Using Cone Index Data to Explain Yield Variation Within a Field

N. E. Isaac[1], R. K. Taylor[2], S. A. Staggenborg[3], M. D. Schrock[2], D. F. Leikam[4]

[1]Agricultural and Biosystems Engineering, Iowa State University, 100 Davidson Hall, Ames, IA 50011, neisaac@iastate.edu

[2]Biological and Agricultural Engineering, Kansas State University, Manhattan, KS, 66506

[3]Northeast Area Extension Office, Kansas State University, Manhattan, KS, 66506

[4]Agronomy, Kansas State University, Manhattan, KS, 66506

Contribution No. 03-40-J Kansas Agricultural Experiment Station, Kansas State University.

Abstract

Three cone index (CI) penetration probes recorded to a depth of 76.2 cm (30 in.) and a soil sample was collected and analyzed for moisture content at 81 locations along a transect measuring approximately 323 m (1060 ft) in length. An average maize plant yield was assigned to each location based on hand harvested ears. The three probes at each location were averaged to obtain a single profile of CI versus depth. The first and second derivatives of CI with respect to depth were determined to indicate rapid changes in soil density and peaks in the CI data, which are indicative of hardpans. Average yield was compared to mean CI, maximum CI, depth of maximum CI, maximum CI rate of change, depth of maximum CI rate of change, CI peaks, depth to CI peaks, and established CI limits of 0.7, 1.4, and 2.0 MPa (100, 200, and 300 psi). The mean CI throughout the 76.2 cm (30 in.) profile best explained yield variation (r=-0.83). The maximum CI also correlated with yield, but to a lesser extent (r=-0.71). Maximum CI readings at or above 1.4 MPa (200 psi) resulted in below average yields for 89-percent of the readings exceeding this limit. No correlation was established between yield and soil density changes and depth of density changes or between yield and CI peaks and their depth of occurrence.

Keywords: Soil strength, Penetrometer, Clay layer, Hardpan, Compaction, Maize yield

Introduction

Grain yield variability within fields exists and can be mapped using precision farming equipment and software. Identifying the causes of yield variability within a field is expected to improve farming profitability by reducing inputs and/or increasing yield. Identifying the causes of yield variability has been challenging for crop producers and researchers because of the vast quantity and quality of data that must be collected, which requires a large investment of capital and time. Due to these challenges, researchers have typically studied a subset of the parameters known to influence yield variability, which include climate, topography, and soil chemical and physical properties. However, the proportionate influence of these parameters upon a plant's yield remains inadequately defined.

Management of a soil's physical properties is necessary for an ideal growing environment. Soil physical properties include soil strength, dry density, penetration resistance, porosity, and plasticity. Cone index (CI) is a measure of a soil's resistance to penetration and is regarded as an indicator of soil strength. Researchers have studied the spatial variation of cone index and its relationship to other soil physical properties. Fulton et al. (1996) researched the spatial variability of bulk density and CI and the economic feasibility of variable depth tillage in a Maury silt loam soil. Both factors are related to soil strength and quantify soil compaction. Results showed that dry bulk density and CI were possibly linked at the 30 and 45 cm (12 and 18 in.) depths, but not at 15 and 60 cm (6 and 24 in.) depths. They concluded that little correlation existed between bulk density and CI at high moisture contents (MC) (28-30% dry basis). Also, based on a root restricting CI value of 2 MPa (300 psi), variable depth tillage was expected to reduce fuel consumption by 50% compared to deep tillage for the entire field.

Hardpan layers in the soil profile are associated with peaks in the CI profile at shallow depths ((15 to 25 cm (6 to 12 in.)) and typically caused by traffic and tillage. Raper et al. (2000b) studied the spatial variation of hardpan depth as influenced by traffic, soil moisture, and elevation. They found two distinct peaks in the CI profile, one at a depth of approximately 20 cm (8 in.) labeled a hardpan, and a second at a depth of approximately 50 cm (20 in.) labeled a fragipan. Hardpan and fragipan depths were determined from the CI profile by locating the depth of the last data point in a series of at least three consecutive data points that exceeded 1 MPa (145 psi) and was greater than the previous value by 0.05 MPa (7 psi). They concluded that traffic decreased the depth of hardpan by 6.7 cm (3 in.) compared to non-trafficked soils. Soil moisture in the 0-15 cm (0-6 in.) layer closely correlated to depth of hardpan in trafficked soil and soil moisture in the 0-30 cm (0-12 in.) layer correlated closely with the depth of hardpan in non-trafficked soils. Elevation had no effect on the depth of hardpan in either trafficked or non-trafficked soils. They also concluded that the hardpan depth was somewhat spatially related and that use of site-specific technology could reduce the effects of a hardpan layer.

Other researchers have used CI data to prescribe tillage depth using CI magnitudes corresponding to root growth restriction (Fulton et al. (1996), Raper et al. (2000a), Wells et al. (2001), and Gorucu et al. (2001)). Root growth restriction has commonly been associated with a CI magnitude of 2 MPa (300 psi) (Fulton et al. (1996), Raper et al. (2000b), Gorucu et al. (2001), Coates (2001), and Aase et al. (2001)).

Gorucu et al. (2001) determined that soil texture had the biggest impact on cotton yield, especially in sandier soils with low clay content. Correct tillage depth was determined using soil electrical conductivity and cone penetration resistance. Cone index was measured to a depth of 45.7 cm (18 in.); measurements exceeding 2 MPa (300 psi) were considered root restricting and used to predict tillage depth. Electrical conductivity showed a strong positive correlation between seed cotton yield and corn yield, and was inversely related to predicted tillage depth, as determined by CI measurements.

Coates (2001) collected CI measurements in the spring, summer, and fall to a depth of 80 cm (31.5 in.). Cone index thresholds were established at 1.5 and 2 MPa (220 and 300 psi) as indicators of moderate and severe root growth retardation, respectively; analysis was based on the mean CI over the depth of the sample at each location. Results indicated that CI was seasonally dependent with largest values occurring in the fall because of drier soil and compaction due to approximately 1 m (40 in.) of irrigation water applied during the cotton growing season. The minimum tillage system studied did not contribute to increased soil compaction compared to conventional tillage.

Aase et. al. (2001) reported CI to 50 cm (20 in.) depth at 10 cm (4 in.) increments. Root growth was considered restricted at 2 MPa (300 psi) and ceased at 3 MPa (435 psi). Cone index related linearly to bulk density (Portneuf silt loam) and was influenced by soil MC; they deemed it unnecessary to correct CI for soil MC differences when comparing CI data between years because the MCs were statistically similar.

Few studies have attempted to show a relationship between CI parameters and yield. Wells et al. (2001) divided four different fields into cells for variable rate tillage application and yield analysis. The depth of the root restricting value (1.5 MPa (220 psi)) was used to prescribe the tillage depth. Five CI penetrations to a depth of 70 cm (27.5 in.) in 2 cm (0.8 in.) increments were made when the soil moisture content was near field capacity. Only the average maximum CI values in the tillage zone (≤ 40 cm (≤ 15.7 in.)) of each cell were used to determine a relationship between yield and CI. Overall, they found an inconsistent relationship between yield (corn and soybean) and the average maximum CI penetrations in the tillage zone. Correlation coefficients ranged from 0.09 to -0.65 in corn, and 0.31 to -0.29 in soybean. The large positive correlation in soybean between the average maximum CI and yield was not explained. They concluded that the inconsistent relationship might indicate that a soil needs to be compacted beyond 1.5 MPa (220 psi) before a strong and consistent correlation emerges. This is consistent with the generally accepted value of 2.0 MPa (300 psi) as a root restricting CI level (Fulton et al. (1996), Raper et al. (2000b), Gorucu et al. (2001), Coates (2001), and Aase et al. (2001)).

Bakhsh et al. (2000) investigated the relationship between yield data and various soil structure and quality parameters for a 22 ha (54 ac) field over a period of four years. GIS layers containing yield, soil type, and topographic data were overlaid to explain the spatial variability of yield. Results showed that tilth index, which is a function of bulk density, CI, organic matter, plasticity index, and uniformity constant, did not correlate to yield. Using stepwise regression analysis, plasticity index, CI, percent clay, and percent sand were correlated to yield for one (Ottosen clay loam) of the three soil types. Mean CI, recorded to 15 cm (6 in.), was inconsistently related among the four years of yield data for two (Ottosen clay loam and Harps loam) of the three soil types with correlation coefficients ranging from 0.67 to -0.79* (*5% level of significance), and uncorrelated to yield in the third soil type (Kossuth silty clay loam). They concluded that the interaction of soil type and topography influenced the yield variability.

Previous studies have demonstrated the use of CI data to determine soil physical properties, such as hardpan depth and root restricting values, and the application of CI data to variable depth tillage for either hardpan depth or root restricting values. No studies were found that related specific CI parameters and thresholds to individual plant yield variations within a field.

The objectives of this research were to:

1. Develop a procedure to derive CI parameters from CI data.
2. Use information obtained from cone penetrometer tests to explain maize yield variations within a field.

Methods

A 12-ha (30-acre) non-irrigated field near Manhattan, Kansas was selected. Corn was planted in 76 cm (30 in) rows on April 26, 2001 into stubble from the previous corn crop with a final stand of approximately 65 000 plants ha^{-1} (26,300 plants ac^{-1}). Approximately 80.8 cm (31.8 in.) of rainfall was recorded during the growing season, which was greater than normal by 20.4 cm (8.0 in.).

The experimental area within the field was selected based on discussions with the cooperating producer regarding field history, yield variability and topography. A transect consisting of a single row of corn was selected in the experiment area. The transect was 323-m (1,060-ft) long and contained 1620 plants with an average plant spacing of 0.20 m plant^{-1} (0.65 ft plant^{-1}). A combine equipped with a 6-row corn head was used to isolate the experiment transect (single row) by harvesting the adjacent rows. The field was harvested on September 27, 2001. As shown in Figure 1, along the transect the field gently undulates and levels toward a creek on the east edge of the field. The general elevation was measured with a Trimble AgGPS 132 GPS unit using the Coast Guard Beacon (305 Hz) for differential correction. The transect soil composition is initially at the west edge a Reading series (fine-silty, mixed, superactive, mesic Pachic Argiudolls) and then changes midway to an Ivan series (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) and Kennebec series (fine-silty, mixed, superactive, mesic Cumulic Hapludolls).

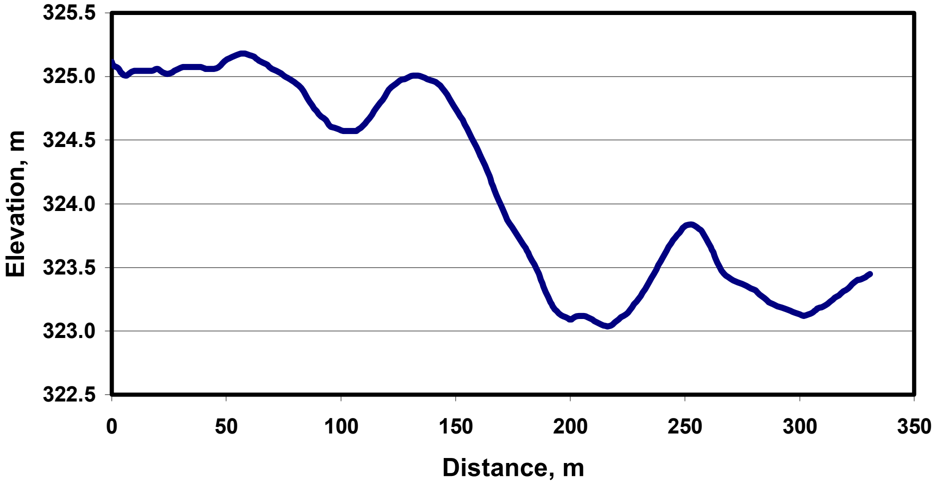

Figure 1. General elevation trend along the transect. The transect begins (zero distance) at the west and runs southwest to northeast.

The first plant on the southwest end of the transect (0 m distance), began at the edge of the turn rows approximately 18.3 m (60 ft) from the west edge of the field. This plant was the reference plant for establishing the location of each plant along the transect. The ear from each individual plant in the transect was picked, husked, and weighed on an electronic scale in the field. At every

20th plant, the ear was retained for hand-shelling to determine the actual grain weight and develop a shelling percentage for estimating the grain weight of the individual ears weighed in the field. The hand-shelled corn had an average moisture content of 15.5%. Finally, at every twentieth plant, three CI penetration probes recorded to a depth of 76 cm (30 in.) and one soil sample was taken. Each soil sample was divided into 15-cm (6 in.) layers and tested for MC (ASAE EP542, 2001). The soil MCs for the layers were assigned to point depths of 7.6, 23, 38, 53, and 69 cm (3, 9, 15, 21, and 27 in.). All data were entered into a spreadsheet for analysis.

Soil Moisture Determination and Bulk Density

Soil moisture was determined gravimetrically by oven-drying at 105° C for 24 hours (Hillel, 1980). Both dry basis (d.b.) and wet basis soil MCs were determined for the five depths at each location. The d.b. MCs ranged from 15.4 to 30.3 across all locations and depths. However, only three observations had d.b. MCs less than 20 percent. The five depths were averaged to determine a single MC at each location. The d.b. MC averaged 24.3 percent for the 81 locations with a minimum of 20.8 percent and a maximum of 27.0 percent.

The authors recognize that bulk density can influence CI measurements and grain yield. However, bulk density is more challenging to measure than CI and was not a part of this experiment's objectives and thus was not measured. Although bulk density can be a valuable soil measurement, some researchers have indicated that bulk density and CI are more correlated at low to moderate soil MCs and less correlated at high soil MCs. Ayers and Perumpral (1982) reported that bulk density did not have a large effect on CI at MCs above 15 percent d.b. for soil compositions of 50-percent clay and 50-percent sand. For 75 percent clay and 25 percent sand soil composition, bulk density did not affect CI at MCs above 20 percent d.b. Fulton et al. (1996) concluded that little correlation existed between bulk density and CI measurements at high soil MCs (28-30% d.b.) in a Maury silt-loam soil. ASAE standard EP542 (2001) recommends collecting CI measurements when the soil water content is near field capacity. Based on the previously cited MC results and average clay content in the field of approximately 25 percent (Reading, Ivan, and Kennebec series), we concluded that for this study CI measurements were not significantly influenced by bulk density.

Individual Plant and Average Location Yields

Plant spacing was used to estimate the effective area available for each plant to produce grain. The effective area of a plant was calculated as the rectangular area equidistant between the two adjacent plants and the row spacing (76.2 cm (30 in.)).

Plant yield was determined by dividing the grain weight (or estimated grain weight) of an ear by the corresponding effective area of the plant. This procedure was repeated for all plants in the transect. As expected, yield varied among adjacent plants due to irregular plant spacing. The yield for each sample location was determined by averaging the plant yield of 21 plants. This consisted of the plant at the location of interest and the 10 plants on both sides of this plant. The mean yield for the transect was 8.5 Mg ha^{-1} (127 bu ac^{-1}) and the mean yield of the 81 locations was 8.6 Mg ha^{-1} (128 bu ac^{-1}), both were similar to the field mean of 8.3 Mg ha^{-1} (124 bu ac^{-1}).

Cone Index Determination

A standard cone with a base area of 323 mm^2 (0.50 in^2.) was used to gather CI data (ASAE S313.3, 2001). The penetrometer was hydraulically driven at a penetration rate of 30 mm s^{-1} (72 in. min^{-1}) (ASAE EP542, 2001). A strain-gauge loadcell was used to measure the force required to penetrate the soil with the force signals sampled at 10 Hz and conditioned with a Calex MK160 signal-conditioning card. Depth was measured with a string potentiometer. Data were recorded with a Daqbook 100 and stored on a laptop computer.

Three penetration probes were recorded at each location, one in the center of the crop row and two located 15 cm (6 in.) on each side of the crop row. To correct for variations in sample time and depth for the three probes, the recorded CI data were interpolated to increments of 12.7-mm (0.5 in.) in depth using the inverse distance method (Equation 1).

$$CI_D = \frac{\sum_{i=1}^{n}\left(\frac{1}{|d_i|}\cdot CI_i\right)}{\sum_{i=1}^{n}\frac{1}{|d_i|}} \qquad (1)$$

Where:

CI_D is the calculated CI value at each depth increment;
D is the specified depth increment of 0, 12.7, 25.4, …, 762 mm (0, 0.5, 1, …, 30 in.);
CI_i is the recorded CI value at the ith position;
d_i is the distance of the recorded ith CI value from the depth increment;
n is the number of CI readings within a 12.7 mm (0.5 in.) range of the depth increment.

Only recorded CI readings within a 12.7 mm (0.5 in.) range of a specified depth were used to calculate the CI value at that specified depth, typically resulting in 8 points used. This calculation aligned the data from each probe at common depth increments. Data from the three probes were averaged at each depth increment to determine a single CI profile per sampling location. Data in the top 10 cm (4 in.) of the CI profile were removed to minimize soil surface effects of CI and CI rate of change spikes. After inspecting the profiles, three locations were removed from the data set because of CI measurement error, resulting in a final analysis of 78 locations.

Soil parameters of interest were determined from the CI profile at each location as were the first and second derivatives (dCI and d^{2}CI) of the CI values with respect to depth. The soil parameters of interest were: mean CI value across depths, maximum CI value, depth at which the maximum CI occurs, depth at which the maximum rate of CI change (max dCI) occurs, and the first depth at which the second derivative is a minimum (minimum d^{2}CI). These two parameters are shown on a CI profile in Figure 2. The dCI was calculated for each depth increment by subtracting the previous CI value from the next CI value and dividing by the distance between the previous and next CI value depths [2.5 cm (1 in.) for the interpolated data] and was used as an indicator of rapid soil density changes. The d^{2}CI was calculated in a similar fashion and used as an indicator of hardpans. Depths at which the CI values first exceeded 0.7, 1.4, and 2.0 MPa (100, 200, and 300 psi) were determined.

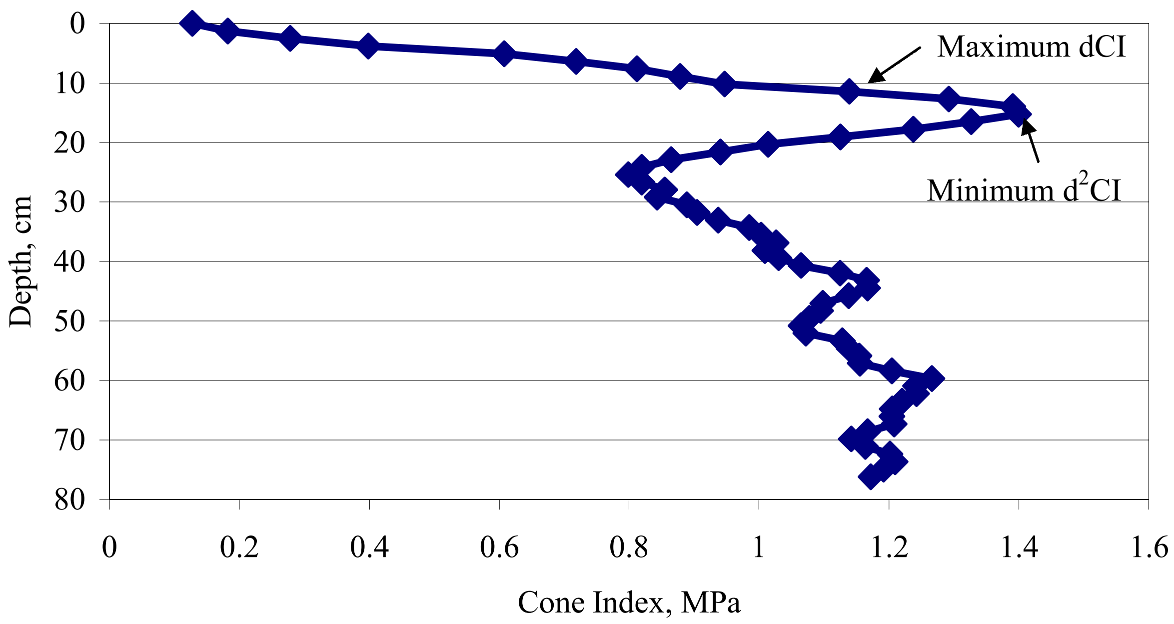

Figure 2. Example profile of CI versus depth with maximum dCI and minimum d^2CI shown.

TableCurve 2D (Jandel Scientific, AISN Software) was used to regress yield as a function of the soil parameters and determine the best-fit curve, R^2 coefficient, F statistic, and 90 percent confidence limits.

Results and Discussion

A strong negative correlation was found between yield and mean CI, maximum CI, and the depth to the maximum CI (r= -0.83, -0.71, and -0.65) (Table 1). Yield was not correlated with other soil parameters, with correlation coefficients ranging from 0.11 to -0.20. The negative relationship between yield and the mean and maximum CI values was expected, but the negative correlation with the depth to the maximum CI was unexpected. This relationship indicates that yield is greater when the maximum CI occurs closer to the surface. It is possible that this occurred because the maximum CI exceeded the previously cited root restricting 2 MPa (300 psi) threshold at only one of the 78 locations.

Table 1. Correlation coefficients for yield and soil parameters

	Mean CI	Max CI	Max CI Depth	Max dCI	Max dCI Depth	Min d^2CI	Min d^2CI Depth
Yield	-0.83	-0.71	-0.65	-0.16	0.11	-0.20	0.06
Mean CI		0.89	0.59	0.44	-0.14	-0.07	-0.02
Max CI			0.56	0.48	-0.02	-0.19	0.03
Max CI Depth				0.03	0.11	0.14	0.12
Max dCI					-0.17	-0.68	-0.13
Max dCI Depth						0.01	0.46
Min d^2CI							0.05

The mean CI for the 78 locations ranged from 0.56 to 1.36 MPa (81 to 197 psi) with an average of 0.94 MPa (137 psi) and yield ranged from 3.9 to 15.6 Mg ha^{-1} (58 and 232 bu ac^{-1}) with an average of 8.6 Mg ha^{-1} (128 bu ac^{-1}) (Fig. 3) (Table 2). In general, yield was greater for lower CI values. Comparing Figures 1 and 3 also indicates that mean CI and yield were most likely related to landscape position. The lower elevations at approximately 200 and 300 m along the transect (Fig. 1) corresponded to lower mean CI values and greater yield values.

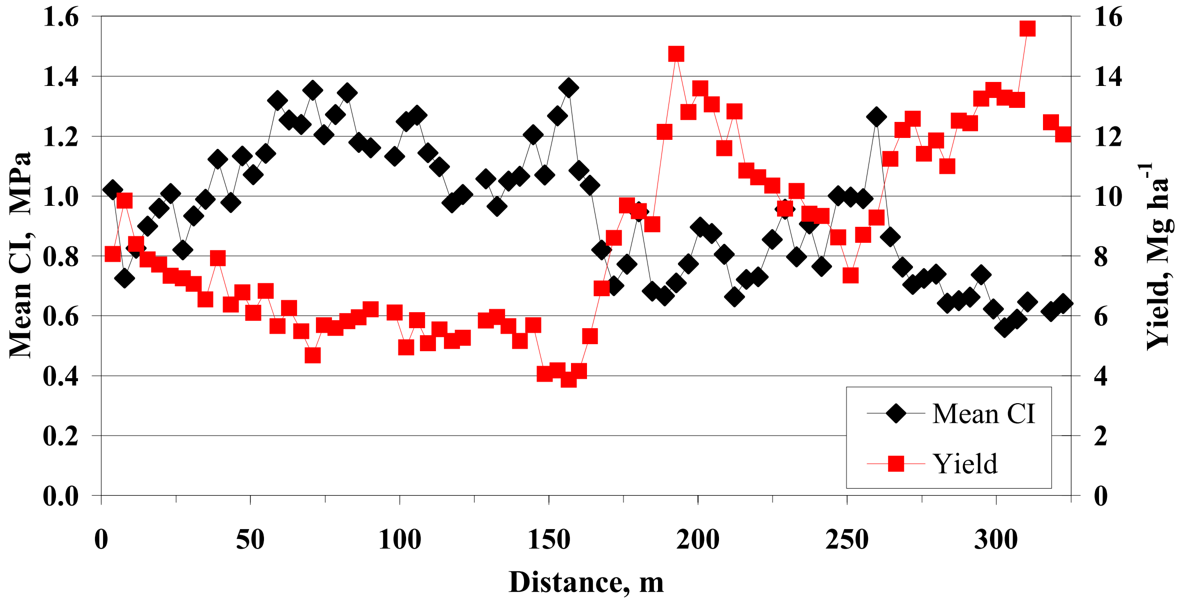

Figure 3. Mean CI and yield trends along the transect.

Table 2. Basic statistics for yield and soil parameters

	Minimum	Mean	Maximum	Std Dev.
Yield, Mg ha^{-1}	3.9	8.6	15.6	3.1
Mean CI, MPa	0.6	0.9	1.4	0.2
Max CI, MPa	0.8	1.4	2.2	0.3
Depth to Max CI, cm	15.2	57.1	76.2	21.7
Max dCI, MPa cm^{-1}	0.1	0.2	0.6	0.1
Depth to Max dCI, cm	10.2	25.6	74.9	18.1
Min d^{2}CI, MPa cm^{-2}	-97.2	-32.1	-11.2	16.4
Depth to Min d^{2}CI, cm	10.2	28.8	74.9	18.2
Soil MC, % d.b.	20.8	24.3	27.0	1.2

Regression analysis for each of the CI parameters showed that mean and maximum CI for the profile and the depth to the maximum CI demonstrated a relationship with yield (Table 3). As previously stated, the relationship between yield and the depth to the maximum CI value is a concern due to the negative slope (b=-0.09).

Table 3. Regression results for yield (Mg ha^{-1}) as the dependent variable and soil parameters as the independent variable.

Independent Variable	Best Fit Eq.	'a'	'b'	R^2	F-Statistic
Mean CI, MPa	$y=ax^b$	7.40	-1.23	0.71	186.7
Max CI, MPa	$y=ax^b$	11.40	-1.05	0.55	94.2
Depth to Max CI, cm	$y=a+bx$	13.86	-0.09	0.42	55.0
Max dCI, MPa cm^{-1}	$y=a+bx$	9.57	-0.01	0.03	1.9
Depth to Max dCI, cm	$y=a+bx$	8.10	0.02	0.01	1.0
Min d^{2}CI, MPa cm^{-2}	$y=a+bx$	7.41	-0.04	0.04	3.0
Depth to Min d^{2}CI, cm	$y=a+bx$	8.30	0.01	0.00	0.3

The relationship between the mean CI and yield is shown in Figure 4 along with the best-fit equation described in Table 3. About 70 percent of the yield variation was explained by the mean CI of the depth profile. While the mean CI values were lower than the root-restricting value of 2 MPa (300 psi) (after Fulton et al. (1996), Raper et al. (2000b), Gorucu et al. (2001), Coates (2001), and Aase et al. (2001)), nearly all (16 of 20) mean CI readings above 1.1 MPa (165 psi) corresponded to yields below 6.7 Mg ha^{-1} (100 bu ac^{-1}) while the average transect yield was 8.6 Mg ha^{-1} (128 bu ac^{-1}).

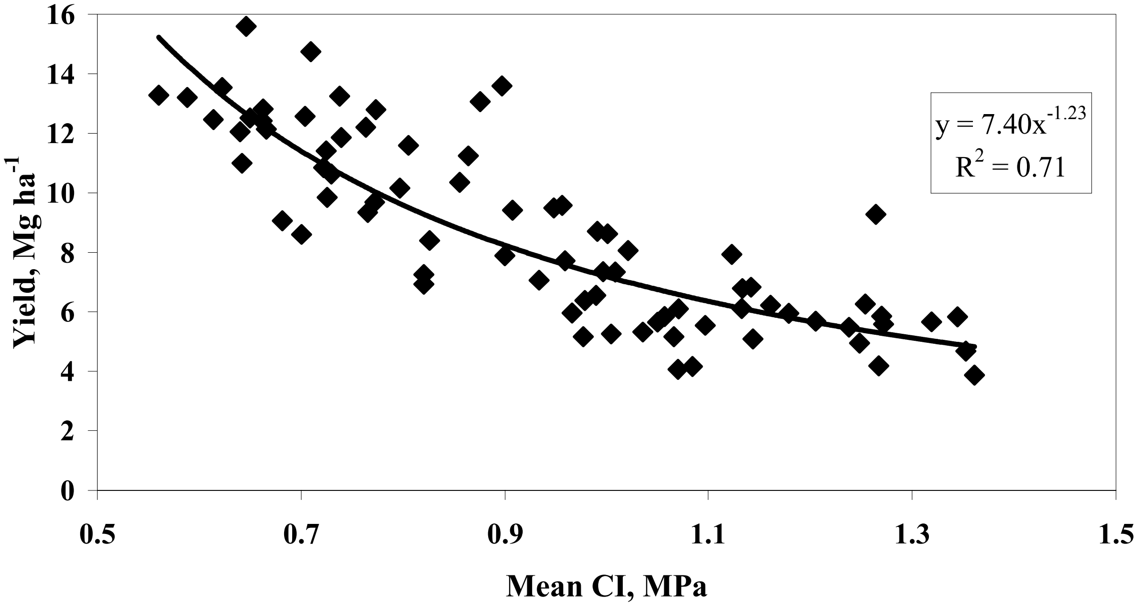

Figure 4. Yield versus the mean profile CI for all locations.

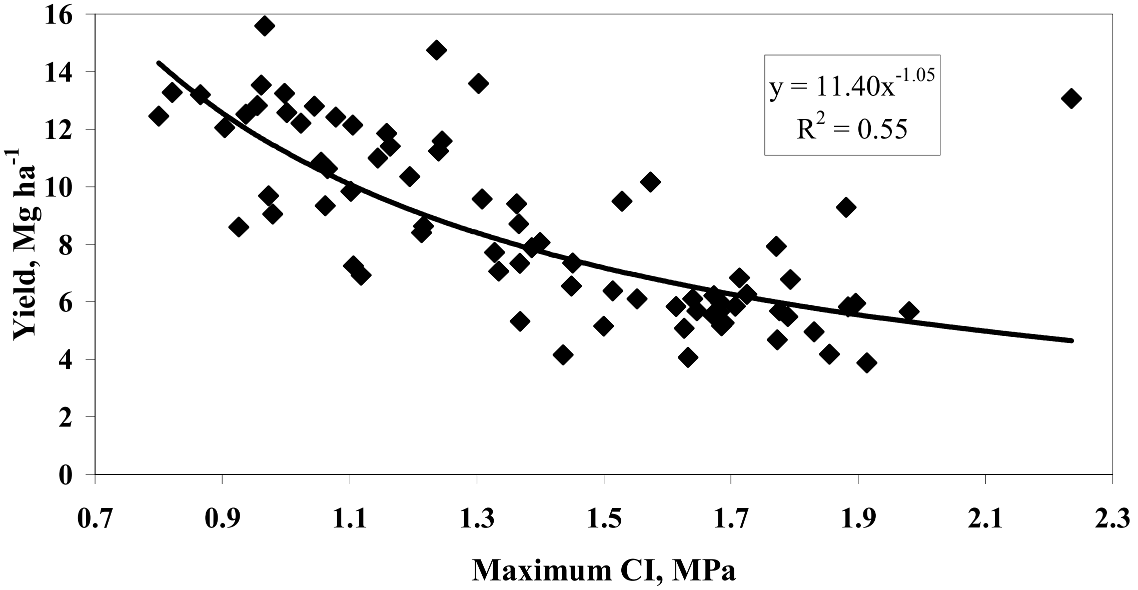

Figure 5. Yield versus the maximum CI for all locations.

Maximum CI also exhibited a decreasing trend (R^2=0.55) with respect to yield (Fig. 5). Maximum CI values ranged from 0.80 to 2.2 MPa (116 to 324 psi) with an average maximum CI of 1.4 MPa (200 psi). Though the power function was deemed the best-fit, it appears that yield is at a relatively constant high when the maximum CI is less than or equal to 1.0 MPa (145 psi) and a relatively constant low when greater than 1.4 MPa (200 psi). The average yield for the locations with a maximum CI less than or equal to 1.0 MPa (145 psi) was 12.2 Mg ha^{-1} (180 bu ac^{-1}), while the average for the locations with maximum CI values exceeding 1.4 MPa (200 psi) was 6.6 Mg ha^{-1} (98 bu ac^{-1}). Thus, it appears that CI values exceeding 1.4 MPa tend to be associated with reduced corn yield in this study, rather than the 2.0 MPa (300 psi) as suggested by previous researchers.

The outlier at 2.2 MPa (324 psi) had a clay layer in the 28 to 43 cm (11 to 17 in.) depth range with the maximum occurring at 34 cm (13.5 in.) However, this observation was located at the 205 m location of the transect which placed it in the low draw depicted in Figure 1. This location possibly received adequate moisture from runoff to compensate for the large maximum CI.

The relationship between yield and depth of maximum CI was described fairly well by a linear equation (R^2=0.42), but the negative slope coefficient was not expected. Fifty-eight percent of the maximum CI depths occurred between the 63 and 76 cm (25 and 30 inch) depth range. But shallow maximum CI depths did not correlate with reduced yield. However, 19 of the 21 locations having a maximum CI depth shallower than 34.3 cm (13.5 inch) were situated either in the draw (185 to 212 m (607 to 696 ft)) or lowland (268 to 323 m (880 to 1060 ft)) depicted in Figure 1. From this, we concluded that the negative relationship between the depth of maximum CI and yield may be influenced by topography.

Maximum dCI did not correlate with yield (r=-0.16). The maximum dCI represents the most rapid change in soil density throughout the profile. The low correlation indicates that sudden changes in soil density did not directly influence yield in this study. One explanation may be that since the recorded CI values did not exceed root restricting magnitudes, changes between any CI data points were not large enough to restrict root growth, and thus yield. Sixteen of 78 locations had a maximum CI rate of change greater than 110 kPa cm^{-1} (40 psi in^{-1}). For these 16 locations, yields were mostly at or below the transect average (13 of 16). The other three locations that met this condition and had greater than average yields were all near the 200 m distance (Fig. 1) (in the draw). The plants in this location potentially received additional moisture from runoff, which would account for the greater yields.

The depths of maximum soil density changes were not correlated to yield, even though most (81 percent) of the depths occurred in the top 30 cm (12 in.). For the 16 locations mentioned previously with a maximum dCI greater than 110 kPa cm^{-1} (40 psi in^{-1}), all depths were in the 11.4 to 42.0-cm (4.5 to 16.5 in.) range. For 13 of these locations where yield was below the transect average, maximum dCIs all occurred in the top 23-cm (9 in.).

Minimum values of the d^{2}CI reveal peaks in the CI profile, which are typically associated with hardpans. This value is different from the maximum CI value, since the maximum CI value is the largest CI magnitude occurring in the CI profile. No correlation was found between minimum magnitudes of the d^{2}CI and yield (r=-0.20). Also, the mean depth (28.8 cm (11.3 in.) of the d^{2}CI indicates the presence of a hardpan layer for several locations in the field, but no correlation was established between the depth of the CI peaks and yield. This may be a result of the recorded CI values not reaching root restricting magnitudes.

The first occurrence of a CI value exceeding the established magnitudes of 0.7 and 1.4 MPa (100 and 200 psi) was determined, along with the corresponding depth. The purpose of this distinction was to verify the CI magnitude that reduces yield. All sample locations had a CI value exceeding

0.7 MPa (100 psi), which did not correlate to yield. Thirty-eight of the 78 locations (49 percent) had a reading greater than 1.4 MPa (200 psi). Of these 38 locations, 34 (89 percent) yielded below the transect average of 8.6 Mg ha^{-1} (128 bu ac^{-1}). This was shown in Figure 5 and discussed with the maximum CI results. In this study, the established magnitude of 1.4 MPa (200 psi) was approximately equal to the average of the maximum CI's. Thus, CI magnitudes greater than 1.4 MPa (200 psi) may be associated with reduced corn yield.

Conclusions

In conclusion, we found that of the CI derived soil measurements, the mean CI throughout the 76.2 cm (30 in.) profile best explained yield variation (R^2=0.70) along the transect. The maximum CI also correlated with yield, but to a lesser extent than the mean CI. Since we had only one CI reading above 2 MPa (300 psi), we could not determine if maximum CI readings at or above 2 MPa (300 psi) corresponded with reduced yields. This may also account for the apparent lack of correlation between CI derivatives and yield. No correlation was established between yield and soil density changes (CI rate of change) and depth of density changes or between yield and CI peaks (hardpans) and their depth of occurrence for this data. However, the data show that CI readings at or above 1.4 MPa (200 psi) were associated with below average yields for 89 percent of the readings that exceeded this limit. Use of the first and second derivatives of the CI profile was an effective method in extracting the CI parameters from the CI profile.

Based on this research, we recommend that this method of CI data analysis be conducted on a field with a substantial number of maximum CI readings exceeding 2 MPa (300 psi).

Acknowledgments

Dr. Gerard Kluitenberg and Mr. Darrell Oard helped harvest corn. Mr. Jason Hooper helped collect soil data and threshed and dried the corn samples. Also, Mr. John Kramer allowed us use of his field and provided information about the field's history.

References

ASAE Standards, 48th Edition. 2001. EP542: Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. St. Joseph, Mich.:ASAE.

ASAE Standards, 48th Edition. 2001. S313.3: Soil Cone Penetrometer. St. Joseph, Mich.:ASAE.

Aase, J. K., D. L. Bjorneberg, R. E. Sojka. 2001. Zone-Subsoiling Relationships to Bulk Density and Cone Index on a Furrow-Irrigated Soil. *Trans. ASAE* 44(3):577-583.

Al-Adawi, S. S., R. C. Reeder. 1996. Compaction and Subsoiling Effects on Corn and Soybean Yields and Soil Physical Properties. *Trans. ASAE* 39(5):1641-1649.

Ayers, P. D., and J. V. Perumpral. 1982. Moisture and density effect on cone index. *Trans. ASAE* 25(4):1169-72.

Bakhsh, A., T. S. Colvin, D. B. Jaynes, R. S. Kanwar, and U. S. Tim. 2000. Using soil attributes and GIS for interpretation of spatial variability in yield. *Trans. ASAE* 43(4):819-828.

Coates., W. E. 2001. Reduced Tillage Systems for Irrigated Cotton: Is Soil Compaction a Concern?. *Appl. Eng. Agric.* 17(3):273-279.

Fulton, J. P., L. G. Wells, S. A. Shearer, and R. I. Barnhisel. 1996. Spatial variation of soil physical properties: A precursor to precision tillage. ASAE Paper No. 96-1002. St. Joseph, Mich.:ASAE.

Gorucu, S., A. Khalilian, Y. J. Han, R. B. Dodd, F. J. Wolak, M. Keskin. 2001. Variable Depth Tillage Based on Geo-Referenced Soil Compaction Data in Coastal Plain Region of South Carolina. ASAE Meeting Paper No. 01-1016.

Hillel, D. 1980. *Fundamentals of Soil Physics*. San Diego, CA: Academic Press, Inc.

Raper, R. L., D. W. Reeves, C. H. Burmester, E. B. Schwab. 2000a. Tillage Depth, Tillage Timing, and Cover Crop Effects on Cotton Yield, Soil Strength, and Tillage Energy Requirements. *Appl. Eng. Agric.* 16(4):379-385.

Raper, R. L., E. B. Schwab, and S. M. Dabney. 2000b. Spatial variation of the depth of the root-restricting layer in an upland soil of northern Mississippi. Ann Arbor, MI: ERIM International, Inc. Vol. 1:249-256. Presented at the Second International Conference on Geospatial Information in Agriculture and Forestry, Lake Buena Vista, Florida. 10-12 January 2000.

Wells, L. G., T. S. Stombaugh, S. A. Shearer. 2001. Application and Assessment of Precision Deep Tillage. ASAE Meeting Paper No. 01-1032