New developments in proximal soil sensing

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Abstract

This presentation provides an overview of contemporary developments in the field of proximal soil sensing (PSS) as it relates to precision agriculture. The ultimate goal of PSS is to enable low-cost acquisition of accurate information on spatial and temporal changes in soil properties across a landscape. Proximal sensing systems rely on gathering signals from transducers placed in contact, or less than 2 m away, from the target. Knowing and understanding the heterogeneity of soil properties helps farmers and other land managers optimize their decision-making process to develop profitable, sustainable, and environmentally friendly operations. The emphasis will be placed on recent efforts in sensor fusion, when sensors that measure different physical phenomena are integrated in a single platform and/or data acquisition process. The recent development of the on-the-spot soil analyser will be used as an example. Under this framework, several sensing methods will be discussed in more detail. These include digital microscopy, soil gas analysis, visible, near-infrared, mid-infrared, gamma-ray as well as laser-induced breakdown spectroscopy, capacitance and apparent electrical conductivity, and ion-selective membranes. Despite their various limitations, these sensing techniques, together with field topography mapping, have been successfully deployed to rapidly determine an array of important physical, chemical and biological soil properties. The recently developed neighbourhood search analysis software has been used to numerically integrate multiple geospatial data layers and produce field areas representing different sensor measurement combinations as well as locating the most informative calibration sites. The presentation will review several alternative approaches to process PSS data to generate thematic soil maps suitable for site-specific management of seed, lime, fertilizer and other soil amendments.

Background

Spatial variability in soils is of interest when optimizing crop production systems, or during other types of landscape management. One of the most discussed strategies for information-based management of crop production is site-specific crop management. It recognises spatial heterogeneity at a sub-field scale and seeks to adjust management practices according to local needs. The initial factors influencing variability in soils relate to the parent material, climate, topography, organisms (including vegetation) and time (Jenny, 1941). Remote sensing of crop vegetation, bare soil imagery, field topography and yield maps have been excellent high-density data sources to assess the changes in growing environments from location to location. However, as vegetation performance reveals the overall effect of a number of factors, such as nutrient and water availability during the growing season, thematic soil maps are needed to understand crop growing conditions in different parts of a field and they are a key component in the decision-making process. It is important to know the physical, chemical and even biological properties of soil in a given location to make a management decision that would maximize agricultural inputs use efficiency and minimize anthropogenic pressure on the environment. Systematic soil sampling, laboratory analysis and spatial interpolation of the obtained results continue to constitute the mainstream technology to produce thematic soil maps. Yet, relatively high affiliated costs limit the density of unbiased measurements and thus, the quality of the representation of true spatial heterogeneity of the key soil properties. Proximal soil sensing technologies have been developed to overcome these cost limitations.

In its ideal deployment, proximal soil sensing can be viewed as a stand-alone or integrated with a traditional field machine (e.g., planter, sprayer, or combine) measurement system providing readouts of soil properties of interest when moving across the field. To date, several popular concepts used to measure soil properties in field conditions can be separated into: 1) electrical and electromagnetic sensors that include most geophysical tools, 2) optical and radiometric sensors that cover different parts of the electromagnetic spectrum, 3) mechanistic sensors that rely on mechanical interactions between sensors and soil, and 4) electrochemcial sensors that directly measure the activity of specific ions. Apparently, only electrochemical sensors may directly infer some indicators of agronomically important soil properties. The majority of sensors presently used for field mapping produce relatively large data arrays that show the dynamics in response to multiple physical and chemical soil attributes that may be specific to a given geological landscape. Therefore, the proximal soil sensing technology discussed in this presentation represents a system comprised of the integration of multiple soil sensing technologies, site-specific sensor calibration processes and interpretation of the obtained results for the purpose of prescribing variable rate technologies, where they are reasonable, feasible and economically justified.

Methods and Discussion

Sudduth et al. (1997), Adamchuk et al. (2004), Shibusawa (2006), and later Viscarra Rossel et al., (2011) provide an overview of proximal sensing systems used to map soil heterogeneity. Commercially available sensing systems rely on several explored measurement principles, and have become standard practice undertaken by specialized precision agriculture service providers around the world. As an entry point to proximal soil sensing, practitioners have combined high-accuracy topography mapping with geophysical instruments to reveal the soil's ability to conduct an electrical charge and the change in this ability with depth. So called apparent soil electrical conductivity (EC_a) is measured using galvanic contact or capacitively coupled resistivity, or electromagnetic induction methods serve as a proxy of the soil's ability to sustain soil water and nutrients during the growing season and hence, the overall ability to support crop growth. Since soil salinity, texture, moisture, organic matter content, bulk density and other relevant attributes all affect the recorded measurements, interpretation of EC_a maps varies from one agro-climatic condition to another. Contemporary developments are linked to an increased number of simultaneously obtained data layers, including signals describing different exploratory depths. Additional interest is in integrating these spatially intense data with measurements of soil water content, or matric potential obtained through stationary sensor networks, or point-based soil profiling tools. While the former allows for observing the spatial dynamics of soil water-related attributes in time, the latter provides the ability to obtain quality, 3-dimentional models of an agricultural field. Both technologies allow users to improve water management (e.g., irrigation and drainage) and indirectly link water availability to the spatial dynamics of crop performance and soil nutrient cycles. Optimization of the number and placement of locations to monitor soil conditions and/or characterize the soil profile is a challenging task. Presented by Dhawale et al. (2016), neighbourhood search analyst (NSA) represents a tool being developed to integrate multiple spatial data layers to define parts of a field with spatially contiguous distinct combinations of input layers. An affiliated circular search method allows for the definition of specific field locations best representing each unique combination recommended for further exploration (e.g., soil sampling, temporal monitoring, or profiling).

Increasing in popularity, soil spectroscopy presents the capability to obtain additional dense layers of data revealing physical, and some chemical, soil characteristics. Thus, similar to $EC_{a,,}$ gamma-ray spectrometry can be used as a proxy for soil series delineation, but with the negligible influence of soil salinity, more attention to soil mineralogy and the greater influence of soil within the rooting depth. Similar to remote sensing, use of visible/near-infrared spectroscopy within the rooting zone offers another view of soil physical characteristics (e.g., texture, moisture, organic matter content), but without the influence of crop residue and highly variable soil water content at the surface. Through intensive, data-rich calibration activities, reliable models of several important soil attributes have been developed at the field, regional, or even global scale. Newly accessible portative mid-infrared spectrometry extends spectral sensing to longer wavelengths that, in many cases, better define certain soil minerals and chemical bonds (Ji et al., 2016). To deepen the rapid assessment of the elemental basis of soil composition, laser induced breakdown spectroscopy (LIBS) and x-ray fluorescence (XRF) have been performed. With the availability of low-cost digital microscopy, rapid characterisation of soil texture/aggregation is now feasible (Sudarsan et al., 2016).

Soil profiling, which was mentioned earlier, is a point-based combination of EC_a and spectral measurement capabilities as well as the mechanical interaction between soil and the soil penetrating instrument. Both the ability of soil to resist penetrating objects and the associated soil/metal friction correspond to unique soil texture/bulk density/moisture combinations, which affect root development and, therefore, are also important agronomically. In the past, many prototype systems have been developed and successfully tested to map mechanical soil impedance horizontally using standardized tools (tines or discs) when moving across a landscape. These types of measurements are geared toward alleviating soil compaction as one important crop growth limiting factor.

In terms of soil fertility management, the sensor systems mentioned above provide indirect rather than direct indicators. Therefore, there is on-going interest in the continued exploration of electrochemical techniques to detect the activity of specific ions (e.g., H^+, K^+, Na^+, NO_3^-, Ca^{2+}, etc.). Commercially available Veris® Mobile Sensor Platform and recently developed on-the-spot analyser (Adamchuk et al., 2014) rely on *in situ* measurement of the soil pH and soluble nutrients in field conditions. Optimized site-specific management of lime and several other soil amendments can be successfully pursued using these technologies. Finally, spatially inconsistent soil health has become another area of interest for both agriculture and the environment. Recently developed systems to measure changes in CO_2 gas concentration in soil air, or as a result of added substrate, provide the capability for the holistic assessment of crop growing conditions at any specific point in time and at any predefined location (Adamchuk et al., 2017).

Conclusion

Proximal soil sensing is important in modern precision agriculture. Field deployment of on-the-go sensing platforms allows high-density mapping of soil attributes directly linked to the soil's ability to supply crops with water and nutrients throughout the growing season. Detailed assessment of soil nutrients is still a challenging task that requires further investigation. In any instance, development of thematic soil maps revealing spatial heterogeneity of a specific agronomic attribute encompassed data collection, model development and interpretation stages that may not be consistent across different geographic regions. However, there is significant evidence that relatively high measurement density as a result of proximal soil sensing provide more accurate and frequently less expensive end results as compared to spatial interpolation of relatively sparse, but very accurate measurements of soil properties conducted in laboratory conditions.

Acknowledgments

This research was supported in part by funds provided through the National Science and Engineering Research of Canada (NSERC) Discovery Grant on integrated proximal sensing of soil and crop.

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