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정병학 정선옥

Site-specific Quantification and Management of Soil Compaction : A Review

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Abstract

Compaction is becoming a greater concern in crop production and the environment because it can have deleterious effects on growing conditions that are difficult to remediate. Because compaction can vary considerably from point to point within a field, and also from depth to depth within the soil profile, it is important to consider quantification and management of the spatial and vertical variability in soil compaction when developing an overall site-specific crop management plan. In this paper, the importance of soil compaction, techniques for quantification of its variability, and the concept of site-specific tillage are examined. Methods and systems to detect within-field variation in soil strength as a surrogate measure of soil compaction and related soil properties are also compared and discussed. Quantification of variability in soil compaction and site-specific compaction management was motivated recently, and sensors and control systems are still under development. Future study will need to address a number of issues related to understanding and applying the sensor measurements.

Keywords : Precision agriculture, Soil compaction, Soil strength, Soil sensor

1. INTRODUCTION

Information on variability in soil properties is important for crop production using the concept of site-specific crop management (SSCM), which relies on point-by-point information on field conditions affecting crop production. Two such conditions are soil physical and chemical properties, which govern the transport of nutrients and water through the soil and the amount of plant available nutrients and water. An important soil physical property is soil compaction caused by wheel traffic of agricultural machinery and/or tillage operations, as well as due to natural phenomena. Compaction is becoming a greater concern in crop production and the environment because it can have deleterious effects on growing conditions that are difficult to remediate. Because compaction can vary considerably from point to point within fields, and also from depth to depth within the soil profile, it is important to consider quantification and management of the spatial and vertical variability in soil compaction when developing an overall SSCM plan.

Techniques to quantify and manage the variability in soil compaction or strength have been developed and tested by many researchers. In this paper, the importance of soil compaction, techniques for quantification of its variability, and the concept of site-specific tillage are examined. Methods and systems to detect within-field variation in soil strength as a surrogate measure of soil compaction and related soil properties are also compared and discussed. Finally, future

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directions for research and development are suggested.

2. THE COMPACTION PROBLEM

Soil compaction is the action of soil becoming more compact, reducing macropores and increasing bulk density. Forces that cause compaction originate mainly from two sources. One source is mechanical forces induced by agricultural activities using machines and animals. These forces are usually applied for short periods and can be measured. The other source of compaction is natural phenomena. For example, drying and other natural processes such as rainfall and settling cause soil compaction (Gill and Vanden Berg, 1968). Natural compaction occurs slowly and is difficult to recognize.

Soil compaction affects physical, biological, and chemical properties of soil, usually causing negative impacts on crop root growth and the environment. As soil compaction increases, the number of particle-to-particle contacts and the binding forces between elementary particles increase, which increases soil strength (Guerif, 1994). Both increased bulk density and increased penetration resistance restrict root development and growth (Taylor and Gardner, 1963; Horn et al., 1995; Lipiec and Stepniewski, 1995). Plant roots must be able to reach water and nutrients in the soil. Therefore, soil strength levels that prevent root penetration and elongation may reduce plant growth and development, because water and nutrients beneath the restricted zones are not available to the plants (Unger and Kaspar, 1994). Varsa et al. (1997) investigated the effect of deep tillage on soil physical characteristics and corn root growth and grain production. They found that deep tillage reduced penetration resistance and soil bulk density, increased root proliferation, improved the depth and uniformity of root development, and resulted in increased corn yields.

Soil compaction negatively affects the biological activity of plant roots and organisms in the soil. It may reduce aeration of the soil so that metabolic activities of roots are prevented (Voorhees et al., 1975). Whalley et al. (1995) stated that soil compaction reduces biotic activity particularly in the case of roots, earthworms and other fauna. Microbial activity changes from aerobic to anaerobic with compaction. Compaction decreases soil pore size and temperature, and increases the proportion of water-filled pore space when soil water content reaches field capacity. These changes affect the activity of soil organisms by decreasing the rate of decomposition of soil organic matter and subsequent release of nutrients (Gill and Vanden Berg, 1968).

There are also environmental concerns regarding soil compaction. Horn et al. (1995) stated that reduced water infiltration might result in soil erosion, with serious negative effects on the environment. Compacted soil might contribute to global atmospheric warming due to increased emission of CO_2, CH_4, and N_2O caused by reduced water infiltration and soil aeration. Soane and Van Ouwerkerk (1995) stated that the environmental degradation from soil compaction and reduced water infiltration included loss of quality of the air, surface waters (due to increased runoff of pollutants), ground waters (due to inflow of nitrate, fertilizers and pesticides), and soil resources.

The amount of compaction is influenced by various soil properties such as texture, water content, air content, organic matter, temperature, and water movement in soil (Koolen and Kuipers, 1983). Thus, the degree of compaction could be different at different within-field locations having specific soil conditions. The causes of soil compaction and the resulting soil deformations may also be different in the various soil depths (i.e., top-soil and subsoil) (Koolen and Kuipers, 1983). Therefore, it is important to consider site-specific quantification and management of the spatial and vertical variability in soil compaction and other soil physical properties induced by natural and human activities for successful SSCM.

3. QUANTIFICATION OF SOIL COMPACTION

A. Soil Sampling and Laboratory Determination

The degree of soil compaction, called compactness, can be expressed by pore space, the volume of pores (water + air) divided by the total volume of the soil; void ratio, the total volume of pores divided by the total volume of solids; or bulk density, the weight of solids in a unit volume (Koolen and Kuipers, 1983). There are a number of ways to quantify the state of soil compaction (Fig. 1). Traditionally,

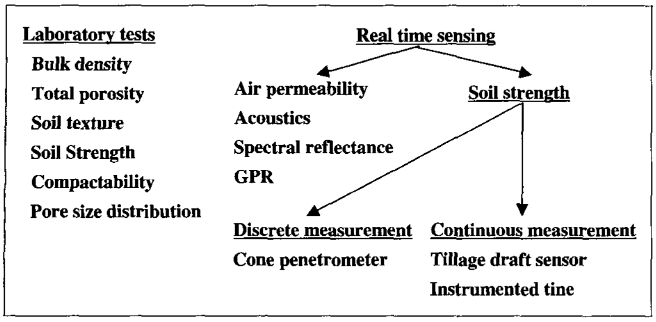

Fig. 1 Techniques for estimation and quantification of soil compaction.

the degree of soil compaction has been determined through laboratory tests with disturbed or intact core soil samples. This type of approach, however, is time-consuming, laborious, and expensive.

B. Real-time *In-situ* Quantification

Even though the degree of soil compaction is generally expressed through measurement of changes in soil bulk density, other properties such as structure, pore size distribution, permeability, aeration characteristics, or strength are also strongly influenced by compaction and may have a greater influence on subsequent crop growth (Soane and Van Ouwerkerk, 1994). To overcome the limitations of laboratory testing, real-time field sensors have been developed to quantify soil compaction and related soil properties. Approaches to compaction measurement include air permeability (Clement and Stombaugh, 2000), acoustics (Grift et al., 2005), spectral reflectance (Dematte et al., 2001), and ground penetrating radar (GPR) (Freeland et al., 1999). Note that these are indirect methods that estimate soil conditions occurring when soil is compacted, rather than measuring soil compaction itself.

Clement and Stombaugh (2000) developed a sensor that measured the pressure required to force a constant flow rate of air into the soil through a specially designed tillage shank. The sensor was tested at a depth of 0.3 m and a forward speed of 0.44 m s^{-1} with an air flow rate of 0.164 m^3 min^{-1}. Tests were repeated in two different soil conditions: 1.83 MPa cone index (CI) and 30% water content (WC) and 2.38 MPa CI and 20% WC. Another test was conducted to compare the effect of different tillage treatments: no tillage (2.69 MPa CI), strip tillage (2.46 MPa CI), and a sub-soiled treatment (2.08 MPa CI). The sensor indicated changes in soil properties including soil structure/compaction, soil water content, and soil type. Disadvantages of this approach included the indirect nature of the measurement and the fact that the sensor was designed to operate at a constant depth, which provided measurements at only one point in the soil profile. Other concerns with the sensor were air leakage and excessive disruption of the soil structure at the point of measurement.

Tekeste et al. (2002) developed an acoustic compaction layer detection sensor by fitting a very small microphone in a horizontally operating cone. This sensor was based on the assumption that the sound level produced by soil-microphone contact might be proportional to the degree of soil compaction since more energy would be required to break up more strongly aggregated soils. When the sensor was tested at a 0.44 m s^{-1} speed at depths increasing from 0 to 30 cm, both the amplitude of the acoustic signal and CI showed a similar depth profile pattern. The authors cautioned that the acoustic approach is purely empirical and does not reveal knowledge about the underlying physical mechanisms of sound generation in soil.

4. MEASUREMENT OF SOIL STRENGTH (MECHANICAL RESISTANCE)

A. Soil Strength and Affecting Factors

An alternative approach to estimate the state of soil compaction is to measure soil strength, since soil strength is strongly associated with degree of compaction, packing density, relative bulk density, and drainable porosity (Canarache, 1991). Soil strength is the ability or capacity of a particular soil in a particular condition to resist or endure an applied force. When external forces are applied, soils react in different modes, according to the characteristics of the internal stress tensor. Each mode corresponds to a given stress-strain relationship, which may involve compaction, brittle failure with dilation, and/or plastic flow without volumetric change (Guerif, 1994). Strength is a dynamic property of soil in the sense that the strength change exhibited in soil due to applied forces is much higher in degree than in many other materials.

Factors affecting soil strength have been identified by analytical models (e.g., Hettiaratchi and Reece, 1974), semi-empirical techniques like dimensional analysis (e.g., Schuring and Emori, 1964; Wismer and Luth, 1972), and experimental study (e.g., Alihamsyah et al., 1990). The factors generally fall into five categories: (1) soil condition (e.g., bulk density, water content, texture, internal friction angle, and cohesion), (2) operating considerations (e.g., speed and depth of operation, and horizontal vs. vertical direction of movement), (3) tool design (e.g., geometry and surface roughness), (4) soil-tool interaction (e.g., friction angle and adhesion), and (5) load distribution on the soil surface. In addition to individual effects of the factors, interactions among the factors also affect soil strength.

B. Cone Penetrometer

The soil cone penetrometer is often used to quantify soil strength with depth and thereby also provide information related to soil morphological characteristics (e.g., Mulqueen et al., 1977). The index of soil strength measured by a cone penetrometer, cone index (CI), is defined as the force per unit base area required to push the penetrometer through a specified small increment of soil. The shapes and operating conditions of a standard cone penetrometer are documented in ASAE Standard S313.3 (ASAE Standards, 2005a) and ASAE Engineering Practice EP 542 (ASAE Standards, 2005b).

The applications of a cone penetrometer were reviewed thoroughly by Perumpral (1987). Douglas and Olsen (1981) used a cone penetration test in soil classification by measuring cone resistance and friction force on the penetrometer shaft; and associating the ratio of the two forces with data used in soil classification. Recently, soil strength data have been intensively collected using electronic cone penetrometers to develop soil strength maps (e.g., Clark, 1999), assess variability in soil strength (e.g., Ley and Laryea, 1994), and to detect depth to restrictive layers (e.g., hardpan) based on the CI level. A cone penetrometer can be combined with other sensors, enabling simultaneous measurement of penetration resistance and soil properties such as soil water content (e.g., Hummel et al, 2004; Sun et al., 2005) and apparent electrical conductivity (ECa) (e.g., Sudduth et al., 2000).

Raper et al. (1999) developed a multiple-probe cone penetrometer that could be tractor-mounted and used to determine soil strength profiles across the row more quickly and easily. Cone penetrometer readings require a “stop-and-go” procedure and only collect data at discrete locations, making it difficult to collect the amount of data required for SSCM, even with a multiple-probe penetrometer. Even in nonspatial analyses, researchers have often collected hundreds of penetrometer readings to investigate treatment differences (e.g., Busscher et al., 1986) and to relate cone index to soil properties such as water content and bulk density (e.g., Sojka et al., 2001). Because of this limitation, it would be laborious and time-consuming to collect enough data with a cone penetrometer to accurately map compaction variations within a field.

C. Tillage Draft Sensors

Another method to estimate the state of soil strength is to use tillage implement draft. McLaughlin and Burtt (2000) investigated the suitability of spatial measurements of implement draft, tractor fuel consumption, engine speed and ground speed for mapping tillage energy. With a nominal speed of 2.25 m s^{-1}, three tillage operations were performed: primary tillage with a disk-ripper at a depth of 8-20 cm, secondary tillage with a tandem disk harrow operating a nominal depth of 8-10 cm, and final tillage with a cultivator. Data were collected for each tillage operation at 100 Hz with integral low-pass filters set at 10 Hz. Maps of the four parameters for a given tillage operation showed similar patterns. Maps for primary tillage showed lines of higher implement draft when traversing subsurface drain tiles, and higher draft in some of the depressions in the field. Differences in operating depth due to areas of soft and hard soil sometimes resulted in higher draft in sandy areas than in dry, hard clay areas.

Van Bergeijk et al. (2001) measured plow draft to locate different topsoil types in a field. Specific draft (draft force per unit area) was measured with a three-furrow plow on a 6-ha field. Clay contents were between 5 to 35% and gravimetric soil water contents ranged from 11 to 23%. Draft maps corresponded well (cross correlation coefficient at zero distance of 0.6) with the clay contents shown by the soil survey but with a higher spatial resolution than contained in the survey. Velocity measurements were important to translate the specific draft to a standard velocity. Gilbertsson (2001) compared a draft force sensor and a soil EC_a sensor as a system for measuring soil parameters. He found good correlations ($r>0.72$) between the combined sensor measurements and clay contents, so clay contents could be predicted more accurately using multiple linear regression analysis combining the two sensors. Even though tillage draft can be used to estimate soil strength properties, as shown by the above researchers, the measurement is limited by the fact that it integrates the soil resistance over the operating depth and width of the tillage tool. Thus, tillage draft cannot provide the horizontal or vertical resolution desirable for SSCM.

D. On-the-go Strength Sensor Using Narrow Tines

To provide better spatial resolution, a number of researchers have developed specialized soil strength sensors. An instrumented chisel was developed using an array of four strain gauges, and used to predict tillage implement draft requirements (Glancey et al., 1989; Glancey et al., 1996). Field experiments were conducted at 2 forward speeds (0.22 and 0.89 m s^{-1}) and 2 chisel depths (153 and 305 mm) in 2 distinct soil conditions (tilled and untilled). Data collected for comparison were bulk density, water content and CI profiles down to a depth of 305 mm. Force distribution over the tillage depth was linear at the shallow depth in both soils, while the distribution was nonlinear at the greater depth of operation in the untilled soil.

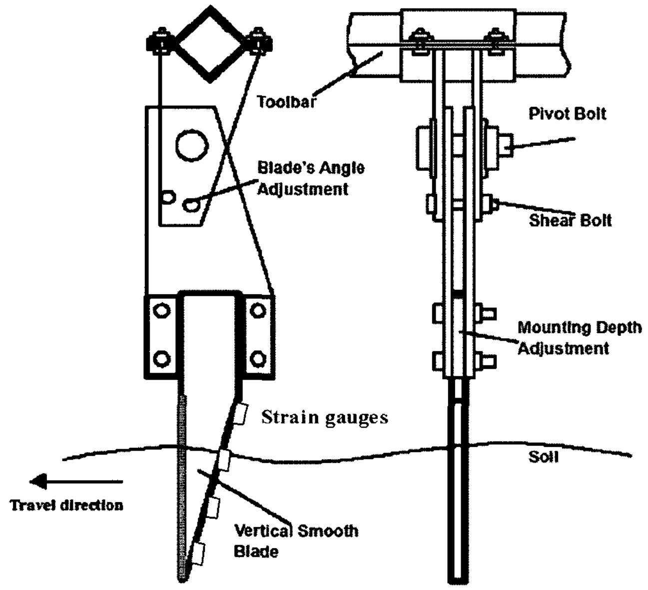

Fig. 2 An instrumented vertical blade (Adamchuk et al., 2001).

Adamchuk et al. (2001) instrumented a vertical blade with an array of four strain gauges to map both horizontal and vertical spatial variation in mechanical soil resistance (Fig. 2). The strain gauge array was attached to the back side of the blade to measure the deformation of the blade due to the applied stress. By using a strain gauge array, the above two systems could predict soil cutting-force distribution over tool operating depths. Drawbacks of this approach were that the strain gauge array detected the deformation of the tools, not soil strength itself; and that the measurements were significantly affected by the geometry of the tools used.

Andrade et al. (2001) developed a soil cutting-force profile sensor that could take measurements up to a depth of 63 cm on increments of 7.5 cm (5-cm active cutting elements separated by 2.5-cm dummy elements). The device consisted of eight cutting edges supported by independent load cells that measured the force on each cutting edge as the system was pulled through the soil (Fig. 3). The test field contained a loam soil of the Yolo series and was prepared to four treatments; combinations of tilled/undisturbed and irrigated/dry conditions. The sensor operated at an average velocity of 0.63 m s^{-1}, and each run had a length of 75 m with a 1.5-m spacing between runs. The soil cutting force was influenced by soil water content, depth of operation of the tine, and location of the cutting edge. Although the system successfully provided a soil cutting-force

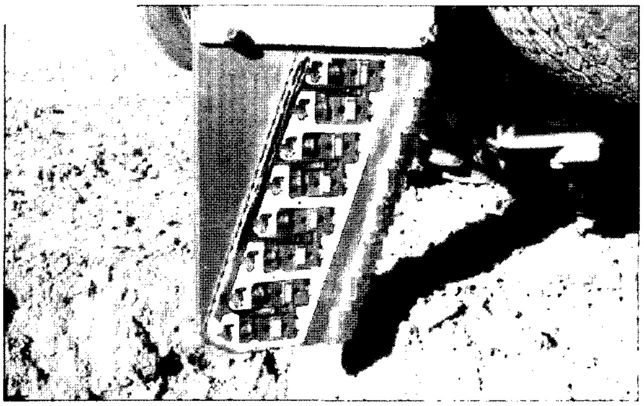

Fig. 3 The UC-Davis compaction profile sensor (Andrade et al., 2001).

profile in front of the tool, the problem of interactions between the adjacent cutting edges was not addressed.

Alihamsyah et al. (1990) designed a horizontally operating penetrometer suitable for on-the-go measurement of soil strength. Experimental treatments were soil type (loamy sand and clay), water content (high and low), penetration rate (3 and 9 cm s^{-1}), and tip type (cone and prismatic shapes). Penetration resistance of the prismatic tip tended to be less than that of the cone tip since the prismatic tip displaced the soil only to the sides while the cone tip displaced the soil radially in all directions. The average penetration resistance values were similar at the two penetration rates.

Chukwu and Bowers (2005) modified the horizontal operating penetrometer of Alihamsyah et al. (1990) so that it could measure soil mechanical impedance at three depths simultaneously (Fig. 4). They utilized three prismatic tips with a 30° apex angle and three load cells similar to those used in the single tip sensor. A 10-cm vertical tip spacing was chosen to provide a 30-cm sensing profile and to minimize measurement interference from one tip to the next. A groove for installing the load cell cables and protecting them from damage was also provided. When operated at a speed of 3 cm s^{-1} through soil layered with different compaction levels, the sensor detected the difference in soil mechanical impedance with depth at a 5% significance level. A potential problem with this configuration was measurement interference between the sensing elements and the main blade of the sensor.

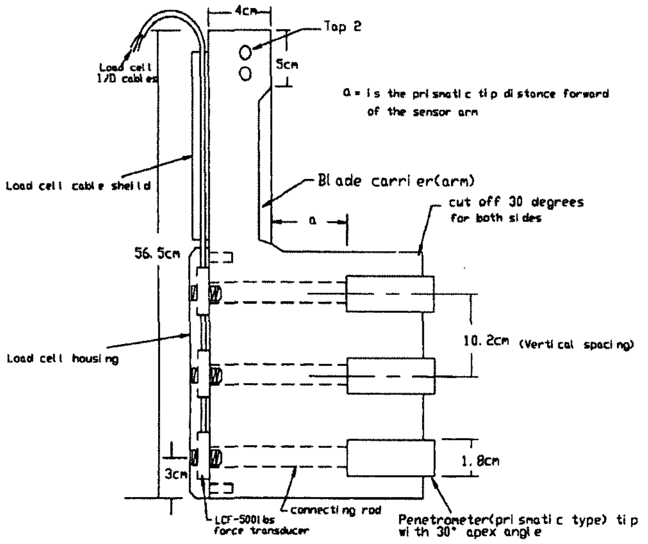

Fig. 4 A multiple-depth mechanical impedance sensor (Chukwu and Bowers, 2005).

Chung et al. (2006) developed a soil strength profile sensor (SSPS) that could take measurements continuously and more efficiently while traveling across the field (Fig. 5). The on-the-go SSPS was designed and fabricated using an array of load cells, each of which was interfaced with a soil-cutting tip. These multiple prismatic tips were extended 5.1-cm forward from the leading edge of a vertical blade and spaced 10-cm apart to minimize interference from the main blade and adjacent sensing tips. The sensing tip had a 60° cutting or apex angle and a base area of 361 mm^2. The design maximum operating depth was 0.5 m, and the upper limit and resolution of soil strength were 19.4 and 0.14 MPa, respectively. A significant (α = 0.01) linear relationship between PSSI and penetrometer cone index (CI), with a slope of approximately 0.6, was found for field data collected at a 30 cm depth. Maps created with sensor data showed spatial and vertical variability in soil strength. Depth to the restrictive layer was different for different field locations, and only 5 to 16% of the tested field areas were highly compacted.

5. SITE-SPECIFIC COMPACTION MANAGEMENT

Raper et al. (2000) investigated effects of tillage depth and timing on cotton yield, soil strength, and tillage require-

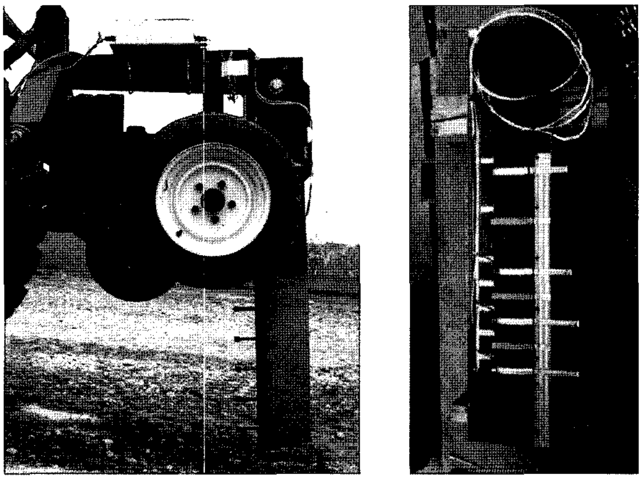

Fig. 5 Side view of the SSPS raised out of the ground, showing the five sensing tips (left), and the main blade with the cover plate open (right) (Chung et al., 2006).

ments. Shallow tillage (0.18 m) and deep tillage (0.33 m) were performed in spring and autumn for five years. They found that shallow tillage required about 50% of the draft and energy of deep tillage and that autumn shallow tillage increased seed cotton yield in some growing seasons. Later, they evaluated the concept of site-specific subsoiling over four years and found that in shallow (25 cm) and medium (35 cm) hardpan conditions, draft force, drawbar power, and fuel use were reduced by 55, 47, and 45%, and 28, 17, and 27%, respectively, by site-specific subsoiling producing equivalent corn yields compared to uniform deep subsoiling (Raper et al., 2005). Busscher et al. (2000) also reported timing effects of deep tillage on penetration resistance and wheat and soybean yield. They found that deep tillage at the beginning of spring or fall, or both seasons, reduced CI and improved wheat and soybean yields. For a decrease in mean profile cone index of 1 MPa, increases in wheat and soybean yields were in the range of 1.5 to 1.7 Mg ha^{-1} and 1.1 to 1.8 Mg ha^{-1}, respectively.

These results indicate that variable depth (and time) tillage based on site-specific soil physical characteristics such as degree of compaction and depth to restrictive layers would reduce tillage energy and increase crop yield. The concept of real-time sensing of soil physical condition and site-specific tillage is not new, but the recent development of on-the-go soil compaction (or strength) profile sensors is emphasizing the need for systems capable of variable-depth and site-specific tillage operations.

Wells et al. (2001) implemented site-specific deep tillage to a depth of 40 cm in four fields. The fields were divided into 0.4-ha grid cells. From each cell, fifteen CI profiles were collected and deep tillage was performed where the maximum CI within the sensing depth was greater than 1.5 MPa. Khalilian et al. (2002) reported on a control system for variable-depth tillage that changed tillage depth based on CI values collected before the tillage operation. The research was motivated by the fact that, based on CI readings collected from their experimental fields, tillage depths to eliminate the hardpan layer ranged from 25 to 45 cm and the thickness of the hardpan layer ranged from 10 to 25 cm. Approximately 75% of the field area required tillage to depths shallower than the conventionally accepted uniform tillage depth. They found that EC_a was inversely related to the predicted tillage depth; therefore tillage depth could be determined using EC_a measurements. Energy savings of 42.8% and fuel savings of 28.4% were achieved with variable-depth tillage compared to conventional uniform-depth tillage.

Gorucu et al. (2003) developed an algorithm to determine the optimum tillage depth in southeastern USA coastal plain soils from soil cone penetrometer data. Their algorithm classified CI profiles into 21 different patterns, each characterized by the depth to and thickness of hardpan layers. A computer program was developed to automate the application of the algorithm to large CI data sets. Adamchuk et al. (2003) developed an algorithm to estimate a nonlinear soil resistance distribution from the discrete data collected by the instrumented tine developed in previous research (Adamchuk et al., 2001). These data could be used to determine whether tillage was necessary or not, but further research was needed to develop an algorithm for closed-loop control of real-time variable-depth tillage.

6. SUGGESTIONS FOR FUTURE STUDY

Compaction problems and associated management issues have been recognized for a long time, but quantification of variability in soil compaction and site-specific compaction management has been motivated by and facilitated with the appearance of precision agriculture. As this happened relatively recently, sensors and control systems are still under development. Future study will need to address a number of issues related to understanding and applying the sensor measurements.

- Soil water content, bulk density, and soil texture are major factors affecting soil compaction measurements. Determination of these soil properties by soil sampling and laboratory tests is laborious, expensive, and time consuming. Therefore, in most cases, such soil property data are available for only a small number of within-field locations. Incorporation of other sensors (e.g., EC_a sensor as a surrogate for soil texture or a capacitive sensor for soil water content and bulk density) would be useful.
- Development and evaluation of different on-the-go soil

strength profile sensors are being pursued by different researchers. Direct comparisons of soil strength measurements from the different sensing systems may not be appropriate. However, standardization of the collection and reporting of on-the-go soil strength data would allow a more reliable comparison among the various sensors and would lead to more reliable application of soil strength measurements from these systems in crop production.

- Soil strength indices from horizontally operating on-the-go soil strength sensors are different from the CI values of vertically operating cone penetrometers due to different soil failure mechanisms. It would be good if relationships between the two soil strength indices could be established since the research literature about the interpretation and application of CI is extensive.
- Site-specific and/or variable-depth tillage operations would require new concepts and components in the design of tillage implements. For example, the appropriate shape of a shank might be different for variable-depth tillage compared with uniform-depth tillage.

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