Variable-depth Tillage based on Geo-referenced Soil Compaction Data in Coastal Plain Soils

Serap Görücü Keskin[a,*], Ahmad Khalilian[b], Young J. Han[b], Roy B. Dodd[b]

[a]Assistant Professor, Department of Agricultural Machinery, Faculty of Agriculture, Mustafa Kemal University, 31040 Antakya, Hatay, Turkey
E-mail: sgorucuk@yahoo.com, Phone: (90) 505 416 3769

[b] Department of Agricultural and Biological Engineering, Clemson University, Clemson, SC 29634, USA

Abstract

This study was carried out to investigate the use of soil cone penetrometer and soil electrical conductivity (EC) measurement systems, in finding the geo-referenced optimum tillage depth for site-specific detection and management of soil compaction in Coastal Plain soils. The effectiveness of variable-depth tillage (VDT) on crop performance, energy consumption, and fuel savings was investigated. VDT, no-tillage (NT) and conventional tillage (CT) systems were compared and the relationships between tillage depth, soil EC, crop responses, and yield were studied in cotton production. The study was conducted in two different fields named Field A and Field B. The results showed that required tillage depths are shallower than conventional tillage depths. A strong positive correlation between EC readings and cotton yield was observed while predicted tillage depths were negatively correlated to soil EC readings. By applying VDT, energy savings of 56.4% and fuel savings of 33.8% were achieved compared to CT.

Keywords: compaction, cotton, electrical conductivity, penetrometer, variable-depth tillage

Introduction

Soil compaction restricts the root and crop development resulting in a reduction in crop yield (Khalilian et al., 1991). Soil compaction management in the Coastal Plain region of the United States relies heavily on the use of annual deep tillage, usually to a uniform depth (40-45 cm) throughout the field. This practice has been shown to improve yields in the Coastal Plain soils, which are subject to the formation of hardpans (Garner et al. 1989; Khalilian et al. 1991). However, there is a great amount of variability in the depth and thickness of hardpan layers in the Coastal Plain soils; moreover, it does not exist in some parts of the field (Clark 1999; Raper et al. 2001; Raper et al. 2007). Optimum tillage depth may be deeper or shallower than what is conventionally applied making uniform-depth tillage costly. Therefore, there is a need for a technology to determine the tillage depth based on the thickness and depth of the compacted layer and apply tillage accordingly. This type of variable-depth tillage technology could be beneficial in optimizing the production costs. Since a high-energy input is required to disrupt the hardpan layer to promote improved root development, variable-depth tillage could result in significant savings in energy required for the tillage. Variable-depth tillage or site-specific tillage is one of the important applications of Precision Agriculture which is based on the concept of treating small areas of the field as separate management units (Ess and Morgan 2003). Variable-depth tillage can be defined as any tillage system that optimizes the physical properties of soil by applying tillage at the required depth.

Soil cone penetrometers are used as an indicator of the soil resistance. Previous studies using penetrometers showed that the crop growth is limited if the soil penetration value is greater than 2-3 MPa (300-435 psi) depending on the crop type (Ehlers et al. 1983). Clark (1999) reported that the depth to the hardpan layer was variable ranging from 10 to 25 cm and accurate soil strength mapping required large amount of penetrometer measurements.Raper (1999) reported that tillage energy cost could be reduced by as much as 34% with variable-depth tillage. Cotton yield increased 10% by applying variable-depth tillage with an energy saving of 57% and a fuel savings of 60% (Raper 1999). Fulton et al. (1996) reported that fuel consumption could be reduced by 50% using variable-depth tillage. Raper et al. (2007) determined the benefits of site-specific subsoiling. Cotton yields were equivalent in site-specific uniform-depth subsoiling. They also reported reductions of 59% and 35% in draft in shallow depth (25 cm) and medium depth (35 cm) hardpan plots by site-specific subsoiling compared to uniform deep subsoiling at 45 cm, respectively. Wells et al. (2001) and Wells et al. (2005) mapped the spatial distribution of soil compaction as indicated by cone penetrometer resistance (soil cone index, CI) on multiple fields. They concluded that precision tillage produced increased yield relative to compacted cells receiving no deep tillage in five of six crops studied (Wells et al. 2005).

Since soil penetrometer requires a stop-and-go operation and it is labor-intensive, time consuming and costly, some researchers studied different methods that could be used on-the-go (Glancey et al. 1989; Adamchuk et al. 2001; Raper and Hall 2003). Weisbach and Wilde (1997) used a pull-type horizontal penetrometer to measure penetration force at three different depths simultaneously and they reported that 35% of the study field did not need deep tillage. Adamchuk et al. (2004) developed instrumented deep−tillage implement to estimate parameters of linear soil resistance pressure distributions. Andrade-Sanchez et al. (2008) developed a soil compaction profile sensor interfaced to a Differential Global Positioning System (DGPS) to generate continuous soil cutting resistance data. They concluded that the sensor data was similar to the cone penetrometer data when integrated over a specific soil layer or at a specific depth and that the device has potential for developing site-specific tillage maps.

Continuous measurement systems such as soil electrical conductivity (EC) appear to be promising as alternative to penetrometers in finding the optimum tillage depth. Soil EC measurement systems provide data continuously and in short time compared to the penetrometers. Sudduth et al. (1998) reported a remarkable correlation between EC data and topsoil depth (r^2=0.59 to 0.93). Nehmdahl and Greve (2001) found a good correlation between soil EC and actual variations in soil types.

Farmers apply uniform-depth tillage requiring higher energy and fuel costs. Variable-depth tillage could be beneficial in optimizing the production costs. The aim of this study was to understand if the variable depth tillage is feasible. The specific objectives of this study were; 1) to investigate the feasibility of using two systems, soil cone penetrometer and soil electrical conductivity meter to determine variability in root-impeding layers and the geo-referenced optimum tillage depth, 2) to compare variable-depth tillage with conventional uniform-depth tillage and no till method in terms of crop performance in cotton production, and 3) to determine the effects of variable-depth tillage on soil physical properties as well as energy and fuel consumption.

2. Materials

2.1Equipment and Instrumentation

A GPS-based, tractor mounted, hydraulically-operated penetrometer system was used to obtain soil strength measurements (ASAE 2001d). The system consisted of a standard cone penetrometer, a depth transducer, a force transducer, a lateral positioning system, a ground surface detection switch, data acquisition system, and a Differential Geographical Positioning System (DGPS) receiver. The penetrometer system could be moved laterally along the main frame using an electric motor to take multiple measurements.

A commercially available soil electrical conductivity measurement system (Model: 3100; Veris technologies; Salina, KS, USA) was used to measure the soil electrical conductivity. The system is equipped with six coulter-electrodes. One pair of electrodes applies electrical current into the soil, while others measure the voltage drop between the coulters and then the system calculates the electrical conductivity in mS m^{-1}.
A front-wheel-assist 78 kW instrumented tractor (Model: 4050, John Deere; Moline, IL, USA) was used to collect the energy consumption data during the tillage operation. The tractor instrumentation system consisted of a three point hitch dynamometer, a fuel flow meter, engine speed (RPM) sensor, several ground speed sensors (fifth wheel, radar, and ultrasonic), a data logger, and an optical sensor determining the start and end of each experimental plot.

A four-row subsoiler-bedder with shank spacing of 96 cm was used for subsoiling operations. The depth of the subsoiler (the tillage depth) was adjusted by gauge wheels. For the no tillage treatment, the shanks were removed and only bedding disks were used.

2.2 Test Fields

A test field with considerable variability was needed to accomplish the study objectives. A 5-ha field located at the Edisto Research and Education Center of Clemson University in Blackville, South Carolina, USA (Latitude 33˚ 20″ N, Longitude 81˚ 19″ W) was selected. The region where the field is located has a mild climate with an average daily maximum temperature of 32°C. The annual precipitation averages 1200 mm with the majority falling between April and September. The soil is classified as Dothan sandy loam (Fine-loamy, Kaolinitic, Thermic Plinthic Kandiudults), which is typical for Coastal Plain Region soils (USDA 2010). The soil EC and yield maps of the selected field obtained in the previous crop season by using a soil EC measurement system and a grain yield monitor with DGPS unit were studied to determine if the field had enough variability (Figure 1). The maps showed a great amount of variability in corn yield and soil electrical conductivity (top 30 cm). Two sub-fields (Field A and Field B) were selected from the main field (Figure 1). The experiment was conducted in Field A in 2000 and in Field B in 2001.

Field A had a 0.73 ha surface area and was divided into 60 rectangular plots (3.86 m x 24.38 m). Three transects, 6.1 m apart from each other, were selected for penetrometer measurements in each plot. Five penetrometer measurements, 0.3 m apart from each other, were taken from each transect giving 15 measurements per plot. The experiment was carried out in Field B (0.66 ha) in 2001 in the same manner.

3. Methods

Penetrometer measurements were taken in May and August. After the tillage operation, four rows of cotton (Delta Pine 458 RR variety) with 96.5 cm row space were planted on each plot. Soil cone penetrometer measurements were taken according to ASAE standard (ASAE 2001c). Soil moisture samples were also simultaneously collected at three depth ranges of 0-13 cm, 13-25 cm, and 25-38 cm to make sure that the moisture content was at field capacity. Then, optimum tillage depth for each plot was determined using an algorithm and the computer program developed by Gorucu et al. (2006). The algorithm was based on the criteria of 2 MPa of root restricting CI value for cotton. Geo-referenced optimum tillage depths were obtained from the raw soil penetrometer data after running the algorithm. The geo-referenced soil electrical conductivity data were collected using the soil electrical conductivity measurement system for both 30 cm and 90 cm depths. These data were used to generate the tillage depth map and the soil electrical conductivity map using a GIS (Geographical Information System) software (ARC/INFO; Version 8.1; ESRI, Redlands, CA, USA). Based on the map of the required tillage depth, Field A was divided into four tillage management zones (tillage depths of 25 cm, 33 cm, 38 cm, and 45 cm).

Field B was divided into three tillage management zones (tillage depths of 33 cm, 38 cm, and 45 cm) since it required relatively deeper soil tillage depths than the Field A. The following tillage treatments were imposed in each management zone: 1) No tillage (**NT**) ignoring the root impeding soil layer, 2) Conventional constant depth tillage (**CT**) completely disrupting the soil at a depth of 45 cm, 3) Variable-depth tillage (**VDT**) tilling the soil slightly below the root impeding layer (25 cm, 33 cm, 38 cm, and 45 cm for Field A and 33 cm, 38 cm, and 45 cm for Field B). The treatments were arranged in a randomized complete block design with five replications (five plots) for the Field A and six replications (six plots) for the Field B. The instrumented tractor was used to obtain the data needed for calculating energy and fuel consumption for VDT and CT treatments in Field A (ASAE 2001a). Data were collected from each plot during the tillage operation with subsoiler for VDT (tillage depths of 25, 33, 38 and 45 cm) and CT (45 cm). Speed of the tractor during the tests ranged between 5.8 and 6.6 km/h. Tillage depths were adjusted by changing the position of the depth adjustment wheels of the tillage equipment. Energy requirements for tillage were calculated based on power-take off (PTO) power and the areas of the field in need of the specific depth of tillage. Fuel consumption was also calculated for each tillage depth for diesel fuel based on the tractor load (ASAE 2001b).

The root lengths, root weights, nutrient contents and yield measurements were obtained to study the crop performance. After the root length measurements, the samples were dried in an oven at 60°C for 72 hours to obtain dry root weights (ASAE 2001e). Then, average root lengths and dry root weights were calculated for each plot. Also, for plant leaf nutrient contents, nutrient analyses were conducted at the Soil and Plant Analysis Laboratory of Clemson University located in Clemson, SC, USA. For yield measurement, two middle rows of each plot were harvested with a John Deere 9910 cotton picker in the harvest season. The plot picker was modified by replacing the storage basket with a platform and a sacking attachment to the discharge end of the pneumatic conveying system to collect harvested material from each plot in burlap sacks. The sacks were weighed for yield determination. Also, small samples from each sack were collected and then ginned to determine the lint and trash contents of the harvested seed cotton. Correlation coefficients between the predicted soil tillage depths, soil EC, and lint cotton yield were obtained by using the CORRELATION command in the GIS software before the classification procedure.

4. Results

The predicted tillage depth and the hardpan thickness for each measurement location were obtained in an output data file after post-processing the raw soil compaction data. Then, average predicted tillage depths were calculated for each plot. Geo-referenced tillage depth maps were generated using the GIS software for both Field A and Field B (Figure 2 and Figure 3). The results revealed that there was a great amount of variability in the depth and the thickness of the hardpan. In field A, about 75% of the test field required shallower tillage depth than the traditional tillage depth of 45 cm (Figure 2). Predicted tillage depth was only 25 cm in about one-fourth of the test field. The second and third one-fourths of the test field required the tillage depths of 33 cm and 38 cm. The predicted tillage depth in the remaining one-fourth of the field was 45 cm (Figure 2). In Field B, approximately 67% (two-thirds) of the test field required shallower tillage depths (Figure 3). The optimum tillage depth was 33 cm for about one-third of the field. Similarly, the second third of the field required a tillage depth of about 38 cm.

The remaining part of the test field required 45 cm tillage depth (Figure 3). Soils in the Coastal Plain region of the US usually have a structure that has three distinct layers: A horizon (sandy to loamy sand), E horizon (yellowish brown sandy to sandy clay), and Bt horizon (sandy clay loam). The E horizon is a compacted layer called hardpan which limits the penetration of the plant roots into the subsoil (Bt horizon) which has high level of moisture and nutrients and consequently reduces plant growth and crop yield. Based on the depth to the Bt horizon, the test fields were divided into two separate sections (Gorucu et al. 2006). The part of the field where the depth to the Bt horizon was 33 cm or less was named "shallow Bt horizon" and the section with a depth to the Bt horizon greater than 33 cm was called "deep Bt horizon".

The soil EC maps were generated for both top 30 cm and 91 cm of soil layer in both fields. Figure 4 shows the soil EC map for the top 30 cm of soil layer in Field A. In Field A, the part of the field that had shallow Bt horizon had also shallower predicted tillage depths and higher soil EC (Figure 4). This reveals that there is an inverse relationship between the recommended tillage depth and the soil EC.

Soil CI profiles for each tillage treatment (CT, NT, and VDT) within management zones taken before tillage operation and three months after tillage were compared to evaluate the effects of the treatments in terms of the CI values. Figure 5 shows the average soil CI profiles for the tillage treatments at the management zone of 33 cm in Field B as an example. In this figure, each line in each chart represents mean soil CI values from six experimental plots. In CT plots, three months after tillage, the hardpan was significantly removed in the crop rows; however, a compacted layer below the soil tillage depth (33 cm) was observed. In the non-trafficked row middles, the CI values before and after tillage were about the same up to the tillage depth while below the tillage depth, the CI values taken three months after tillage were higher than those taken before tillage (Figure 5). In NT plots, the CI values were mostly increased in rows but not in row middles three months after the tillage. The reason of this was the traffic imposed by agricultural machinery operations (Figure 5). In VDT plots, CI values in both rows and row middles were generally decreased in the layer up to the tillage depth (33 cm) after tillage. But in the layer below the tillage depth, the CI values were mostly increased in rows after tillage due to agricultural machinery operations (Figure 5). Similar analyses were carried out for the other management zones for Field A and Field B and in general, similar results were obtained.

The data from instrumented tractor were used to calculate energy requirements and fuel consumption for each tillage depth. The energy requirements and fuel consumption were observed to be increased with the increased tillage depth in VDT while they were about same for CT (Table 1). The results showed that energy savings of 56.4% and fuel savings of 33.8% could be achieved by adopting the variable-depth tillage over the constant-depth conventional tillage (Table 1).

A statistical analysis was performed to compare the taproot lengths of the cotton plants from CT, NT, and VDT plots using the SAS software (SAS, 1999, Version: 8.02; SAS Institute Inc., Cary, NC, USA). In both fields, cotton taproot length was significantly shorter in the no-till plots compared to conventional and variable-depth plots ($P<0.05$) (Figure 6). The reason for the shorter taproot length in NT plots was the existence of the hardpan leading the lateral root growth. On the other hand, the taproot lengths for the CT and VDT were about same in both fields (Figure 6). These results reveal that there is no need to till soil deeper than needed in terms of taproot length.

Regarding the dry root weights, the statistical analysis showed that CT, NT, and VDT treatments were not significantly different between tillage treatments in Field A and Field B ($P>0.05$) (Figure 7). This can be explained in such a way that in the no-till plots, plants had more lateral roots to compensate for shorter taproots. However, the average dry root weights were adversely affected by the location of the Bt horizon in Field A. In the deep Bt horizon part of the soil with deeper tillage depths, dry root weights were less than those of the shallow Bt horizon part of the field (Figure 7). This could be due to the fact that the shallow Bt horizon part of the field had higher clay content meaning more nutrients and moisture.

The tillage treatments were also compared according to the plant leaf nutrient contents. The tillage systems had no significant effect on plant nutrient contents in Field A. However, the tillage depth (management zone) significantly affected plant P, K, Mg, Zn, Cu, Mn, Fe, and B contents ($P<0.05$). In Field B, the tillage systems had no effect on plant nutrient contents except Nitrogen. The results also showed that the tillage depth significantly affected plant P, K, Ca, Mg, S, and Mn ($P<0.05$).

Another comparison of the tillage treatments was also carried out for cotton lint yield. In Field A, cotton yields in shallow Bt horizon part were significantly higher than the deep Bt horizon part ($P<0.05$) (Figure 8). The difference among tillage treatments was found to be significant only for the deep Bt horizon part of the field ($P<0.05$).

The cotton yield of no-till plots was less than those of the other two tillage systems (Figure 8). Similar results were obtained in Field B. There were no significant differences in cotton yield between the three tillage systems in the management zone of 33 cm ($P>0.05$). However, there was a significant difference in the yield between no-till and the other two tillage treatments for the management zones of 38 cm and 45 cm ($P<0.05$). The lowest yields occurred for all of the subsoiling treatments at the deep hardpan depths of 38 - 45 cm. The yields were higher in the shallower hardpan depths.

A correlation analysis was conducted in the GIS software. A strong negative correlation was found between the tillage depth and both shallow ($r = -0.83$) and deep ($r = -0.84$) EC readings in Field A (Table 2). However, in Field B, the correlation was relatively lower between the tillage depth and the shallow ($r = -0.56$) and deep ($r = -0.56$) EC readings. Positive strong correlations were found between lint cotton yield and both shallow ($r = 0.90$) and deep ($r = 0.83$) EC measurements in Field A. In Field B, the correlation was relatively lower for both shallow ($r = 0.60$) and deep ($r = 0.63$) EC readings. The correlation between predicted soil tillage depths and lint cotton yield was negative and found to be higher in Field A ($r = -0.88$) than the one in Field B ($r = -0.51$) (Table 2).

5. Discussion

The results showed that it is possible to determine the required tillage depth from soil penetrometer data and soil EC data. These findings are in agreement with the results found by some other researchers. Clark (1999) reported that the depth to the hardpan layer was completely variable ranging from 10 to 25 cm. Raper et al. (2005) used three different tillage depths as 25 cm, 35 cm, and 45 cm on 44 plots in Alabama. The number of plots required shallower tillage depths of 25 cm and 35 cm were 10 and 22, respectively while 12 plots required 45 cm tillage depths. About two-thirds of the plots required shallower tillage depths.

Negative correlations were found between recommended soil tillage depth and the soil EC data. These results for the relationship among topsoil depth, EC, and clay contents were in agreement with the results of some previous studies. Sudduth et al. (1998) estimated topsoil depth from EC data with $r^2=0.59$ to 0.93. Nehmdahl and Greve (2001) found a remarkable correlation between soil EC data and actual variations in soil types.
By applying VDT, it was possible to save energy by 56.4% and save fuel by 33.8% over constant depth tillage. Fulton et al. (1996) and Raper et al. (2007) reported similar results on the energy and fuel savings. Fulton et al. (1996) reported that variable depth tillage could result in 50% fuel savings. Raper et al. (2007) reported draft reductions of 59% and 35% and fuel savings of 43% and 27% for site-specific subsoiling in shallow depth (25 cm) and medium depth (35 cm) hardpan plots compared to uniform deep subsoiling at 45 cm, respectively.

The adverse effects of hardpan layer on crop performance were also observed. These effects have been also reported by Ishaq et al. (2003) and Busscher and Bauer (2003). Many studies reported the positive effects of subsoiling on root growth. The findings from the experiments showed the similar positive effects of subsoiling and the adverse effects of compaction on cotton root growth (Ehlers et al. 1983; Raza et al. 2007). Cotton yields were also adversely affected from compacted layer. Similar results were found by Raper et al. (2007) who explained the reason of the lower yields with deep hardpan depths as the higher peak values of CI. In our study, we can see that the yields were lower in the deep hardpan depths since the roots of cotton could not reach to the Bt horizon. These results reveal that the key factor on cotton yield was the depth of the Bt horizon.

The findings on correlation coefficients among among yield, soil EC, and the tillage depth in this study were also confirmed by several researchers (Sudduth et al. 2001; Corwin et al. 2003; Johnson et al. 2003; Ezrin et al. 2010).

6. Conclusions

Soil compaction restricts the root and crop development and results in a reduction in crop yield. A great amount of variability in the depth and thickness of hardpan layers exist in the Coastal Plain soils of the United States. However, farmers till the soil at constant depth leading to higher tillage costs. Optimum tillage depth may be shallower in some parts of the field. VDT could be beneficial in optimizing the production costs. The aim of this study was to understand if the VDT is feasible. The following conclusions were obtained from the study:

- Tillage depth can be determined by either soil cone penetrometer system or electrical conductivity measurement system.
- Approximately 75% of Field A and 67% of Field B required shallower tillage depths than the conventional tillage depth.

- In both fields, taproot length was significantly shorter in the no-till plots compared to conventional and variable-depth plots; however, there was no significant difference in dry root weights among the treatments because of the lateral root development.
- The location of the Bt horizon overrode the effects of deep tillage operation. The cotton yield in no till (NT) plots was significantly lower than conventional tillage (CT) and variable depth tillage (VDT) plots for the parts of the field in which the depth to Bt horizon was more than 33 cm.
- The predicted tillage depths were negatively correlated to the soil EC readings (r =-0.83 for Field A, r = -0.56 for Field B).
- The energy savings of 56.4% and fuel savings of 33.8% could be achieved by adopting the variable-depth tillage system over the uniform and constant-depth (conventional) tillage. Therefore, VDT is recommended due to its advantages on energy and fuel savings.

Acknowledgement

The authors acknowledge the support of Cotton Incorporated and the Clemson University's Agricultural Productivity & Profitability Competitive Grant.

References

Adamchuk V I, Morgan M T, Sumali H (2001) Application of a strain gauge array to estimate soil mechanical impedance on-the-go. Transactions of the ASAE 44(6):1377-1383.

Adamchuk V I, Skotnikov A V, Speichinger J D, Kocher M F (2004) Development of an instrumented deep-tillage implement for sensing of soil mechanical resistance. Transactions of the ASAE 47(6):1913-1919.

Andrea-Sanchez P, Upadhyaya S K, Pluffe C, Poutre B (2008) Potential use of the UCDavis soil compaction profile sensor (UCD-SCPS) for site-specific tillage applications. ASAE Paper No. 083927. St. Joseph, Michigan, USA.

ASAE (2001a) ASAE Standards - D497.4: Agricultural machinery management data. American Society of Agricultural Engineers. St. Joseph, MI.

ASAE (2001b) ASAE Standards - EP496.2: Agricultural machinery management. American Society of Agricultural Engineers. St. Joseph, MI.

ASAE (2001c) ASAE Standards - EP542: Procedures for using and reporting data obtained with the soil cone penetrometer. American Society of Agricultural Engineers. St. Joseph, MI.

ASAE (2001d) ASAE Standards S313.3: Soil cone penetrometer. American Society of Agricultural Engineers. St. Joseph, MI.

ASAE (2001e) ASAE Standards - S358.2: Moisture measurement - forages. American Society of Agricultural Engineers. St. Joseph, MI.

Busscher W J, Bauer P J (2003) Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand. Soil and Tillage Research 74: 151–159.

Clark R L (1999) Evaluation of the potential to develop soil strength maps using a cone penetrometer. ASAE Paper No. 993109. St. Joseph, Michigan, USA.

Corwin D L, Lesch S M, Shousea P J, Soppeb R, Ayars J E (2003) Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity. Agronomy J 95: 352-364.

Ehlers W, Popke V, Hesse F, Bohm W (1983) Penetration resistance and root growth of oats in tilled and untilled loam soil. Soil and Tillage Research 3: 261-275.

Ezrin M H, Amin M S M, Anuar A R, Aimrun W (2010) Relationship between rice yield and apparent electrical conductivity of paddy soils. American Journal of Applied Sciences 7 (1): 63-70.

Ess D, Morgan M (2003) The Precision Farming Guide for Agriculturists. Deere & Company, Moline, Il, USA.

Fulton J P, Wells L G, Shearer S A, Barnhisel R I (1996) Spatial variation of soil physical properties: a precursor to precision tillage. ASAE Paper No. 961012. St. Joseph, Michigan, USA.

Garner T H, Khalilian A, Sullivan M J (1989) Deep tillage for cotton in Coastal Plain soils-costs/returns. In: Proceedings of Beltwide Cotton Production Research Conferences, pp.168-171.

Glancey J L, Upadahyaya S K, Chancellor W J, Rumsey J W (1989) An instrumented chisel for the study of soil-tillage dynamics. Soil and Tillage Research 14: 1-24.

Gorucu S, Khalilian A, Han Y J, Dodd R B, Smith B R (2006) An algorithm to determine the optimum tillage depth from soil penetrometer data in Coastal Plain soils. Applied Engineering in Agriculture 22(5): 625-631.

Ishaq M, Ibrahim M, Lal R (2003) Persistence of subsoil compaction effects on soil properties and growth of wheat and cotton in Pakistan. Exp. Agric. 39(4): 341-348. Cambridge, U.K.: Cambridge University Press.

Johnson C K, Mortensen D A, Wienhold B J, Shanahan J F, Doran J W (2003) Site-specific management zones based on soil electrical conductivity in a semiarid cropping system. Agronomy J 95: 303–315.

Khalilian A, Hood C E, Palmer J H, Garner T H, Bathke G R (1991) Soil compaction and crop response to wheat/soybean interseeding. Transactions of the ASAE 34: 2299-2303.

Nehmdahl H, Greve M H (2001) Using soil electrical conductivity measurements for delineating management zones on highly variable soils in Denmark. In: Proceedings of the 3rd European conference on precision agriculture (Eds. G Grenier, S Blackmore). Montpellier, France, 1: 461-466.
Raper R L (1999). Site-specific tillage for site-specific compaction: is there a need? In: Proceedings of the International Conference of Dryland Conservation/Zone Tillage, Beijing, China.
Raper R L, Schwab E B, Dabney S M (2001) Measurement and variation of site-specific hardpans. ASAE Paper No. 01108. St. Joseph, Michigan, USA.
Raper R L, Hall E H (2003) Soil strength measurement for site-specific agriculture. U.S. Patent No. 6,647,799.
Raper R L, Reeves D W, Shaw J N, Van Santen E, Mask P L (2005) Site-Specific subsoiling benefits for cotton production. ASAE Paper No. 051025. St. Joseph, Michigan, USA.
Raper R L, Reeves D W, Shaw J N, Van Santen E, Mask P L (2007) Benefits of site-specific subsoiling for cotton production in Coastal Plain soils. Soil and Tillage Research 96: 174–181.
Raza W, Yousaf S, Nadeem Y, John A (2007) Compaction and subsoiling effects on soil properties, plant nutrient concentration and yield of cotton (Gossipium hirsutum L.). American Eurasian J. Agric. Environ. Sci. 2 (4): 375-381.
SAS (1999) SAS Institute Inc., SAS/STAT® User's Guide, Version 8.02, Cary, NC: SAS Institute Inc.
Sudduth KS, Kitchen N R, Drummond S T (1998) Soil conductivity sensing on claypan soils: comparison of electromagnetic induction and direct methods. In: Proceedings 4th Intl. Conf. On Precision Agriculture. Madison-WI, USA, 979-990.
Sudduth K A, Drummond S T, Kitchen N R (2001) Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. Comput. Elect. Agric., 31: 239-264.
USDA (2010) Dothan series. National Resources Conservation System, United States Department of Agriculture (USDA). Available at
http://www2.ftw.nrcs.usda.gov/osd/dat/D/DOTHAN.html (verified on July 19, 2010).
Weisbach M, Wilde T (1997) The horizontal penetrograph-big scale mapping device for soil compaction. 3rd International Conference on Soil Dynamics (ICSD III). August 3-7, 1997, Tiberias, Israel.
Wells L G, Stombaugh T S, Shearer S A (2001) Application and Assessment of Precision Deep Tillage. ASAE Meeting Paper No. 011032. St. Joseph, Michigan, USA.
Wells L G, Stombaugh T S, Shearer S A (2005) Crop yield response to precision deep tillage. Transactions of the ASAE 48(3): 895−901.

Table 1. Energy and Fuel Consumption for Variable-Depth Tillage (VDT) and Conventional Tillage (CT) in Field A.

Tillage system	Predicted tillage depth (cm)	Field size (ha)	Time (h)	Draft (kN)	Drawbar power (kW)	PTO power (kW)	Energy (kW-h)	Fuel consumption (L)
VDT	25 (shallow Bt)	0.2023	0.21	6.80	11.98	18.84	3.96	2.95
	33 (shallow Bt)	0.2023	0.20	8.01	14.76	23.21	4.64	3.13
	38 (deep Bt)	0.2023	0.21	8.35	14.57	22.91	4.81	3.27
	45 (deep Bt)	0.2023	0.22	8.92	14.91	23.44	5.16	3.46
	Total	0.8092	0.84	32.09	56.22	88.40	18.6	12.8
CT	45 (shallow Bt)	0.4046	0.45	18.72	30.22	47.52	21.38	9.71
	45 (deep Bt)	0.4046	0.45	17.83	29.82	46.89	21.10	9.64
	Total	0.8092	0.90	36.56	60.04	94.40	42.48	19.35
Total savings with VDT vs CT							56.4%	33.8%

Table 2. Correlation Coefficients among Soil Electrical Conductivity (EC), Predicted Tillage Depth, and Cotton Yield in Field A and Field B.

		EC (30 cm)	EC (91 cm)	Predicted tillage depth	Cotton yield
Field A	EC (30 cm)	1	-	-	-
	EC (91 cm)	-	1	-	-
	Tillage depth	-0.83	-0.84	1	
	Cotton yield	0.90	0.83	-0.88	1
Field B	EC (30 cm)	1	-	-	-
	EC (91 cm)	-	1	-	-
	Tillage depth	-0.56	-0.56	1	
	Cotton yield	0.60	0.63	-0.51	1

FIGURES

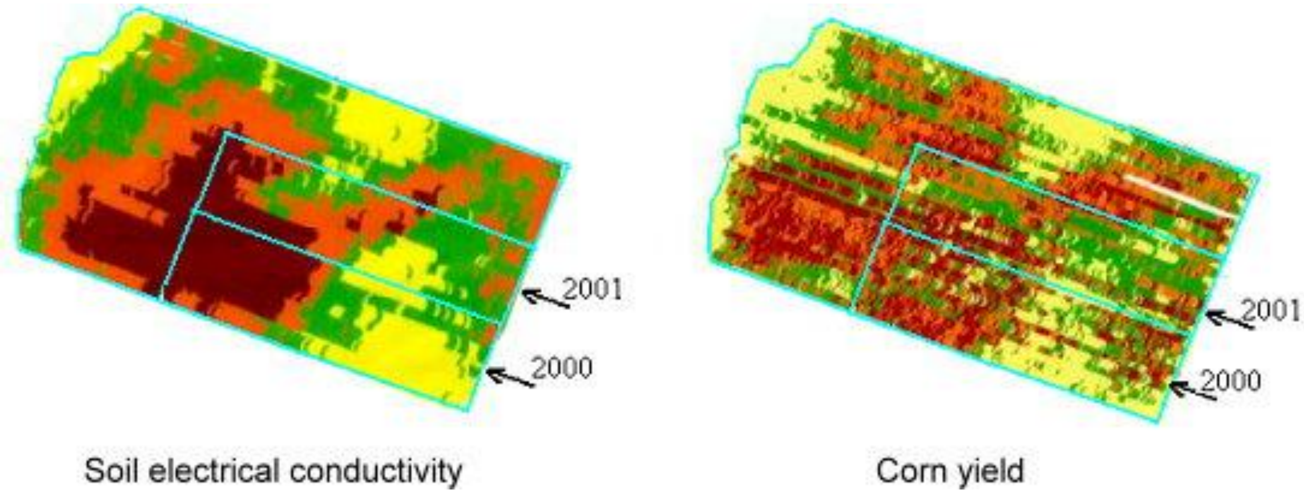

Figure 1. Soil electrical conductivity and corn yield maps of the main field.

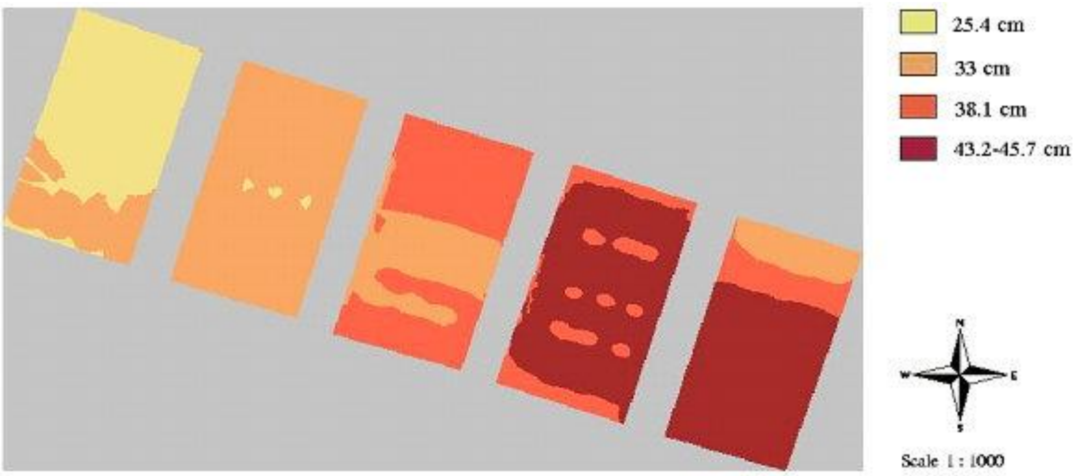

Figure 2. Predicted tillage depth map of Field A.

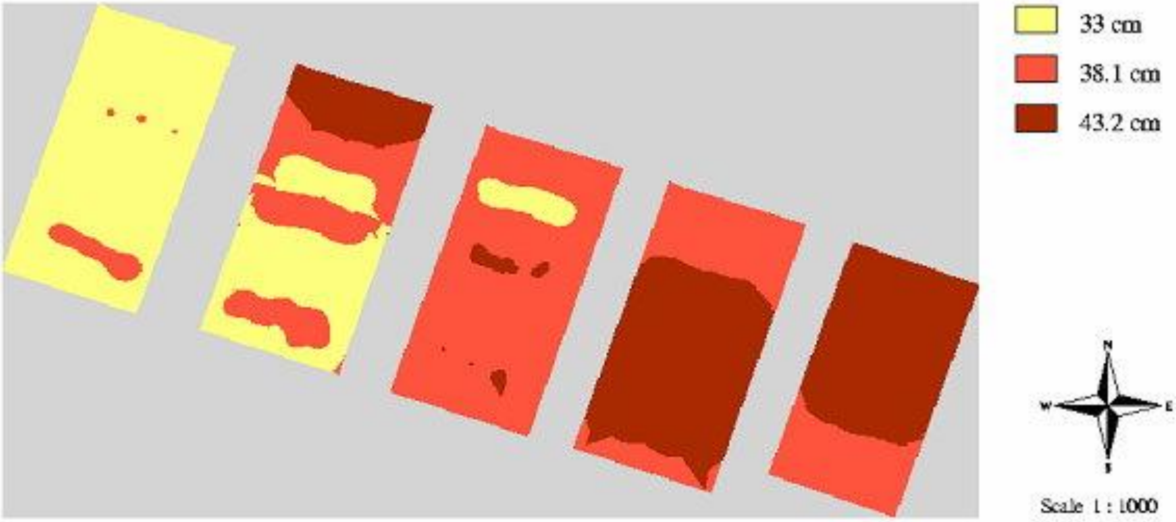

Figure 3. Predicted tillage depth map of Field B.

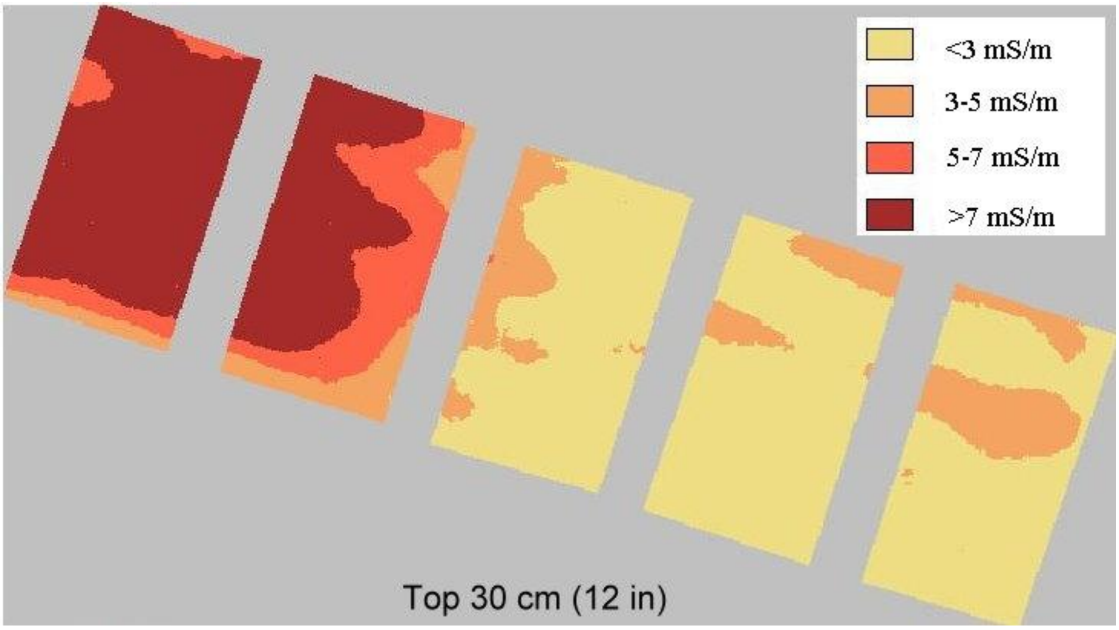

Figure 4. Spatial variability of the soil electrical conductivity (EC) in Field A.

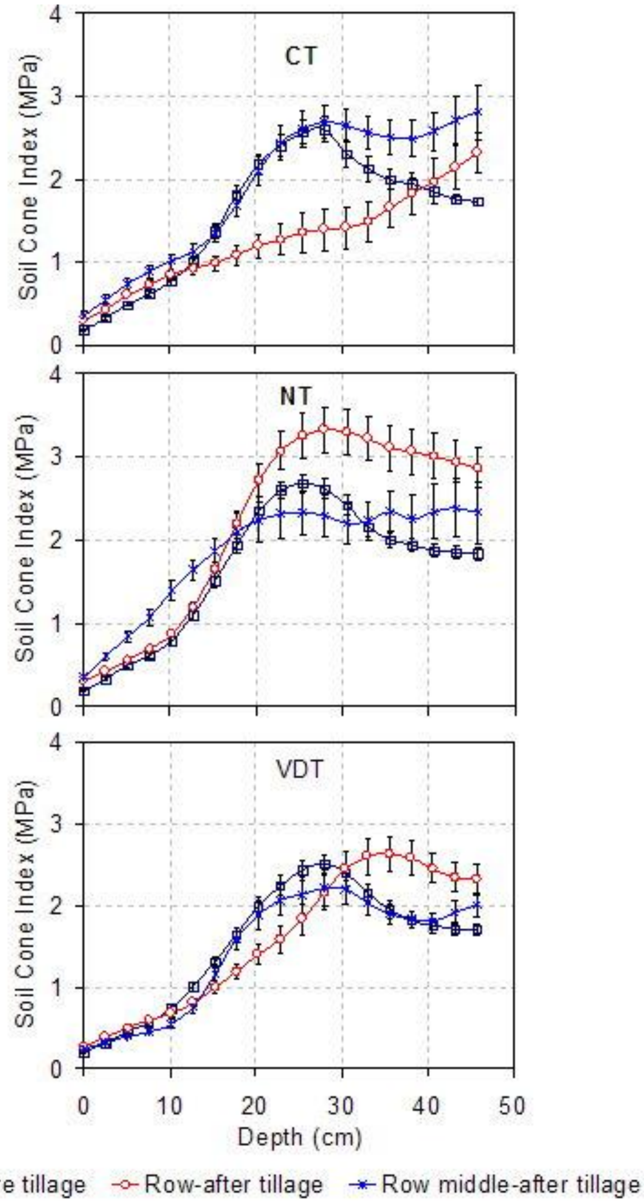

Figure 5. Average CI profiles for the tillage treatments (CT, NT, and VDT) at management zone of 33 cm in Field B.

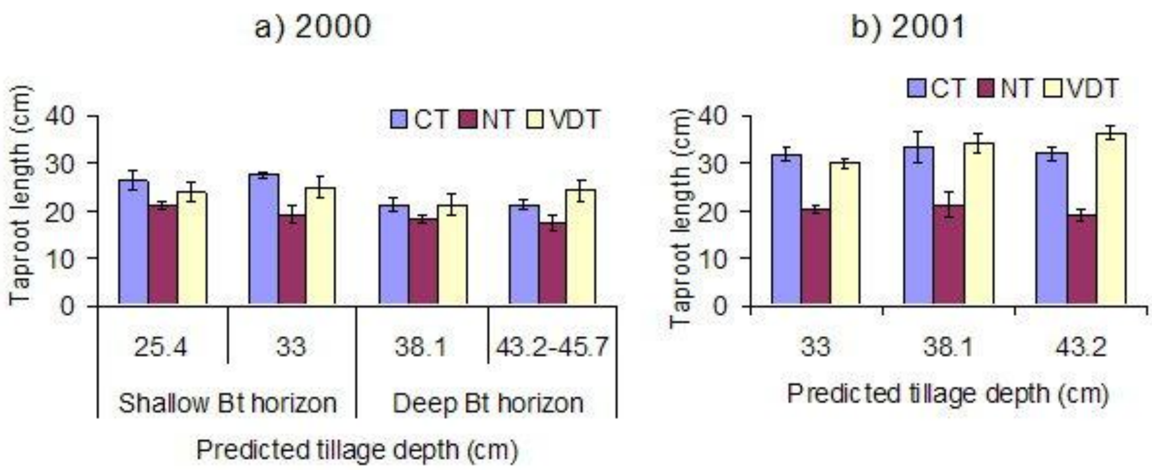

Figure 6. Average taproot length in Field A and Field B.

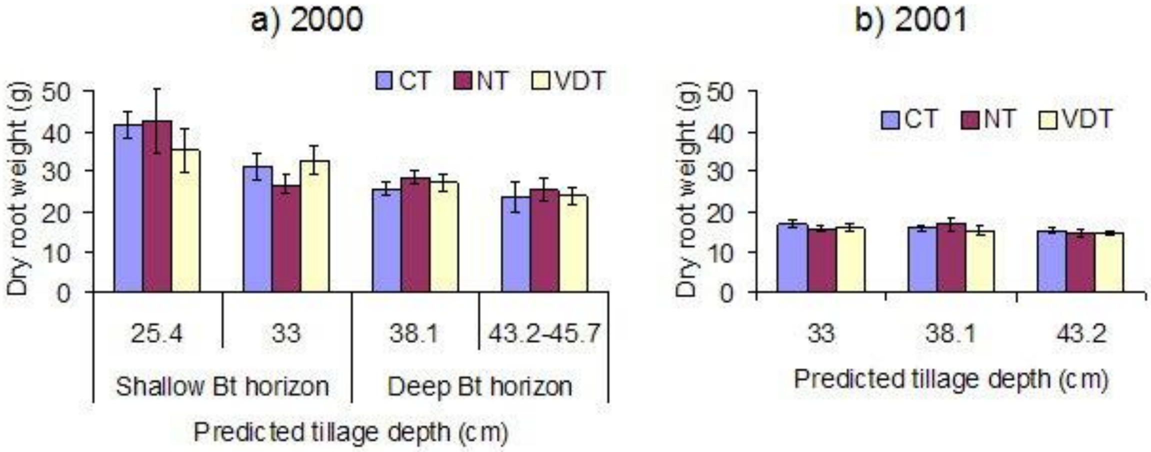

Figure 7. Average dry root weights in Field A and Field B.

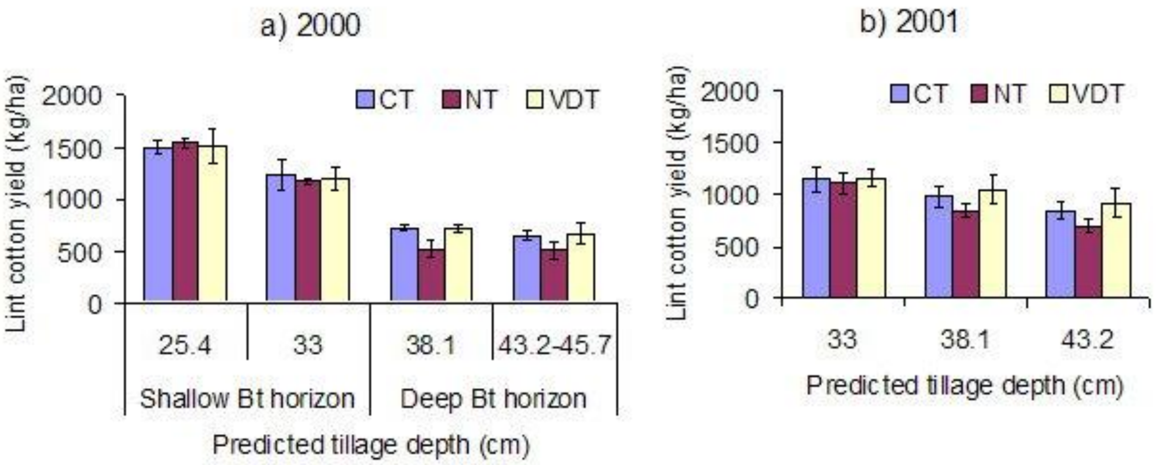

Figure 8. Lint cotton yield in Field A and Field B