Sensor Technologies for
Precision Soil Nutrient Management and Monitoring

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Abstract: Problem statement: Growing concerns about the need to increase crop productivity without causing environmental injury have led to the deployment of site-specific strategies in soil nutrient management, where nutrients are applied in variable rates to fit local requirements. Variable rate application of nutrients is typically based on a rigorous sampling regime and time-consuming data analyses. The ability to monitor soil nutrient concentration efficiently is highly desirable. **Approach:** On-site monitoring of soil nutrient concentration offers the opportunity for higher density measurements at relatively lower costs. This would allow for an efficient mapping of nutrient variability to facilitate variable-rate nutrient application. **Results:** Implementation of nutrient management programs using sensor technology potentially promotes environmental stewardship while maintaining crop productivity and profitability. Rapid and non-destructive quantification of spatially-variable soil nutrients has been made possible with on-the-go sensors such as optical, electromagnetic and electrochemical sensors. **Conclusion:** This review demonstrates the potential of on-the-go sensors for non-destructive and rapid characterization of soil nutrient variability within crop fields.

Key words: Precision agriculture, sensors, sustainability, soil nutrient management

INTRODUCTION

Enhanced management of essential soil nutrients is a vital goal in achieving sustainable agriculture and maintaining necessary increases in food production while minimizing economic losses and environmental impacts (Goulding *et al.*, 2008). Technology plays a catalytic role in striking a common ground between environmental and economic goals. Recent advances indicate that efficient nutrient management in crop fields can be attained through the application of Precision Agriculture (PA)-based geo-spatial technologies such as global positioning system, geographical information system, remote sensing, geostatistics and variable rate application (Gebbers and Adamchuk, 2010; Robert, 2002). Variable-rate fertilizer application, one of the basic tenets of PA, has been shown to optimize fertilizer use efficiency by overcoming the problem of over- and under-fertilization (Schirrmann and Domsch, 2011). Ultimately, this strategy is envisaged to increase crop yields and quality, reduce resource waste and promote environment stewardship.

Spatial and temporal variability in crop and/or soil productivity are influenced by both intrinsic (e.g., soil forming factors such as parent material, climate, topography, fauna/flora and time) and extrinsic factors (e.g., farm management practices and maintenance operations) (Sun *et al.*, 2003). Quantifying the spatial and temporal variability of soil properties and responding to such variability via carefully designed site- and time-specific input application are believed to enhance nutrient assimilation in crops.

Conventionally, the spatial and temporal variability of nutrients in soils are assessed based on a rigorous field sampling followed with laborious soil testing, both of which can be time-consuming and costly. More often than not, soil sampling is performed destructively.

At present, development of sensors suited to quantify soil properties at the scale required for accurate mapping of within-field variability is a necessity. Ideally, sensor devices are fitted with a global positioning system to allow for soil data to be captured on-the-go and instantaneously converted into distribution maps. This would facilitate real-time monitoring and intervention of soil nutrient

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status, which can potentially offset limitations imposed by the inherent spatial and temporal variability in soil nutrient supply.

This review attempts to examine new case scenarios with regard to the application of on-the-go sensors for assessment of spatially-distributed soil nutrients.

MATERIALS AND METHODS

Spatial variability of soil nutrients: Generally, soil properties vary greatly across space and time. The spatial distribution of soil nutrients under agricultural systems is affected by natural conditions as well as management practices (Atreya *et al*., 2008; Barton *et al*., 2004). Soil spatial variability within a crop field may be attributed to the chemical, physical and biological properties of soil.

The existence of variability in soils is a result of dynamic interactions between natural environmental factors. Soil properties and in turn plant growth, are significantly controlled by the variation in landscape attributes including slope, aspect and elevation (Wang *et al*., 2009). Knowledge about the spatial variability of soil nutrients is important for refining agricultural management practices and for improving sustainable land use (McGrath and Zhang, 2003). According to Bouma and Finke (1993), soil variability can occur on any scale including area, field and regions within the field and even between a few millimeter spacing. This makes the quest to match the supply of nutrients from the soil to the needs of the crop a complex task. Thus, to achieve high nutrient use efficiency, an integrated approach that is based on spatial and temporal data is necessary.

The complexities of soil nutrient dynamics and variability in space and time suggest the need for computer-based systems. Such systems will facilitate the synthesis of relevant information so that end users can make informed agronomic and economic decisions. Recently, geo-statistics, neural networks, regression trees and fuzzy logic systems have been used to analyze soil nutrient distributions (Zhang *et al*., 2007; Liu *et al*., 2006; Park and Vlek, 2002; DeBusk *et al*., 1994). The deployment of these techniques has been useful in understanding nutrient dynamics within crop fields.

One of the primary factors affecting soil nutrient distribution is the physical movement of soil. Typically, runoff and erosion processes displace topsoil from upper slope areas to lower slope positions. This would alter the spatial distribution of soil and water and affect soil nutrient content in both affected areas (Noorbakhsh *et al*., 2008; Balasundram *et al*., 2006).

Precision nutrient management: Precision nutrient management necessitates a comprehensive understanding of the spatial variability of soil nutrients (Jin and Jiang, 2002). This is because crop fields often vary in soil type, elevation, soil fertility and productivity. Studies have highlighted the benefits of PA strategies in reducing nutrient loss and off site impacts. Baker *et al*. (2005) showed that PA practices were able to reduce the potential off-site transport of agricultural chemicals via surface runoff, subsurface drainage and leaching. Snyder (1996) demonstrated that total use of nitrogen fertilizer in a 2-year cropping cycle was lesser using precision nitrogen management as compared to conventional nitrogen management. Law *et al*. (2009a; 2009b) in comparing the spatial variability of soil carbon between young and mature oil palm (*Elaies guineensis* Jacq.), proposed that site-specific crop management be considered as a strategy to increase soil organic carbon sequestration in oil palm. Berry *et al*. (2005; 2003) used a mapping approach, based on integration of geographical information system and geostatistics, to spatially model water and solute transport in large-scale croplands. Their findings demonstrated hot spots for surface runoff and sediment and agrochemical transport out of the cropland, as well as buffers that potentially reduce off site transport. Such information can guide site-specific applications of crop inputs, particularly nutrients, so as to minimize non-point source pollution.

Variable Rate Technology (VRT) is one of the key components of PA. VRT for fertilizer application has been in existence for the past several years and has been developed for a variety of cropping systems (Koch and Khosla, 2003). In essence, VRT sequentially involves assessment of spatial variability of plant and/or soil nutrients, followed by clustering and mapping of nutrient concentrations in relation to crop yields (Balasundram *et al*., 2008a). Information about the spatial distribution of nutrient concentration is often overlaid onto yield data to construct nutrient management zones, which practically allow farm operators to determine 'how much,' 'when,' and 'where' to apply optimum rates of fertilizers so as to improve the efficiency of nutrient uptake by crops (Balasundram *et al*., 2008b; Balasundram *et al*., 2007).

Nutrient application using VRT can be tedious and time consuming due to the inevitable need to perform extensive plant and/or soil sampling followed with laboratory analysis to determine concentration values prior to production of variability maps. More often than not, VRT can pose cost and timing constraints (Gebbers and Adamchuk, 2010; Mallarino and Wittry, 2004). The

inability to quantify soil variability rapidly and inexpensively remains one of the biggest limitations of PA (Adamchuk *et al*., 2004). At present, cutting edge technologies that facilitate intensive grid sampling non-destructively in a cost- and time-efficient manner are being developed to drive precision soil nutrient management and monitoring.

RESULTS

Nutrient sensing technologies: Intensive grid sampling is generally regarded as one of the most accurate methods of mapping the variability of crop and soil attributes in PA (Brevik *et al*., 2006). However, intensive grid sampling is laborious, time consuming and expensive (King *et al*., 2005; Srinivasan, 2006) and thus impractical for implementation in large scale (McCormick *et al*., 2009). It is, therefore, desirable to develop a more rapid means of obtaining spatial and temporal data for detailed variability mapping (Brevik *et al*., 2006; King *et al*., 2005). The efficiency of site- and time-specific crop-soil management and monitoring strategies can be improved by using low-cost sensors to estimate soil properties that impact crop yields.

On-the-go soil sensor technologies that can serve as a rapid method for measuring soil mechanical, physical and chemical properties (Adamchuk *et al*., 2004) are steadily developing. Soil sensors can be used to generate real-time soil data, such as pH, electrical conductivity, salinity, dissolved oxygen and nutrient concentration, which are subsequently turned into geo-referenced maps to facilitate site-specific nutrient application. Numerous on-the-go sensors have been manufactured (Table 1) to measure mechanical, physical and chemical soil properties and most of them have been based on electrical and electromagnetic, optical and radiometric, mechanical, acoustic, pneumatic and electrochemical measurement concepts (Adamchuk *et al*., 2004).

Table 1 shows the commonly used sensors and their targeted soil properties. Quite often, an acceptable correlation between sensor output and a particular agronomic soil property is found for a specific soil type or when the variation of interfering variables was negligibly small (Adamchuk *et al*., 2004). However, it is still inconclusive as to which sensor combination could be used to simultaneously describe the spatial variation of several agronomic soil properties in diverse crop growth conditions.

Generally, the main concerns in sensor performance efficiency are the issues of precision and accuracy (PPI, 1999). Precision refers to the ability of the sensor to repeat its own measurement in the same location and time, while accuracy refers to how well the sensor measurements correlate to an actual soil property that is determined using the conventional (reference) measurement technique. Based on optimum precision and accuracy of the sensor output, a given soil property can be reliably predicted. In most sensor-based studies, the goodness of fit between sensor outputs and conventional measurements are expressed either as Pearson coefficient of correlation (r) or coefficient of determination (R^2).

DISCUSSION

This review mainly focuses on the application of selected on-the-go-sensors that are currently used for *in-situ* soil assessment and could potentially be deployed for precision nutrient management and monitoring. Although there is an array of sensor design concepts, most on-the-go soil sensors involve optical or electrochemical sensing. Optical sensing is based on reflectance spectroscopy, which detects the level of energy absorbed or reflected by soil particles, while electrochemical sensing uses ion-selective electrodes to generate a voltage or current output as a response to the activity of selected nutrient ions (Kim *et al*., 2009).

Electrochemical sensors: Electrochemical sensors are capable of assessing spatial variability of different soil chemical properties directly or indirectly.

Table 1: On-the-go soil sensor types and their applications

Sensor type	Example applications	Reference
Electrochemical	Soil pH, nitrate, potassium	Adamchuk *et al*. (2007; 2004)
Electrical and electromagnetic	Soil texture (sand, silt, clay), soil moisture content, soil depth variability (depth of topsoil, depth to hardpan), cation exchange capacity	Kim *et al*. (2009); King *et al*. (2005): Sudduth *et al*. (2003)
Optical and radiometric	Soil organic matter, soil moisture	Rossel *et al*. (2006); Chang *et al*. (2001)
acoustic	Soil texture (sand, silt, clay), soil bulk density (compaction), soil depth variability (depth of topsoil, depth to hardpan)	Grift *et al*. (2002)
Mechanical	Soil compaction, compacted soil layers	Stafford and Werner (2003); Manor and Clark (2001)

Soil fertility is usually measured using either an ion-selective electrode (glass or polymer membrane), or an ion-selective field effect transistor. This approach measures the potential voltage difference between sensing and reference parts of the system, which relates to the concentration of specific ions (i.e., H^+, K^+, NO_3^-) (Adamchuk *et al*., 2004). Ion-selective membrane sensors offer opportunities for on-the-go soil nutrient(s) and pH measurements (Schirrmann and Domsch, 2011). Presently, the limitation of the technology is that the values obtained may not be as accurate as a laboratory test, but the high sampling density may increase the overall accuracy of the resulting soil nutrient or pH maps. It appears that in the future, on-the-go electrochemical sensing may allow for cost-effective monitoring of heterogeneous soils at high sampling resolution.

In a recent study, Schirrmann and Domsch (2011) evaluated soil pH and base nutrients using an on-the-go vehicle-based electrochemical sensor. Maps derived from the on-the-go electrochemical sensing revealed more spatial features relevant for variable-rate fertilization, as compared to maps derived from standard sampling. The sensor-derived maps also yielded a higher data accuracy for calculating fertilizer requirements.

There has been a considerable progress with the application of on-the-go soil nutrient sensing based on ion-selective electrode technology. A soil pH mapping system is now commercially available. Additionally, a real-time soil NO_3–N analyzer has recently been improved with an automated sampler that provides precise estimates of the sample mass (Kim *et al*., 2009).

Electrical and electromagnetic sensors: Electrical and electromagnetic sensor technology uses various measurement systems based on electrical circuits to determine the ability of soil media to conduct or accumulate electrical charge. Generally, the physical and chemical characteristics of soil can affect circuit behavior and, thus, the measured electrical response. Adamchuk *et al*. (2004) opined that due to rapid response, low cost and high durability, electrical and electromagnetic sensors have become the most attainable technique for on-the-go soil mapping. The maps generated from electrical and electromagnetic sensing correlate well with soil properties such as texture, salinity, organic matter and moisture content.

The salt concentration of soil is commonly estimated via electrical resistivity or electrical conductivity. The use of on-the-go electromagnetic sensors for measurement of electrical resistivity and/or conductivity has been demonstrated on crop fields (Sudduth *et al*., 2003). Their work compared electromagnetic induction and contact sensors for the mapping of soil properties across crop fields. Results showed that soil electrical conductivity was significantly correlated with temporally stable soil properties such as soil clay content and cation exchange capacity but poorly correlated with other soil properties such as moisture, silt, sand and organic carbon. The utility of electromagnetic sensors is limited by operation speed and contact height, fluctuations in soil moisture and soil temperature, topsoil depth and instrumentation drift with time (Sudduth *et al*., 2001).

Optical and radiometric sensors: Optical sensing technology uses visible and near-infrared wavelength ranges to rapidly quantify soil properties. The principle of this approach is the interaction between incident light and soil surface properties, such that the reflected light vary as a function of soil physical and chemical properties (Mouazen *et al*., 2005). Optical nutrient sensing techniques are non-destructive and are often more favored in comparison to electrochemical sensing (Chang *et al*., 2001; Rossel *et al*., 2006). Optical soil sensors have a high potential for estimation of soil organic matter content based on soil color (Adamchuk *et al*., 2004). In optical sensing of soil, the visual and near-infrared spectral reflectance can potentially estimate texture, moisture, CEC and other soil parameters if proper data analysis techniques are applied.

Recently, Holzapfel *et al*. (2009) evaluated the feasibility of using optical sensors in canola (*Brassica napus* L.) for determination of optimal N management strategies. Results showed that sensor-based N management, in comparison to the conventional practice of N banding, resulted in a 34 kg N h^{-1} reduction in fertilizer use without affecting seed yields. It was concluded that sensor-based N management is a feasible option for canola production in western Canada and has the potential to increase long-term agronomic N-use efficiency.

Ground Penetrating Radar (GPR) is another sensor that provides reliable and inexpensive acquisition of soil reflectance measurements. GPR consists of a transmitter which radiates pulses of high-frequency electromagnetic waves and a receiver which detects the reflected electromagnetic waves as a function of time (Dane and Topp, 2002). The potential application of GPR includes mapping soil properties such as texture, organic matter, thickness and depth of soil horizons. Typically, the application of GPR requires visual

inspection of the site and interpretation of the radargram based on clustered regions, followed by ground-truthing for validation. Recently, improvement to the GPR has allowed for automation of these protocols. If a quantitative procedure for systematic classification can be developed, GPR has the potential for broad use in PA as a non-invasive technique to delineate subsurface features. This will require improvements to the intelligent system design. To accomplish on-the-go mapping, commercial GPR systems have been mounted on mobile platforms.

Acoustic sensors: Acoustic sensors are usually equipped with a sound-recording device (i.e., microphone) that records sound produced through interaction of the soil and the shank having a rough surface and hollow cavity. This approach is ideal for differentiating between mechanical and physical characteristics of soil. A similar system was developed and tested by Grift *et al*. (2002), where sound waves were used to detect soil compaction layers. Their study demonstrated that acoustic sensing could successfully detect a hard pan at a particular depth. The use of acoustic sensors in characterizing the physical state of soil is still poorly understood and additional research is needed. However, such a novel sensor may be a strong candidate for sensor fusion, in which multiple data streams are fused to improve estimation of targeted soil attributes.

Mechanical sensors: Mechanical soil sensors are designed to measure soil strength, which is conventionally done by measuring mechanical resistance. Soil strength is known to influence crop yields, particularly when a soil has a hard pan. High soil strength inhibits root penetration and consequently plant growth. Regions of high mechanical resistance within crop fields may arise naturally, or as a result of compaction from the use of heavy farm machinery, or by the formation of plow pans. In each scenario, soil particles are positioned closer to each other. This process is known as soil compaction. Compacted soils reduce root growth and thus limit the availability of water and nutrients to the plant.

Conventionally, soil compaction is measured using a standard vertical cone penetrometer. This method is time consuming and can give highly variable results. To overcome these limitations, a number of prototype systems have been developed for on-the-go sensing of soil mechanical resistance. Adamchuk *et al*. (2001) developed a system that measures soil resistance to a depth of 30 cm (three measurements at one time). These

measurements were geo-referenced using a global positioning device in order to generate soil resistance maps. Andrade *et al*. (2001) developed an improved system that measures soil resistance to a depth of 63 cm (eight measurements at one time).

Hanquet *et al*. (2004) studied the variability of soil strength in a crop field using an on-the-go mechanical sensor. The soil strength maps generated from their study confirmed the existence of two field zones demarcated based on soil strength. Such information can be combined with the variability maps of soil nutrients and other important crop-soil properties to decipher yield influencing/limiting factors.

CONCLUSION

On-the-go sensors have the advantage of providing non-destructive and rapid quantification of soil variability to enable precision soil nutrient management and monitoring. The prospects of electrochemical, electrical and electromagnetic and optical and radiometric sensors for real-time mapping of important soil chemical and physical properties to facilitate precision soil nutrient management and monitoring are promising.

However, the possibility of on-the-go sensor fusion that would allow simultaneous spatial variability quantification of important crop-soil properties under diverse growing conditions is still unclear.

Increasing population growth coupled with the increasing risks associated with climate change inevitably requires a commensurate increase in agricultural productivity. Key to this challenging task is to ensure sustainable soil productivity while maintaining high crop yields and reducing environmental pollution. To this end, the implementation of sensor technologies for soil nutrient management and monitoring is a step in the right direction.

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