Site-Specific
Management Guidelines

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Characterizing Soil Variability Using On-the-Go Sensing Technology

Summary

One of the major objectives of precision agriculture technologies is the site-specific management of agricultural inputs to increase profitability of crop production, improve product quality, and protect the environment. Information about the variability of different soil attributes within a field is essential to the decision-making process. The inability to obtain soil characteristics rapidly and inexpensively remains one of the biggest limitations of precision agriculture. Numerous researchers and manufacturers have attempted to develop sensors for measuring soil properties on-the-go. These sensors have been based on electrical and electromagnetic, optical and radiometric, mechanical, acoustic, pneumatic, and electrochemical measurement concepts. The major benefit of on-the-go sensing has been the ability to quantify the heterogeneity (non-uniformity) of soil within a field and to adjust other data collection and field management strategies accordingly. As new on-the-go soil sensors are developed, different real-time and map-based variable rate soil treatments may become economically feasible.

Introduction

The concept of precision agriculture emerged from the belief that variability of growing conditions is one of the major contributors to field-scale differences in yield, and that varying the agricultural inputs according to local changes in soil properties could be beneficial. Many producers have already accumulated a yield history from several growing seasons. However, to engage in an effective decision-making process, it is equally important to obtain high quality information about the spatial structure of different soil attributes which may limit the yield in certain areas of the field. The ability to generate such information rapidly and at an acceptable cost remains one of the biggest limitations. Conducting a variable rate application of fertilizers, lime, and other agricultural inputs without accurate soil maps is frequently inappropriate and may result in economical losses. Therefore, sensor development is expected to increase the effectiveness of precision agriculture. In particular, sensors for on-the-go measurement of soil properties have the potential to provide benefits from the increased density of measurements at a relatively low cost (Pierce and Nowak, 1999).

Numerous researchers and manufacturers have attempted to develop on-the-go soil sensors for precision agriculture. Although a few sensor systems are commercially available, there is an on-going effort to develop new prototypes (Hummel et al., 1996; Sudduth et al., 1997; Adamchuk et al., 2004). The purpose of this publication is to overview the status of current developmental efforts and to provide forecasting on future research related to on-the-go soil sensing.

Sensor Overview

Global positioning system (GPS) receivers, used to locate and navigate agricultural vehicles within a field, have become the most common sensors in precision agriculture. In addition to having the capability to determine geographic coordinates (latitude and longitude), high-accuracy GPS receivers allow measurement of altitude (elevation) and the data can be used to calculate slope, aspect and other parameters relevant to the terrain.

When a GPS receiver and a data logger are used to record the position of each soil sample or measurement, a map can be generated and processed along with other layers of spatially variable information. This method is frequently called a “map-based” approach. Previously, several prototype on-the-go soil sensing systems were developed for “real-time” applications in which the generated sensor signal was used to control variable rate application rate without data recording. Although considered rather attractive, the “real-time” approach has limited applicability due to poorly understood relationships between sensor signal output and agro-economically optimized agricultural input needs. Furthermore, many management strategies (e.g., nitrogen [N] fertilizer application) require multiple layers of georeferenced data as well as the involvement of an expert for successful development of “prescription” maps. Soil maps generated using on-the-go measurements can only serve as a part of this decision-making process.

Although there are many design concepts, most on-the-go soil sensors being developed involve one of the following measurement methods: 1) electrical and electro-

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magnetic sensors that measure electrical resistivity/conductivity or capacitance affected by the composition of the soil tested, 2) optical and radiometric sensors that use electromagnetic waves to detect the level of energy absorbed/reflected by soil particles, 3) mechanical sensors that measure forces resulting from a tool engaged with the soil, 4) acoustic sensors that quantify the sound produced by a tool interacting with the soil, 5) pneumatic sensors that assess the ability to inject air into the soil, and 6) electrochemical sensors that use ion-selective membranes producing a voltage output in response to the activity of selected ions (e.g., hydrogen [H], potassium [K], nitrate [NO_3^-], etc.).

An ideal soil sensor responds to the variability of a single soil attribute and is highly correlated to conventional analytical measurements. However, in reality, every sensor developed responds to more than one soil property and separation of their effects is difficult and sometimes non-feasible. **Figure 1** provides a classification summary of on-the-go soil sensors with corresponding agronomic soil properties affecting the signal. In many instances, an acceptable correlation between the sensor output and a particular agronomic soil property was found for a specific soil type or when the variation of interfering properties was negligible.

Electrical and Electromagnetic Sensors

Electrical and electromagnetic sensors use electric circuits to measure the capability of soil particles to conduct or accumulate electrical charge. When using these sensors, the soil becomes part of an electromagnetic circuit and the changing local conditions immediately affect the signal recorded by a data logger. Several such sensors have become commercially available. For example, one way to estimate soil electrical conductivity (EC) is by electromagnetic induction using Geonics Limited EM38 meter. The transmitting coil induces a magnetic field that varies in strength with soil depth. The magnetic field strength/depth can be altered to measure different depths of the soil to a maximum of 1.5 meters (about 5 ft.). A receiving coil measures the primary and secondary "induced" currents in the soil and relates the two to the soil electrical conductivity. Another instrument for mapping soil EC, the Veris® EC Surveyor™, measures EC more directly (galvanic contact resistivity method). It uses a set of coulter electrodes to send and receive electrical signals through the soil, indicating the EC for several different depths (always starting at the surface). Alternatively, several researchers have used capacitor-type soil sensors to study dielectric properties of the soil. It appears that both conductive and capacitive soil properties which can be measured on-the-go are affected by several agronomic soil characteristics, including soil type (mainly soil texture), soil salinity, moisture, and other characteristics. Capacitor-type sensors have been useful in determining volumetric moisture content in combination with the mechanical sensors described later.

Optical and Radiometric Sensors

Optical and radiometric sensors use light reflectance or another electromagnetic wave signal (ground penetrating radar) to characterize soil. Optical sensors can simulate the human eye when looking at soil as well as measure near-infrared, mid-infrared, or polarized light reflectance. Vehicle-based optical sensors use the same principle as remote sensing. To date, various commercial vendors provide remote sensing services that allow measurement of bare soil reflectance using a satellite or an airplane platform. Cost, timing, cloud coverage, and heavy plant residue cover are major issues limiting the use of bare soil imagery from these platforms. Close-range, subsurface, vehicle-based optical sensors have the potential to be used on-the-go in a way similar to electrical and electromagnetic sensors. They also have the ability to provide more information about individual data points since reflectance can be easily measured in more than one portion of the spectrum at a time. Several investigators have worked on the development of optical sensors to predict clay, organic

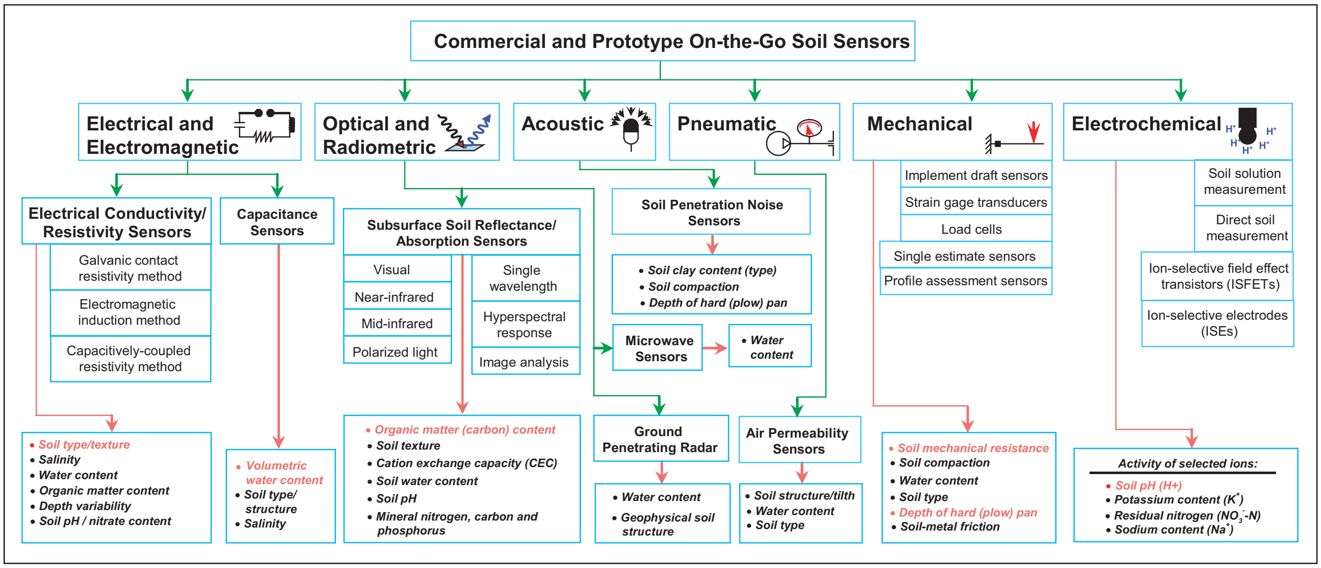

Figure 1. Classification of on-the-go soil sensing systems (soil properties indicated by red font are the most probable to distinguish).

matter, water content, and cation exchange capacity. In addition, several researchers have correlated soil reflectance with soil chemical properties…i.e., soil NO_3 or phosphorus (P) content and pH. Some researchers are utilizing ground-penetrating radars (GPR) to investigate wave movement through the soil. Changes in wave reflections may indicate changes in soil density or restricting soil layers. Ground penetrating radar has great potential for geophysics, in general, and agriculture, in particular, especially to support water management. There is no widely used commercial optical or radiometric sensor developed for precision agriculture at this time.

Mechanical Sensors

Mechanical sensors can be used to estimate soil mechanical resistance (often related to compaction). These sensors use a mechanism that penetrates or cuts through the soil, and records the force measured by strain gages or load cells. Several investigators have developed prototypes that show the feasibility of continuous mapping of soil mechanical resistance, however, none of these devices is commercially available. As an example, **Figure 2** illustrates an instrumented system comprised of a mechanical, an electrical and an optical sensing component. The vertical blade instrumented with an array of strain gages was designed to detect spatial and depth variability of soil mechanical resistance within a soil profile between 5 and 30 cm (2 to 12 in). Simultaneously, a capacitor-type sensor detects spatial variability in soil moisture when two sets of photodiodes and light-emitting diodes protected with a sapphire window are used to determine soil reflectance in blue and red portions of the spectrum. This system is expected to help delineate field areas with potential compaction, excessive moisture and/or low organic matter level.

Acoustic and Pneumatic Sensors

Acoustic and pneumatic sensors serve as alternatives to mechanical sensors when studying the interaction between the soil and an agricultural implement. Acoustic sensors have been investigated for determining soil texture and/or bulk density by measuring the change in noise level due to the interaction of a tool with the soil particles. Pneumatic sensors were used to measure soil air permeability on-the-go. The pressure required to force a given volume of air into the soil at a fixed depth was compared to several soil properties, such as soil structure and compaction. At this time, the relationship between sensor output and the physical state of soil is poorly understood and additional research is needed.

Electrochemical Sensors

Electrochemical sensors can provide the most important type of information needed for precision agriculture – soil nutrient availability and pH. When soil samples are sent to a soil-testing laboratory, a set of recommended laboratory procedures is performed. These procedures involve sample preparation and measurement. Some measurements (especially determination of pH) are conducted using an ion-selective electrode (ISE), or an ion selective field effect transistor (ISFET). These electrodes detect the activity of specific ions (NO_3, K, or H in the case of pH). Several investigators are trying to adopt existing soil preparation and measurement procedures essentially to conduct a laboratory test on-the-go.

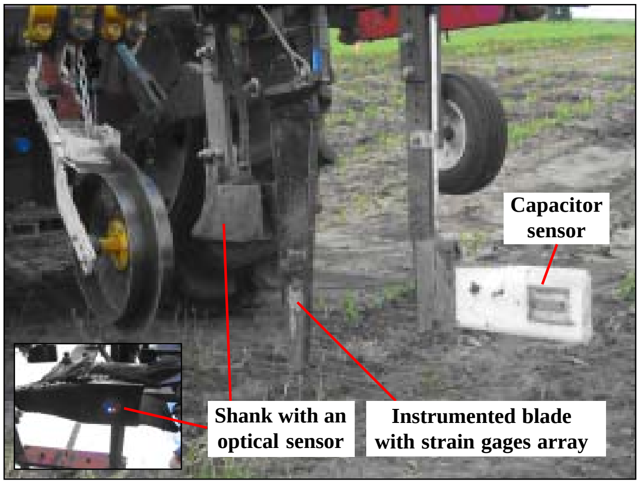

Figure 2. **Prototype system comprised of mechanical, electrical, and optical sensing components (University of Nebraska-Lincoln, Lincoln, Nebraska).**

For example, recently commercialized by Veris Technologies, an automated soil pH mapping system (Veris® Soil pH Manager™) uses two ion-selective electrodes to directly determine the pH of naturally moist soil (Adamchuk et al., 1999). While traveling across the field, a soil sampling mechanism located on a mobile frame obtains a horizontal core sample of soil from approximately 10 cm (4 in.) depth and brings it into firm contact with the sensitive membranes and reference junctions of two combination ion-selective electrodes. As soon as the output stabilizes (approximately 10 s) the electrode surfaces are rinsed with water and a new sample is collected. Each data point obtained using this method has a greater error than the laboratory analysis of a composite soil sample. However, increasing the sample density more than 10 times suggests that a higher quality of soil pH maps can be generated at the same cost. An agro-economic analysis showed that higher resolution maps can significantly decrease pH estimation errors and increase potential profitability of variable rate liming. A simulation comparing 1 ha (2.5 acre) grid point sampling and automated mapping resulted in $6.13/ha higher net return over the cost of liming during a 4-year growing cycle in a corn-soybean rotation. There is an on-going effort to integrate additional ion-selective electrodes to map soluble K and residual NO_3-N along with soil pH. The drawback of this method is that it does not provide real-time ion extraction. Therefore, the measurements represent “snapshots” of ion activity and current recommendations cannot be applied directly to prescribe variable rate lime and fertilizer applications. However, such recommendations could be developed if the ion activity measurements are collocated with a soil-buffering estimate, such as cation exchange capacity (CEC), that can be predicted based on electrical conductivity and/or soil reflectance measurements. That is why the Veris® pH Manager™ is integrated with a more tradition EC Surveyor™ mapping unit (**Figure 3**). Other prototypes allowing for real-time extraction of targeted ions are being developed as well.

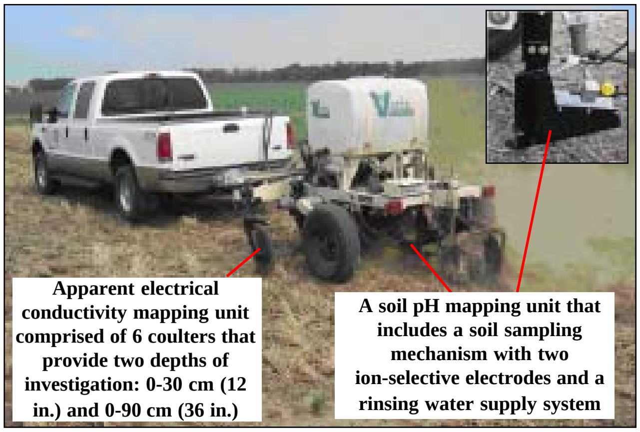

Figure 3. Veris® Mobile Sensor Platform integrating soil electrical conductivity and pH mapping units (Veris Technologies, Inc, Salina, Kansas).

Potential Applications

Although various on-the-go soil sensors are under development, only the electrical and electromagnetic sensors have been widely used in precision agriculture. Producers prefer sensors that provide direct inputs for existing prescription algorithms. Instead, commercially available sensors provide measurements such as EC that cannot be used directly since the absolute value depends on a number of physical and chemical soil properties such as texture, organic matter, salinity, moisture content, temperature, etc. In contrast, electrical and electromagnetic sensors give valuable information about soil differences and similarities which make it possible to divide the field into smaller and relatively homogeneous areas referred to as finite management elements (FME) or management zones. For example, such FME could be defined according to the various soil types found within a field. In fact, EC maps usually reveal boundaries of certain soil types better than conventional soil survey maps. Various anomalies such as eroded hillsides or ponding can also be easily identified on an EC map. Different levels of productivity observed in yield maps also frequently correspond to different levels of electrical conductivity. In many instances such similarities can be explained through differences in soil. In general, the EC maps may indicate areas where further exploration to explain yield differences is needed.

Therefore, it seems reasonable to use maps produced by the electrical and electromagnetic sensors along with other data layers (e.g., yield maps, aerial imagery, terrain, management history, etc.) to discover the heterogeneity (variability) of crop growing conditions within a field. When based on multiple data layers, FMEs with a similar EC and relatively stable yield may receive a uniform treatment that can be prescribed based on a reduced number of soil samples located within each FME. In addition, soil sensors may be useful in identifying areas within fields which are less profitable or environmentally risky to farm. Work by Corwin and Lesch (2003), and by Heiniger et al. (2003), can serve as examples of site-specific data management that includes processing of EC maps.

Besides the idea of FMEs, integrating different measurement concepts into a single mapping unit is one of the current topics of research. Ultimately, just two or three sensor platforms could be used to generate multi-layer field maps which could serve as the input for a decision-support system. The data processing algorithm could be developed to either predict specific soil properties (intermediate step) or generate variable soil treatment recommendation maps (final step).

Another important issue with regard to the application of on-the-go soil sensing is the agro-economic value of the data obtained. For example, data produced by EC soil sensors were originally anticipated to correlate with other specific soil properties. However, further research showed that EC itself might be directly used for making management decisions and the number of such applications remains unknown. Similarly, reliable and relatively inexpensive soil sensors that are based on alternative measurement concepts may have quite extraordinary and probably region-specific applications in the future. Ultimately, it is anticipated that new soil sensors will be involved in agronomic and economic studies demonstrating the potential value of information achievable through on-the-go soil sensing for precision agriculture.

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