ON-THE-GO SENSING TECHNOLOGY FOR IMPROVED CROP NUTRIENT MANAGEMENT

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Abstract

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 finally 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.

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., 2004a). The purpose of this publication is to overview the status of current developmental efforts and to discuss applicability of on-the-go soil sensors to improve soil fertility management. Results of our recent research on integrated on-the-go mapping of chemical soil properties were used as an example.

Sensor Overview

Global Positioning System (GPS) receivers, used to locate and navigate agricultural vehicles within a field, have become the most common sensor 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 being 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 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 is a large variety of design concepts, most on-the-go soil sensors being developed involve one of the following measurement methods: 1) electrical and electromagnetic 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, potassium, nitrate, 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 types 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.

<u>Electrical and electromagnetic sensors</u> 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. Some of them are produced by Veris Technologies, Inc. (Salina, Kansas, USA), Geonics Limited (Mississauga, Ontario, Canada), Geocarta (Paris, France), Geometrics, Inc. (San Jose, California, USA). Dualem, Inc. (Milton, Ontario, Canada), and Crop Technology, Inc. (Bandera, Texas, USA). 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. 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 Probe, measures EC more directly (galvanic contact resistivity method). It uses a set of coulter electrodes that sends out an electrical signal through the soil. The signal is received by another set of electrode coulters that measure the voltage drop due to the resistivity of 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. It has been observed that soil types (mainly soil texture) significantly affect the output of most commercially available electrical resistivity/conductivity sensors. Field variability of soil salinity, moisture and other characteristics interferes with this relationship. Capacitor-type sensors have been useful in determining volumetric moisture content in combination with the mechanical sensors described later.

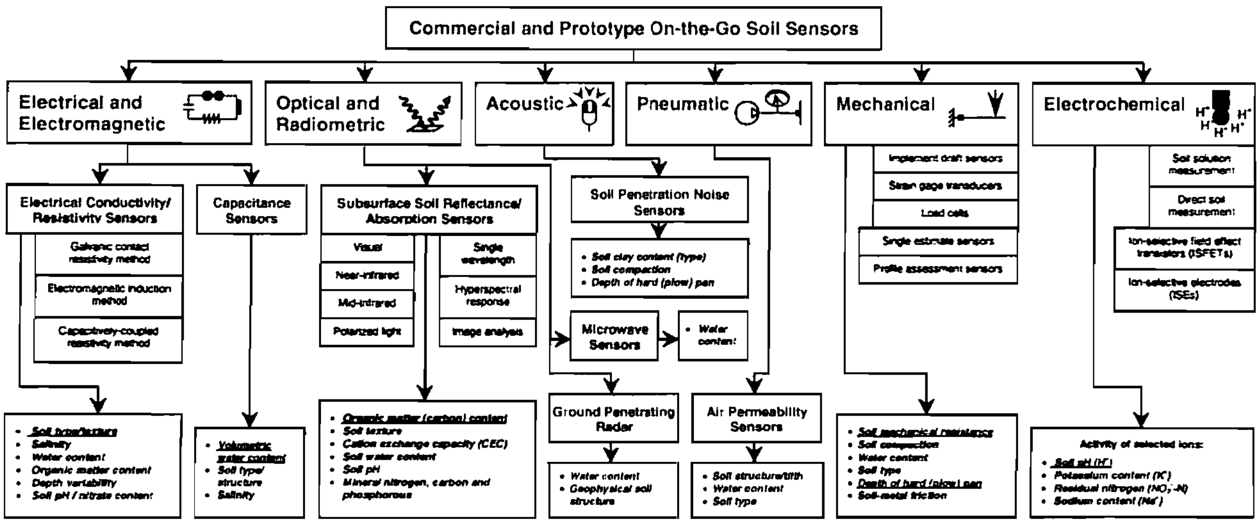

Figure 1. General classification of on-the-go soil sensing systems (underlined soil properties are the most probable to distinguish).

Optical and radiometric sensors use light reflectance or another electromagnetic wave signal (ground penetrating radar or gamma-radiometer) 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 matter, water content, and cation exchange capacity. In addition, several researchers have correlated soil reflectance with soil chemical properties (i.e., soil nitrate or phosphorous content and pH). Rather than using optical reflectance. 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. Also, portable γ-radiometers have been recently used to study soil mineralogy. There is no widely used commercial optical or radiometric sensor developed for precision agriculture at this time.

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 resistance, however, none of these devices is commercially available. Results of research aimed at assessing the benefits of variable tillage are still limited. A number of investigations have attempted to search for soil depth where a local maximum of soil mechanical resistance (plow or hard pan) occurred. Adjusting tillage depth to remove the hard pan has a potential economic impact.

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. 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. Potentially, several different soil treatment practices could be altered based on the data obtained.

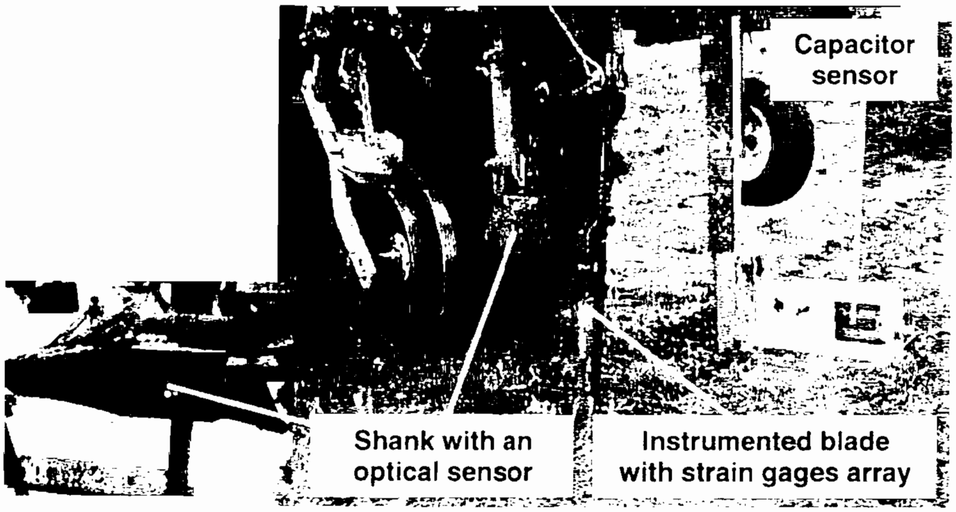

Figure 2. Prototype system comprised of mechanical, electrical and optical sensing components (University of Nebraska-Lincoln, Lincoln, Nebraska).

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. Because of conceptually different measurement principles, acoustic and pneumatic sensors may be strong candidates for sensor fusion in which multiple data streams are merged to improve prediction of targeted soil attributes.

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 (nitrate, potassium, or hydrogen in case of pH). Several investigators are trying to adopt existing soil preparation and measurement procedures essentially to conduct a laboratory test on-the-go.

For example, recently commercialized by Veris Technologies, an automated soil pH mapping system (Veris® Soil pH ManagerTM) 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 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 obtained. 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 ten times suggests that a higher quality of soil pH maps can be generated at the same cost. An agro-economic analysis by Adamchuk et al. (2004b) 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 four-year growing cycle in a corn-soybean rotation. There is an on-going effort to integrate additional ion-selective electrodes to map soluble potassium and residual nitrate-nitrogen 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 CEC) that can be predicted based on electrical conductivity and/or soil reflectance measurements. That is why the Veris® pH ManagerTM is integrated with a more tradition EC SurveyorTM mapping unit (Figure 3). Other prototypes allowing for real-time extraction of targeted ions are being developed as well.

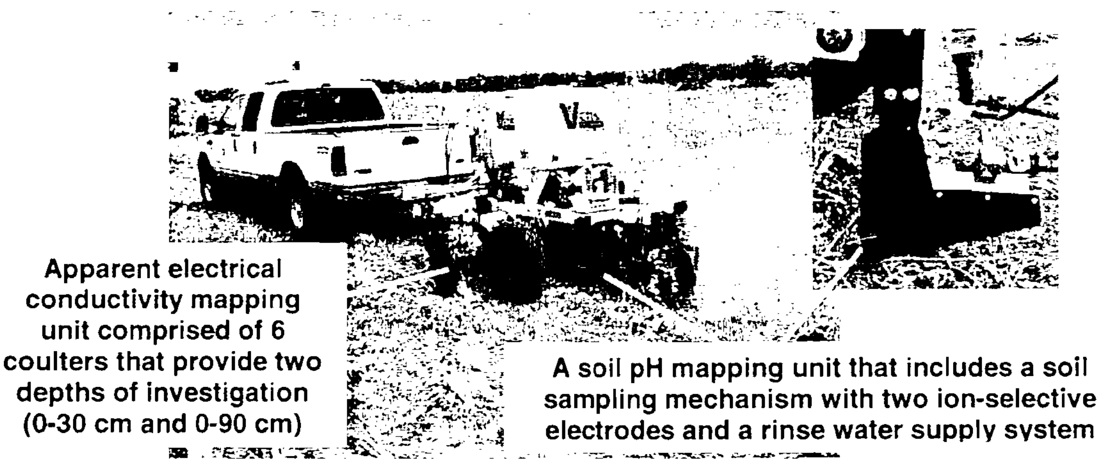

Figure 3. Veris® Mobile Sensor Platform integrating soil electrical conductivity and pH mapping units (Veris Technologies, Inc, Salina, Kansas).

Soil Fertility Management Applicability

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 management zones. For example, these management zones 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 (Corwin and Lesch, 2003; Heiniger et al., 2003).

Besides the idea of management zones, integrating different measurement concepts into a single mapping unit is one of the current topics of research. The degree of association between different soil properties and conceptually different sensor outputs is not the same. Therefore, maps generated by different sensors can be integrated to improve their applicability. The proper combination of sensors to be integrated while mapping the field and corresponding data processing algorithm should be specific for given climatic and crop growing conditions.

For example, in our recent research, the soil pH measurement equipment shown in Figure 3 was expanded to simultaneously determine soluble potassium and residual nitrate contents (Figure 4). Tested in laboratory conditions, the concept involved integration of different ion-selective electrodes to measure the activity of hydrogen, potassium and nitrate ions in an aquatic solution to be prepared on-the-go.

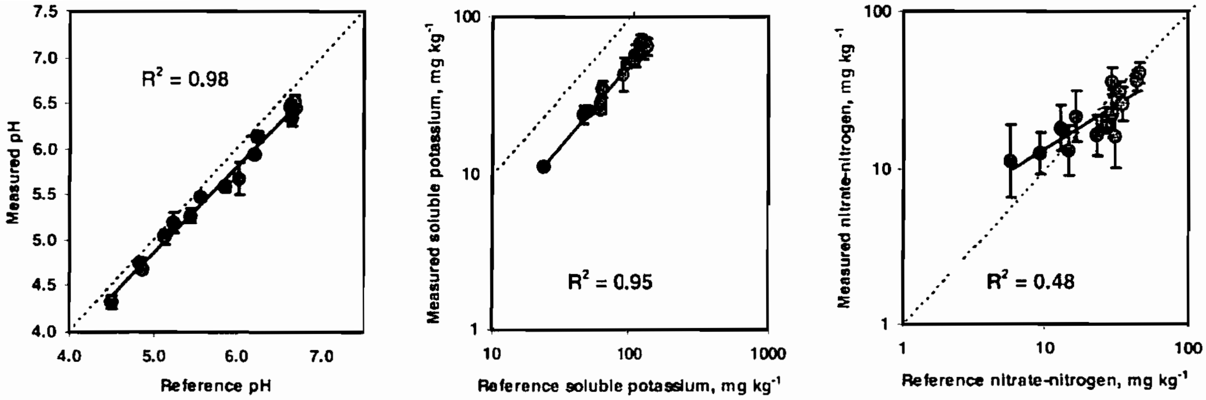

Figure 4. Relationships between measured and reference a) soil pH, b) soluble potassium and c) residual nitrate-nitrogen contents. The measured estimates were obtained using the method discussed and the reference measurements were conducted in a commercial soil laboratory.

Although both pH and soluble potassium contents can be mapped on-the-go, these measurements are not sufficient to prescribe lime and potassium fertilizer application rates. In many states, buffer pH and exchangeable potassium measurements are required. Although chemical extraction of ions while moving through the field presents some technical difficulties, knowing the soil buffering characteristics determined using EC or other reviewed methods can aid in development of spatially variable soil treatment prescriptions.

For example, Figure 5 illustrates relationships between measured and predicted buffer pH and exchangeable K values for fifteen diverse Nebraska soils. In both cases, the cation exchange capacity (CEC) was used to indicate soil buffering through a multivariable regression analysis. The CEC itself was estimated using measured percent clay and organic matter content.

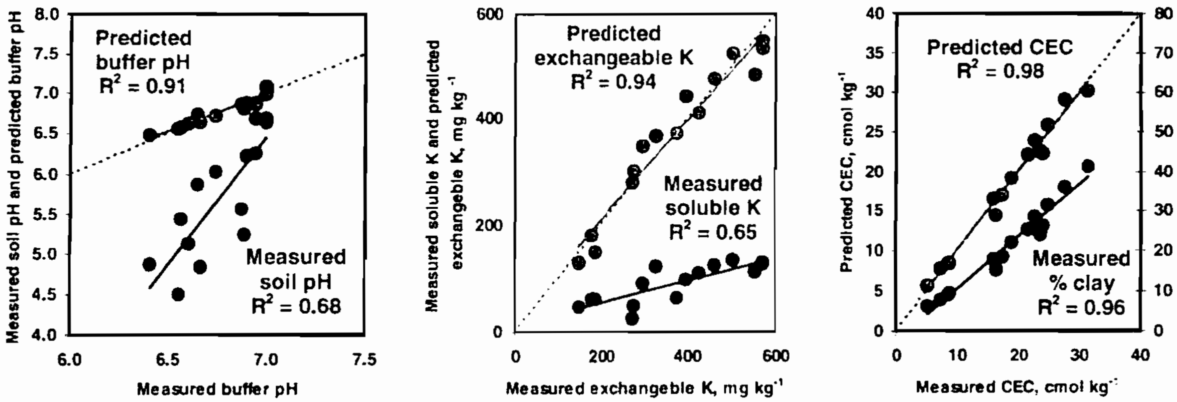

Figure 5. Relationships between a) measured soil pH / predicted buffer pH and measured buffer pH, b) measured soluble K / predicted exchangeable K and measured exchangeable K, and c) predicted CEC / % clay and measured CEC. These measurements were obtained in several commercial soil laboratories for fifteen Nebraska soils.

Based on this example, it appears that, in certain conditions, a predictor of soil texture (most likely EC) and perhaps of organic matter content (optical reflectance) should be sufficient to determine site-specific soil buffering characteristics and use on-the-go measurements of soil pH and soluble K obtained simultaneously to determine needs for lime and potassium fertilizer using exisitng recommendations. However, the data processing algorithm could be developed to predict specific soil properties (intermediate step) as well as to generate variable soil treatment recommendation maps (final step). The inability to directly measure soil phosphorous remains the biggest limitation toward development of electrochemical on-the-go soil sensors.

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.

Summary

On-the-go soil sensors being developed can provide high density information about soil variability. The ability to map specific agronomic soil attributes remains questionable due to the sensitivity of each sensor to a sensor-specific array of these properties. Combining different sensors may be beneficial to separate the effects of individual soil properties and to provide sufficient data for the decision-making process. New and improved sensors are still under development. A comprehensive agro-economic evaluation of the value of sensor-based information is needed

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