished data). Others have noted that soils with heavy-textured sub-soils and thin topsoil are prone to compaction when mechanical operations are conducted under moist conditions (Anderson and Cassel, 1984).

We conclude planting and spraying traffic at this time with this no-tillage system was the source of greater CI, especially for the footslope position. In this situation, the compaction problem was only partly due to no-tillage management, as often found in other research and reviewed by Hamza and Anderson (2005). For this poorly drained landscape the addition of cover crops extended wet soil conditions in the springtime, resulting in greater susceptibility to soil compaction. This is in contrast to research on other soil types where cover crops have been found to prevent or ameliorate soil compaction (Raper et al., 2000).

The effects of CS on CI, BD, and WC are presented for the five soil depths in Fig. 3. An increase in soil strength due to grain CS (MTCS, NTCS, and NTCSW) was evidenced in the top two soil depths. In the third soil depth, this trend continued for two grain CS (MTCS and NTCSW). Conversely, CI was least with CRP and varied little through the profile. Low CI values with CRP would be expected since this system was in perennial grasses and was only trafficked when mowed every other year. Of the grain CS, CI was greatest with the NTCSW CS, averaging 1.97 MPa in the 5–25 cm depth. These high values of CI indicate a soil environment that could inhibit crop root growth (Taylor and Gardner, 1963). As discussed previously, we attribute the increased soil strength in this system to springtime planting traffic on soils that stayed relatively wetter than the other CS because of the cover crop and heavy plant residues.

For BD, only one significant difference was observed between CS using the method we employed. At the 45–55 cm depth NTCS BD was significantly less than CRP BD. However, it should be emphasized that the BD measurements from this study came from one profile core from each experimental location (or three cores per CS × LP treatment), using a methodology that is not as precise as other more intrusive BD methods. A more rigorous BD

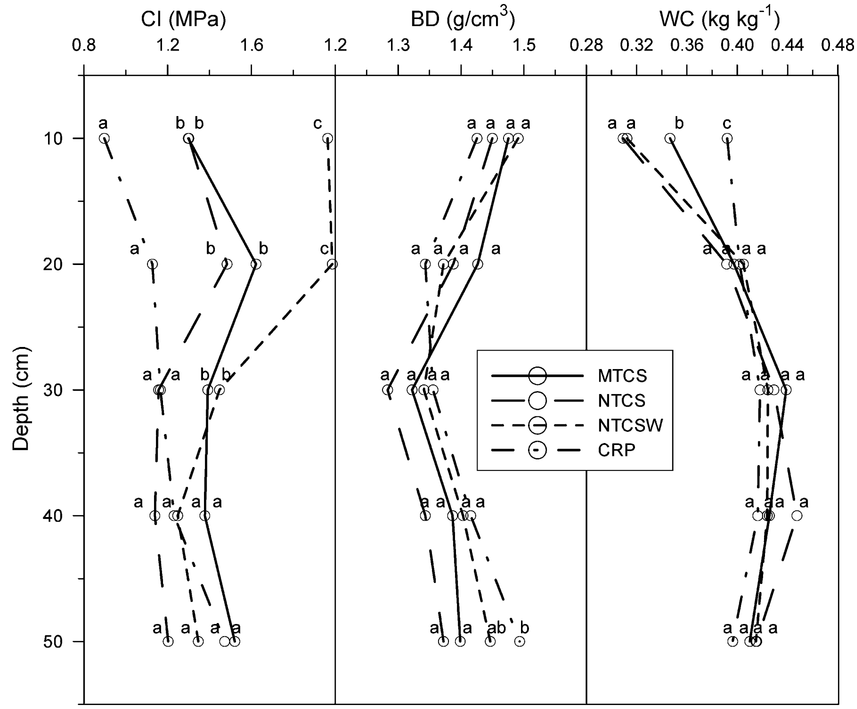

Fig. 3. Cone index (CI), soil bulk density (BD), and soil water content (WC) as affected by cropping system. MTCS: Mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system. Independent analyses were conducted for each sampling depth, and within each depth points followed by the same letter are not significantly different.

evaluation was not possible due to the requirement to not overly disturb these long-term research plots. In contrast, a total of 30 probe insertions were obtained to represent the CI of each treatment evaluated, reinforcing the value of using cone penetrometry for assessing compaction trends over larger areas.

Soil water content differences by CS were only seen at the shallow (5–15 cm) depth. The CRP system had the highest and the no-till grain CS (NTCS and NTCSW) had the lowest WC. Wetter conditions under the CRP could be expected since the perennial grasses provided a sod-like surface and cover from wind and solar drying. Additionally, this system had been shown to have greater aggregate stability and infiltration rates than the grain CS (Jung et al., 2007). Because the grain CS plots evaluated were those that had previously been cropped to corn and there was no cover crop

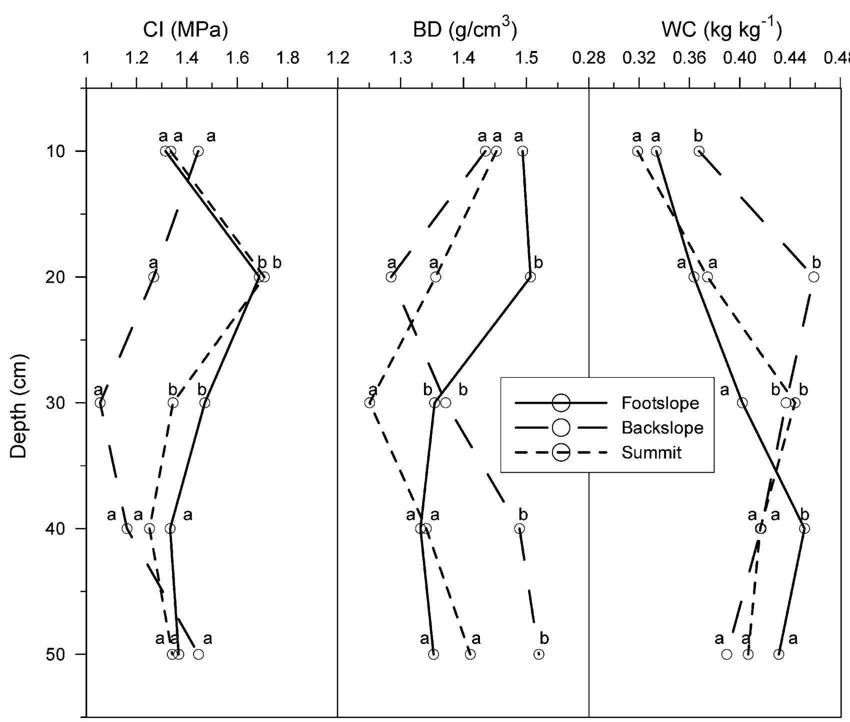

Fig. 4. Cone index (CI), soil bulk density (BD), and soil water content (WC) as affected by landscape position. Independent analyses were conducted for each sampling depth, and within each depth points followed by the same letter are not significantly different.

Table 4
Analysis of variance and main effect means for profile-level (0–55 cm) CI measurements. Measurements include maximum cone index (Max CI), depth to maximum cone index (depth to Max CI), depth to 2 MPa, thickness of 2 MPa, and an ideal-root distribution weighted CI (RDW CI index).

Source of variation	df	Max CI	Depth to Max CI	Depth to 2 MPa[a]	Thickness of 2 MPa[a]	RDW CI index
Block	2	–	–	–	–	–
Cropping system (CS)	3	<0.01	<0.01	na	na	0.02
Landscape position (LP)	2	0.78	0.02	na	na	0.68
CS × LP	6	0.48	<0.01	na	na	0.34
Main effect means		MPa	cm	cm	cm	MPa
Cropping system						
MTCS		1.99 a	34.9 b	25.5	8.0	1.24 b
NTCS		1.71 a	18.1 a	15.2	5.7	1.19 b
NTCSW		2.44 b	15.7 a	9.9	11.9	1.68 c
CRP		1.68 a	44.4 b	48.5	6.5	0.94 a
Landscape position						
Summit		2.01 a	24.5 a	18.4	8.2	1.28 a
Backslope		1.97 a	33.8 b	25.1	7.5	1.21 a
Footslope		1.89 a	26.5 ab	11.8	14.2	1.30 a

[a] Unable to complete analysis of variance and perform valid mean separation because of excessive missing data. Out of a potential $n = 9$ for cropping system, $n = 3, 2, 8$, and 2 for MTCS, NTCS, NTCSW, and CRP, respectively. Out of a potential $n = 12$ for landscape position, $n = 6, 5$, and 4 for summit, backslope, and footslope, respectively.

after corn in the NTCSW system, the amount of residue on the soil surface (although not measured) would have been somewhat similar between the grain CS.

In other studies CI has often been positively related to BD (e.g., Sojka et al., 2001; Lampurlanes and Cantero-Martinez, 2003). However we found no correlation between BD and CI ($r = 0.16$). This may have been due to the relatively low precision of the BD measurements we obtained using the core method. Although a decrease in soil pore space (and concomitant BD increase) is the most often noted manifestation of compaction, decreased pore size or reduced pore continuity may result even if total pore space does not change (Johnson and Bailey, 2002). As these are important effects of compaction that can restrict plant growth due to soil water being held more tightly, BD alone has been described as insufficient for accurate assessment of compaction-induced changes (Lipiec and Hatano, 2003).

We found CI to be weakly and significantly correlated with WC ($r = -0.36$) over the soil profile. Other researchers (e.g., Busscher et al., 1997; Lampurlanes and Cantero-Martinez, 2003) have also reported negative relationships between WC and CI. When the top two depths were examined alone, WC and CI were more strongly correlated ($r = -0.52$). This is similar to the finding of Sojka et al. (2001), who reported strong relationships between WC and CI when data were segregated by depth interval but only weak relationships with data from a 0.6 m soil profile.

Cone index, BD, and WC also varied within the soil profile in different ways over the landscape (Fig. 4). While CI for the summit and footslope were similar at all soil depths, CI at the backslope position was considerably different. At the backslope the high-clay content claypan horizon is nearer the surface (Table 1). Therefore, water content is typically higher and BD lower for the top 30 cm of claypan backslope soils (Jiang et al., 2007a; Jung et al., 2008), when compared to summit or footslope LP. This relationship can be verified by examining the top 30 cm of the BD and WC panels of Fig. 4. The WC and BD differences undoubtedly contributed to the lower CI in the top 30 cm of soil at the backslope position. Below 30 cm, differences in CI between the LP were minor, even with a greater BD measured at the backslope and slightly higher WC at the footslope. Soil properties other than BD and WC may be important for interpreting CI measurements on claypan soils. These include amount and quality of organic carbon, complexation of organic carbon with clay and the associated effects on soil physical properties (Dexter et al., 2008), soil structure below the tillage zone, and secondary chemical precipitates (such as Fe-Mg-oxide nodules). However, we presume such landscape-dependent properties would be relatively stable over the duration of this study.

4.2. Whole-profile compaction measures.

Analysis of variance results for the response variables of Max CI, depth to Max CI, depth to 2 MPa, thickness of 2 MPa, and RDW CI index are presented in Table 4. Main effect means by CS and LP are provided along with mean separation indicators when analysis of variance showed significance, except for depth to 2 MPa and thickness of 2 MPa (because of missing data as described above). The NTCSW CS had a higher Max CI than the other systems (Table 4). This outcome, also seen in Fig. 3 for the 5–25 cm depth was discussed previously. Cropping system differences in depth to maximum CI were only significant at the backslope position (Fig. 5), where depth to maximum CI was greatest for the CRP and MTCS systems. Although not significant, the trend of greater depth to maximum CI with CRP was also seen at the summit and footslope LP. Thus, not only did the CRP system have the lowest soil strength, but the location of the maximum soil strength was deeper in the soil profile.

For the backslope position, the depth of maximum CI for the MTCS system was equivalent to CRP and much deeper than the

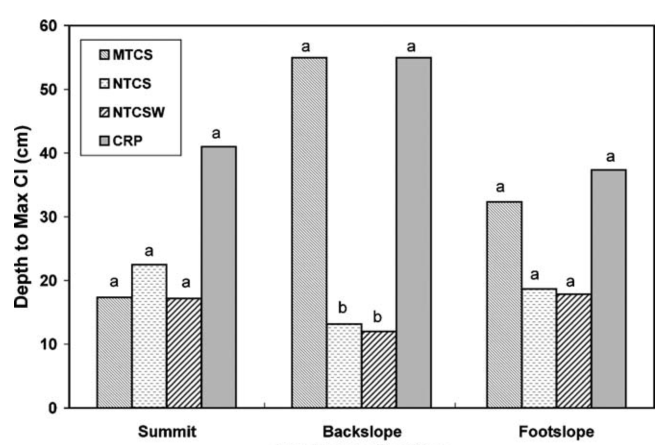

Fig. 5. Depth to maximum cone index (Max CI) as affected by cropping system and landscape position. MTCS: Mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system. Within a landscape position, bars followed by the same letter are not significantly different.

other grain CS. A similar but non-significant trend was also observed at the footslope position. Although the depth to the maximum CI was deeper for this grain CS, the maximum CI value was not different than the other grain CS. This outcome pointed out the need for a compaction index that would take into account both the magnitude of the CI as well as its location within the profile, leading to the development of the RDW CI index (discussed later).

As explained, the depth to 2 MPa and thickness of 2 MPa variables had a number of missing values and therefore statistical analysis of the means was not possible (Fig. 6). For the MTCS system, a CI of 2 MPa was only reached at the summit and backslope LP. Whereas this 2 MPa layer was shallow and over 10 cm in thickness at the summit, it was significantly deeper in the profile (~50 cm) and only 3 cm thick at the backslope position. As stated, for this LP either tillage helped remediate soil compaction or compaction did not develop to the same extent because the soils were drier during tractor operations. For the NTCS system, a CI of 2 MPa was only reached at the summit and footslope, and was generally found in the top 20 cm of soil. The NTCSW system was the only system that reached 2 MPa at all LP. In this system the depth to 2 MPa was shallow and the thickness of the compacted layer was 8 cm or more. At the footslope position the thickness of the 2 MPa layer was over 16 cm. These findings support the earlier discussion that lower claypan soil LP were most vulnerable to compaction from cropping, especially when crop residues were maintained on the soil surface.

Results with the RDW CI index are displayed in Fig. 7. While treatment influences were qualitatively similar to those already presented, this index removes the ambiguity that arises with varying CI values at different soil depths and with different compaction zone thicknesses. Clearly the RDW CI index was

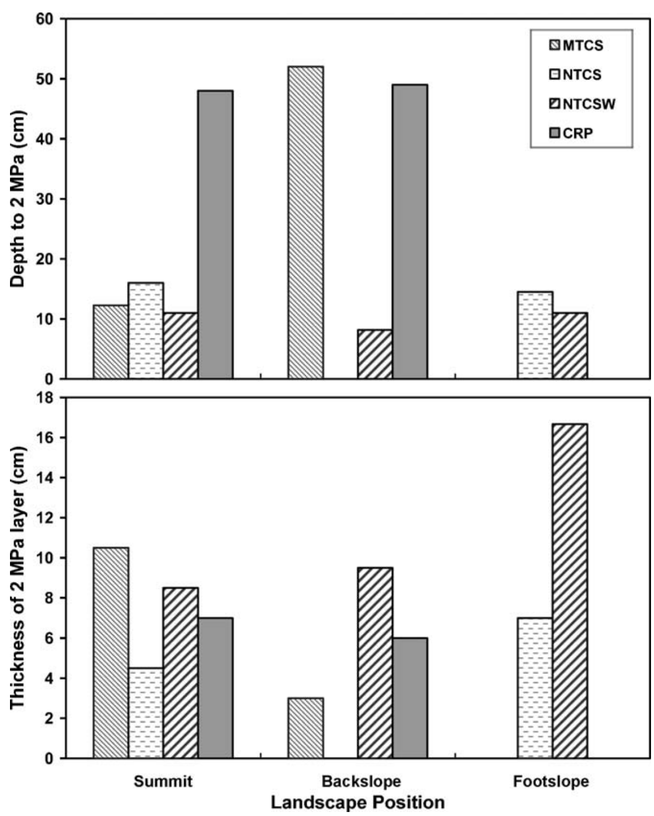

Fig. 6. Depth to 2 MPa (top) and thickness of the 2 MPa layer (bottom) as affected by cropping system and landscape position. Mean separation not conducted because of missing data. MTCS: Mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system.

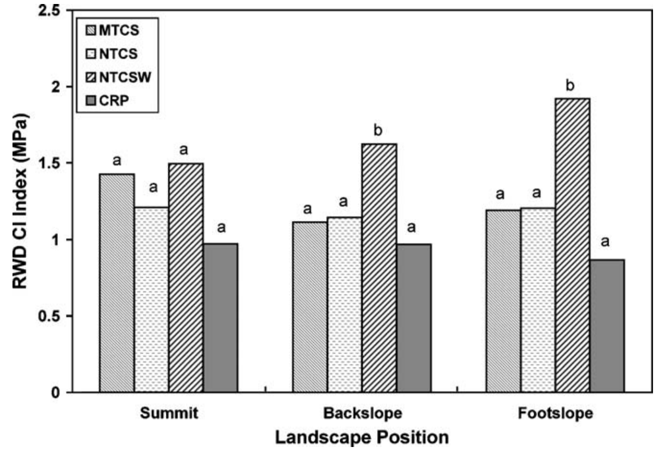

Fig. 7. Ideal-root distribution weighted cone-index Index (RDW CI index) as affected by cropping system and landscape position. RDW CI is calculated as a weighted-average CI over the profile, where the weighting function is from an ideal root distribution function. MTCS: Mulch tillage corn–soybean rotation; NTCS: no-till corn–soybean; NTCSW: no-till corn–soybean–wheat rotation; CRP: conservation reserve program system. Within a landscape position, bars followed by the same letter are not significantly different.

highest for the NTCSW at the footslope and backslope positions. Reasons for including a perennial legume cover crop in the NTCSW system were to protect the soil from erosion, increase soil carbon and nitrogen, and decrease nitrogen fertilizer inputs. Though commendable goals, this system created soil compaction issues for these poorly drained soils. Success of this type of no-till system may require adjustments. One strategy currently being explored is to remove the cover as a hay or haylage crop a few weeks prior to corn planting, allowing for better drying of the seedbed and improved planting conditions.

5. Conclusions

This study was conducted to evaluate the effects of CS, LP, and their interactions on soil compaction expressed in terms of CI. Soil compaction is both management (e.g., vehicular traffic, plant residue, tillage, rotation) and landscape dependent, and as such interactions are likely to occur. This investigation revealed interactions between management practices and claypan soil LP. When managed in no-till with cover crops, the lower portions of the claypan landscape exhibited persistently wet soils when spring operations needed to be performed. This resulted in CI levels that may reduce grain yield. As such, this is not a suitable practice for claypan soils, unless the cover crop can be removed in the spring to facilitate drying before planting operations, or occasional tillage can be employed to remediate compaction that develops. Another approach would be to put footslope areas of the landscape that do not dry as quickly into a management system that requires little or no trafficking in the spring and early summer (e.g., CRP, perennial hay crop, bioenergy crop). However this recommendation is unlikely to be acceptable to many farmers since these same lower landscape soils often produce the highest yields and therefore are the most profitable in the grain production system (Massey et al., 2008). Farmer education programs should include information about the conditions where compaction may result, both when no-till and tillage practices are used.

Compaction in the upper soil layers of CRP in this study was less than the other CS over all LP due to much less traffic and perennial grass sod that provided resistance to compaction when traffic did occur. For fields or field areas that have already been experienced severe erosion and grain productivity has been lost, CRP or a perennial hay crop can help prevent further degradation (including compaction), and is a logical first step for remediation of these soils. In many cases, fields already converted to CRP were selected on this very basis.

Understanding the interactions of CS and soils over varying landscapes is crucial to developing soil and crop management practices that will maintain optimal crop growing conditions. These findings help bring to light where in claypan soil landscapes, given certain types of grain crop management, compaction is more likely to have occurred. These areas could be targeted for further soil strength testing and then remediation actions taken, such as specific tillage practices assigned to compaction-affected parts of the landscape.

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References

Allmaras, R.R., Kraft, J.M., Miller, D.E., 1988. Effects of soil compaction and incorporated crop residue on root health. Ann. Rev. Phytopath. 26, 219–243.
Anderson, S.H., Cassel, D.K., 1984. Effect of soil variability on response to tillage of an Atlantic coastal plain ultisol. Soil Sci. Soc. Am. J. 8, 1411–1416.
ASABE, 2008a. Standard S313.3: Soil Cone Penetrometer. ASABE, St. Joseph, MI.
ASABE, 2008b. Engineering practice 542: Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. ASABE, St. Joseph, MI.
Baer, J.U., Anderson, S.H., 1997. Landscape effects on desiccation cracking in an Aqualf. Soil Sci. Soc. Am. J. 61, 1497–1502.
Bengough, A.G., Mullins, C.E., 1990. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. J. Soil Sci. 41, 341–358.
Blanco-Canqui, H., Gantzer, C.H., Anderson, S.H., Alberts, E.E., Ghidey, F., 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci. Soc. Am. J. 66, 1596–1602.
Braunack, M.V., 1986. The residual effects of tracked vehicles on soil surface properties. J. Terramech. 23 (1), 37–50.
Bray, R.H., 1935. The origin of horizons in claypan soils. Am. Soil Surv. Asssoc. Bull. 16, 70–75.
Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E., 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil Tillage Res. 43, 205–217.
Canarache, A., 1991. Factors and indices regarding excessive compactness of agricultural soils. Soil Tillage Res. 19, 145–164.
Cassel, D.K., 1982. Tillage effects on soil bulk density and mechanical impedance. In: Unger, P.W., Van Doren, D.M. (Eds.), Predicting Tillage Effects on Soil Physical Properties and Processes. ASA Spec. Publ. 44. ASA, SSSA, Madison, WI, pp. 45–67.
Chung, S.O., Sudduth, K.A., Hummel, J.W., 2006. Design and validation of an on-the-go soil strength profile sensor. Trans. ASABE 49, 5–14.
Dexter, A.R., Richard, G., Arrouays, D., Czyz, E.A., Jolivet, C., Duval, O., 2008. Complexed organic matter controls soil physical properties. Geoderma 144, 620–627.
Ehlers, W., Popke, V., Hesse, F., Bohm, W., 1983. Penetration resistance and root growth of oats in tilled and untilled loam soil. Soil Tillage Res. 3, 261–275.
Elbanna, E.B., Witney, B.D., 1987. Cone penetration resistance equation as a function of the clay ratio, soil moisture content and specific weight. J. Terramech. 24 (1), 41–56.
Flowers, M., Lal, R., 1998. Axle load and tillage effect on soil physical properties and soybean grain yield on a mollic ochraqualf in Northwest Ohio. Soil Tillage Res. 48, 21–35.
Ghidey, F., Blanchard, P.E., Lerch, R.N., Kitchen, N.R., Alberts, E.E., Sadler, E.J., 2005. Measurement and simulation of herbicide transport from the corn phase of three cropping systems. J. Soil Water Conserv. 60, 260–273.
Gorucu, S., Khalilian, A., Han, Y.J., Dodd, R.B., Smith, B.R., 2006. An algorithm to determine the optimal tillage depth from soil penetrometer data in coastal plain soils. Appl. Eng. Agric. 22, 625–631.
Grunwald, S., Rooney, D.J., McSweeney, K., Lowery, B., 2001. Development of pedotransfer functions for a profile cone penetrometer. Geoderma 100, 25–47.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes, and possible solutions. Soil Tillage Res. 82, 121–145.
Jiang, P., Anderson, S.H., Kitchen, N.R., Sadler, E.J., Sudduth, K.A., 2007a. Landscape and conservation management effects on hydraulic properties on a claypan-soil toposequence. Soil Sci. Soc. Am. J. 71, 803–811.
Jiang, P., Anderson, S.H., Kitchen, N.R., Sudduth, K.A., Sadler, E.J., 2007b. Estimating plant-available water capacity for claypan landscapes using apparent electrical conductivity. Soil Sci. Soc. Am. J. 71, 1902–1908.
Johnson, C.E., Bailey, A.C., 2002. Soil compaction. In: Upadhyaya, S.K., Chancellor, W.J., Perumpral, J.V., Schafer, R.L., Gill, W.R., VandenBerg, G.E. (Eds.), Advances in Soil Dynamics, vol. 2. American Society of Agricultural Engineers, St. Joseph, MI, pp. 155–178.
Jung, W.K., Kitchen, N.R., Sudduth, K.A., Anderson, S.H., 2006. Spatial characteristics of claypan soil properties in an agricultural field. Soil Sci. Soc. Am. J. 70, 1387–1397.
Jung, W.K., Kitchen, N.R., Anderson, S.A., Sadler, E.J., 2007. Crop management effects on water infiltration for claypan soils. J. Soil Water Conserv. 62, 55–63.
Jung, W.K., Kitchen, N.R., Sudduth, K.A., Kremer, R.J., 2008. Crop management and landscape impact on claypan soil quality properties. Soil Sci. Plant Nutr. 54, 960–971.
Kiniry, L.N., Scrivner, C.L., Keener, M.E., 1983. A soil productivity index based upon predicted water depletion and root growth. Res. Bull. 1051. Univ. of Missouri–Columbia, College of Agriculture, Columbia, MO.
Lampurlanes, J., Cantero-Martinez, C., 2003. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. Agron. J. 95, 526–536.
Lerch, R.N., Sadler, E.J., Kitchen, N.R., Sudduth, K.A., Kremer, R.J., Myers, D.B., Baffaut, C., Anderson, S.H., Lin, C.H., 2007. Overview of the Mark Twain Lake/Salt River Basin conservation effects assessment project J. Soil Water Conserv. 63, 345–359.
Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop yields. Geoderma 116, 107–136.
Lipiec, J., Ferrero, A., Giovanetti, V., Nosalewicz, A., Turski, M., 2002. Response of structure to simulated trampling of woodland soil. Adv. Geoecol. 35, 301–352.
Littell, R.C., Stroup, W.W., Freund, R.J., 2002. SAS for Linear Models, 4th ed. SAS Institute Inc., Cary, NC.
Lowery, B., Schuler, R.T., 1994. Duration and effects of compaction on soil plant growth in Wisconsin. Soil Tillage Res. 29, 205–210.
Lutz, A., Menge, J., O'Connel, N., 1986. Citrus root health: hardpans, claypans and other mechanical impedances. Citrograph 71, 57–61.
Massey, R.E., Myers, D.B., Kitchen, N.R., Sudduth, K.A., 2008. Profitability maps as input for site-specific management decision making. Agron. J. 100, 52–59.
Mosaddeghi, M.R., Hajabbasi, M.A., Hemmat, A., Afyuni, M., 2000. Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. Soil Tillage Res. 55, 87–97.
Motavalli, P.P., Anderson, S.H., Pengthamkeeri, P., 2003. Suface compaction and poultry litter effects on corn growth, nitrogen availability, and physical properties of a claypan soil. Field Crops Res. 84 (3), 303–318.
Mulqueen, J., Stafford, J.V., Tanner, D.W., 1977. Evaluation of penetrometers for measuring soil strength. J. Terramech. 14, 137–151.
Myers, D.B., Kitchen, N.R., Sudduth, K.A., Miles, R.J., Sharp, R.E., 2007. Soybean root distribution related to claypan soil properties and apparent soil electrical conductivity. Crop Sci. 47, 1498–1504.
Ngunjuri, G.M.N., Siemens, J.C., 1995. Wheel traffic effects on corn growth. Trans. ASAE 38, 691–699.
Raper, R.L., Reeves, D.W., Burt, E.C., 1998. Using in-row subsoiling to minimize soil compaction caused by traffic. J. Cotton Sci. 2, 130–135.
Raper, R.L., Washington, B.H., Jarrell, J.D., 1999. A tractor-mounted multiple-probe soil cone penetrometer. Appl. Eng. Agric. 15, 287–290.
Raper, R.L., Reeves, D.W., Burmester, C.H., Schwab, E.B., 2000. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Appl. Eng. Agric. 16, 379–385.
SAS Institute Inc., 2005. SAS Online Document. V9.1.3 SAS Institute Inc., Cary, NC.
Schabenberger, O., Pierce, F.J., 2002. Contemporary Statistical Models for the Plant and Soil Science. CRC Press, Boca Raton, FL.
Scrivner, C.L., Conkling, B.L., Koenig, P.G., 1985. Soil productivity indices and soil properties for farm-field sites in Missouri. Missouri Agric. Exp. Stn. Publ. EC0947. Univ. of Missouri–Columbia, Columbia, MO.
Soane, B.D., Van Ouwerkerk, C. (Eds.), 1994. Soil Compaction in Crop Production. Developments in Agricultural Engineering Series, vol. 11. Elsevier Science, Amsterdam, Netherlands, p. 662.
Soane, B.D., Van Ouwerkerk, C., 1995. Implications of soil compaction in crop production for the quality of the environment. Soil Tillage Res. 35, 5–22.
Soil Survey Staff, 1981. Land resource regions and major land resource areas of the United States. USDA Agricultural Handbook 296. US Govt. Printing Office, Washington, DC.
Sojka, R.E., Busscher, W.J., Lehrsch, G.A., 2001. In situ strength, bulk density, and water content relationships of a *Durinodic Xeric Haplocalcid* soil. Soil Sci. 166, 520–529.
Stepniewski, W.J., Glinski, J., Ball, B.C., 1994. Effect of compaction on soil aeration properties. In: Soane, B.D., Van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Elsevier Science, Amsterdam, Netherlands, pp. 167–189.
Sweeney, D.W., Kirkham, M.B., Sisson, J.B., 2006. Crop and soil response to wheel-track compaction of a claypan soil. Agron. J. 98, 637–643.
Taylor, H.M., Gardner, H.R., 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96, 153–156.
Thompson, A.L., Gantzer, C.J., Anderson, S.H., 1991. Topsoil depth, fertility, water management, and weather influences on yield. Soil Sci. Soc. Am. J. 55, 1085–1091.

USDA-NRCS, 2000. Major land resource areas. USDA-Natural Resources Conservation Service, Washington, DC.

Wang, F., Fraisse, C.W., Kitchen, N.R., Sudduth, K.A., 2002. Site-specific evaluation of the CROPGRO-soybean model on Missouri claypan soils. Agric. Sys. 76, 985–1005.

Yang, J., Hammer, R.D., Thompson, A.L., Blanchar, R.W., 2003. Predicting soybean yield in a dry and wet year using soil productivity index. Plant Soil 250, 175–182.

Young, F.J., Geller, A.W., 1995. Soil Survey of Audrain County. National Cooperative Soil Survey, USDA-NRCS, Columbia, MO.