

# DEVELOPMENT OF AN ON-THE-SPOT ANALYZER FOR MEASURING SOIL CHEMICAL PROPERTIES

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## ABSTRACT

The goal of this research is to develop an on-the-spot soil analyzer (OSA) capable of simultaneously deploying several different sensors to measure soil properties at a predefined depth. The mechanism developed is able to rapidly remove topsoil, condition the soil surface and bring the designated sensors into direct contact with the soil. After the measurements are obtained and the geographical coordinates are recorded, the analyzer is converted into transportation mode and is then ready for the next set of measurements. Unlike other systems, this mechanism allows for the deployment of multiple sensors at a given measurement depth and in a completely automated mode of operation. This technology should provide an opportunity to extend the suite of deployable sensors and to automate the process, thus allowing for advanced sensor fusion algorithms and integrated data acquisition practices.

**Keywords:** Proximal soil sensing, ion-selective electrodes, autonomous vehicles, soil pH, nitrate.

## INTRODUCTION

Sensor systems have been widely used to obtain information on soil physical, chemical and biological attributes. Depending on the distance to the target, existing sensing platforms are remote (aerial and satellite-based systems) or proximal, when sensors are placed in contact with soil or at a distance of less than 2 m (Viscarra Rossel *et al.*, 2011). Unlike conventional soil sampling and laboratory analysis, many proximal soil sensing (PSS) systems have been developed to obtain data which reveals spatial (horizontal and vertical) as well as temporal changes in selected soil properties. Thus, PSS reduces the number of soil samples needed for follow-up measurements of soil attributes required by traditional techniques.

PSS-based data have been used in agriculture, construction, ecology, archeology, and other important activities. PSS measurements can be combined with geographic coordinates to create geographical maps. With different instruments that are based on electrical, electromagnetic, optical, radiometric, magnetic, seismic, mechanical, acoustic, electrochemical and other measurement techniques, it is possible to better understand spatial and temporal soil heterogeneity. Due to

the complex nature of soil, sensors respond to a variety of soil properties, which leads to the need to pursue sensor fusion (Adamchuk *et al.*, 2011). By combining different data sources (including remote sensing and destructive soil sample analysis), it is possible to increase the quality of the information obtained while minimizing costs.

One of the most attractive approaches is to create high-resolution thematic soil maps using sensor systems that are moved across landscapes (Hummel *et al.*, 1996; Sudduth *et al.*, 1997; Adamchuk *et al.*, 2004; Shibusawa, 2006). These on-the-go soil sensors make periodic measurements while traveling across the terrain and they associate each measurement with geographic coordinates. The main disadvantage of on-the-go sensing is the limited time allowed for each measurement and, when using contact techniques, soil distortion is created along the entire path. This is especially relevant to mapping soil chemical attributes using potentiometry, as shown in Figure 1. According to Adamchuk *et al.* (1999), this method requires the collection of a small amount of soil from a predefined depth and bringing it into contact with combination ion-selective electrodes (ISEs). In a typical commercial operation, an average 12 s per measurement allows for more than 20 measurements per hectare while operating at 10 km/h in parallel passes 15 m apart.

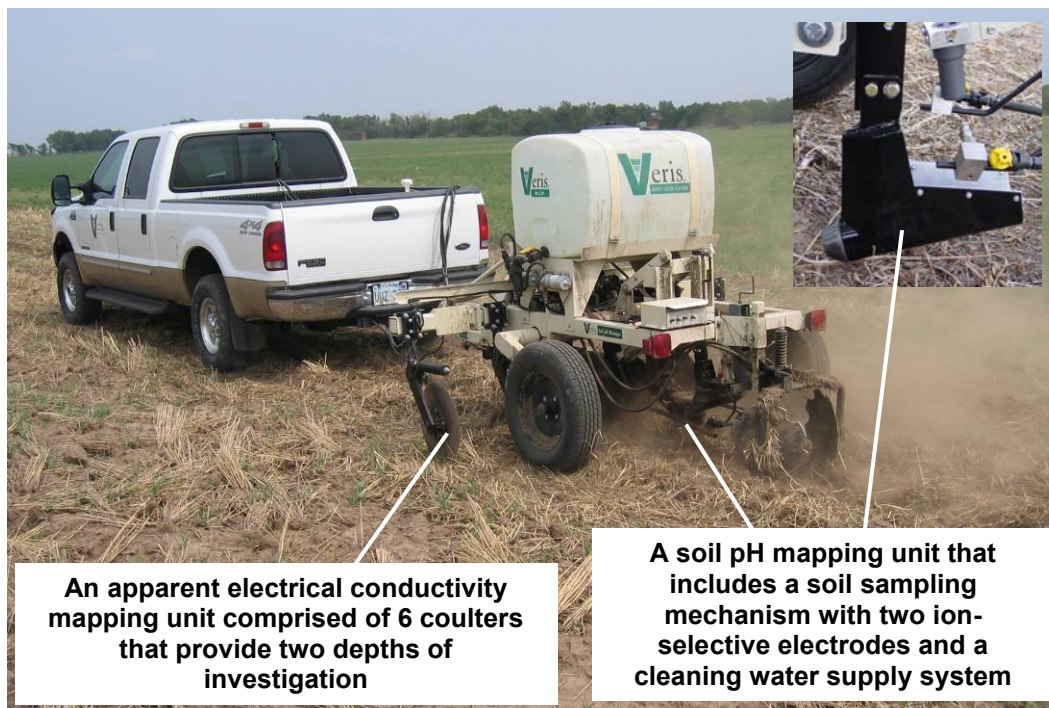


Figure 1. Veris<sup>®</sup> Mobile Sensor Platform (MSP)<sup>1</sup>.

<sup>1</sup> Mention of a trade name, proprietary product, or company name is for presentation clarity and does not imply endorsement by the authors, McGill University, or exclusion of other products that may also be suitable.

As an alternative to on-the-go mapping techniques, on-the-spot measurements can be made in situations where spatially sporadic test locations are needed or soil coverage does not allow for the continuous engagement of soil and parts of the sensor system (e.g., pasture). For example, the manual probe shown in Figure 2 can be used to make real-time measurements of soil pH, soluble potassium, or residual nitrate (depending on the type of ISE) while walking the test area. An all-terrain vehicle (ATV) mounted with equipment shown in Figure 3 can be used to make similar measurements in a consistent and more ergonomic manner. In both cases, equipment has been limited to only one electrode and the need for the operator to conduct the test.



Figure 2. Manual probe for on-the-spot soil ion activity measurements.

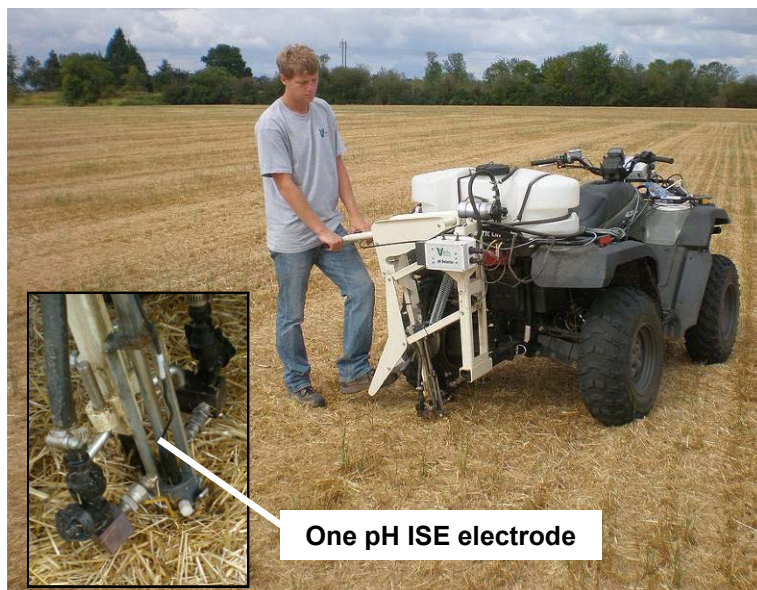


Figure 3. Veris® pH Detector (<http://www.veristech.com>).

The aim of this paper is to report on the development of an on-the-spot soil analyzer (OSA) capable of simultaneously deploying several different sensors to measure soil properties at a predefined depth using a preconditioned soil surface in contact with the sensors. This technology should provide an opportunity to extend the suite of deployable sensors and to automate the process thus allowing for advanced sensor fusion algorithms and integrated data acquisition practices.

## MATERIALS AND METHODS

Although the OSA should be suitable for different types of sensors, enhancing the electrochemical *in situ* measurement capabilities appears to be the most rewarding. Compared to other PSS solutions, electrochemical sensors are direct when measuring the concentration of specific ions in a soil solution. The most common technique is to measure soil pH, and use of ISEs for measuring other ions is common in environmental monitoring applications. Various prototypes have been developed to use ion-selective electrodes and ion-selective field effect transistors (ISFETs) to map soil pH, lime requirement and macro-nutrients (e.g. Adamchuk *et al.*, 1999; Adsett and Zoerb, 1991; Birrell and Hummel, 2001; Sibley *et al.*, 2009; Viscarra Rossel and McBratney, 1997; Viscarra Rossel *et al.*, 2005). Kim *et al.* (2009) provides a recent review. ISEs are potentiometric sensors that use ion-selective membranes to determine the concentration of the target species in a solution surrounding the membrane. During measurements, an electromotive force is generated at the sensing surface proportional to the log of the ion activity. This electromotive force is measured using a reference electrode (liquid junction). Many ISEs (e.g., pH, nitrate, sodium, potassium, calcium) are commercially available.

### System Development

To successfully deploy any electrochemical sensors, the OSA should: 1) remove cropping material and topsoil to expose soil at a given depth, 2) apply water or a salt solution when necessary, 3) bring all electrodes into gentle, yet firm, contact with the wet soil surface, 4) analyze sensor response to predict a steady-state output, 5) record geographic coordinates along with the sensor output, 6) retrieve and wash the sensors, and 7) cover the exposed area if needed. The entire process should be automated and suitable for different vehicle platforms. This requires a compact, lightweight design which uses a 12V DC power supply.

Based on these requirements, an OSA system was designed (Figure 4) and includes the following components: 1) soil preparation mechanism 2) sensor deployment mechanism, 3) electrode rinsing system, 4) sensors, 5) data acquisition and control system, and 6) supplementary and optional components. The system was prototyped for mounting using the hitch of an ATV, SUV or a pickup truck (Figure 5).

Figure 6 illustrates the complete set of electro-mechanical components used to operate the OSA components. The soil preparation mechanism was constructed using two cutting blades attached to opposite sides of two parallel disks rotated using a 12 VDC powered gear motor (300 RPM, 337 W, AndyMark, Inc., Kokomo, Indiana, USA). These discs were mounted using a special pivoted bracket. A linear actuator (45 cm stroke, Robotzone, LLC, Winfield, Kansas, USA) was used to move the pivoted part of the bracket to displace the discs up and down along a less than quarter-circle arch.



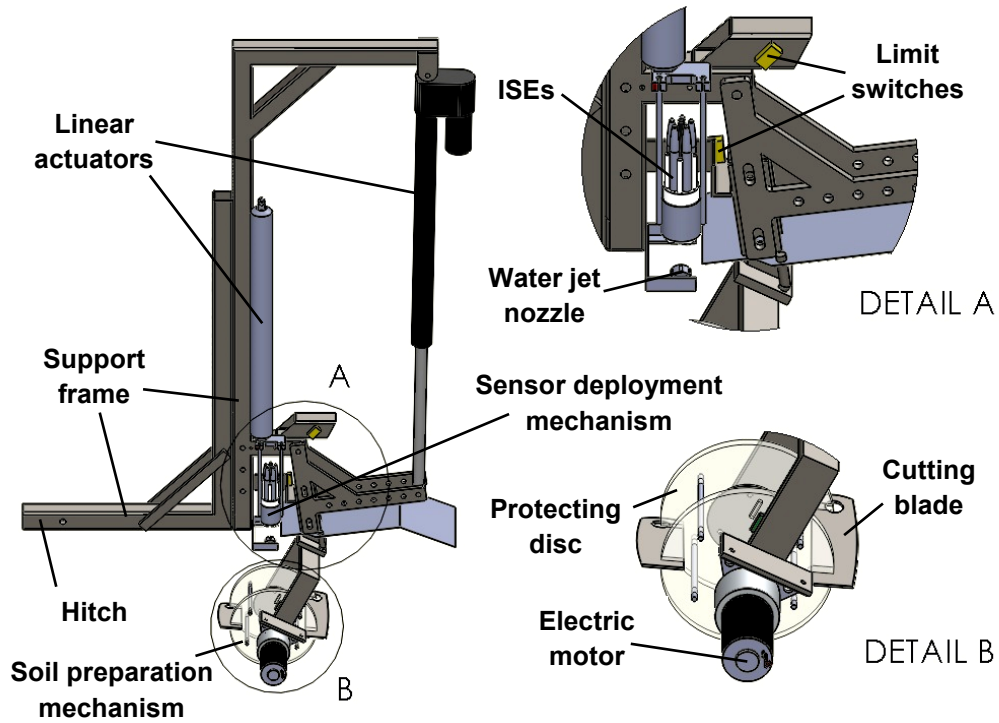


Figure 4. On-the-Spot Analyzer (OSA) including soil preparation (detail A) and sensor deployment (detail B) mechanisms.

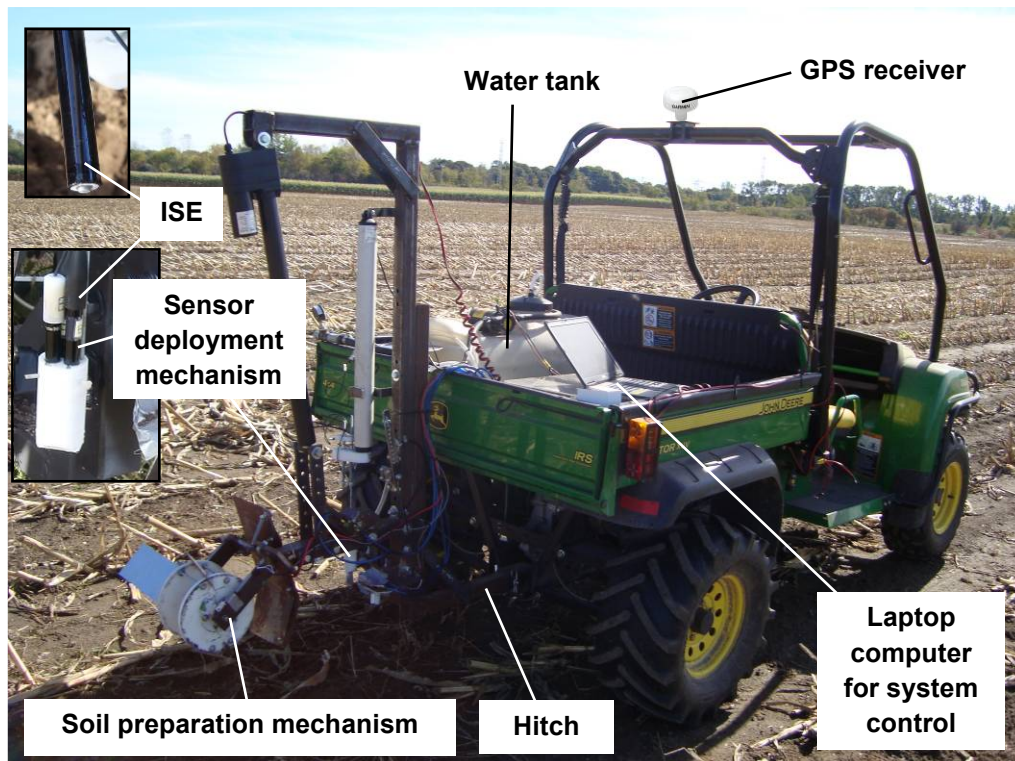


Figure 5. The OSA prototype during 2013 field testing.

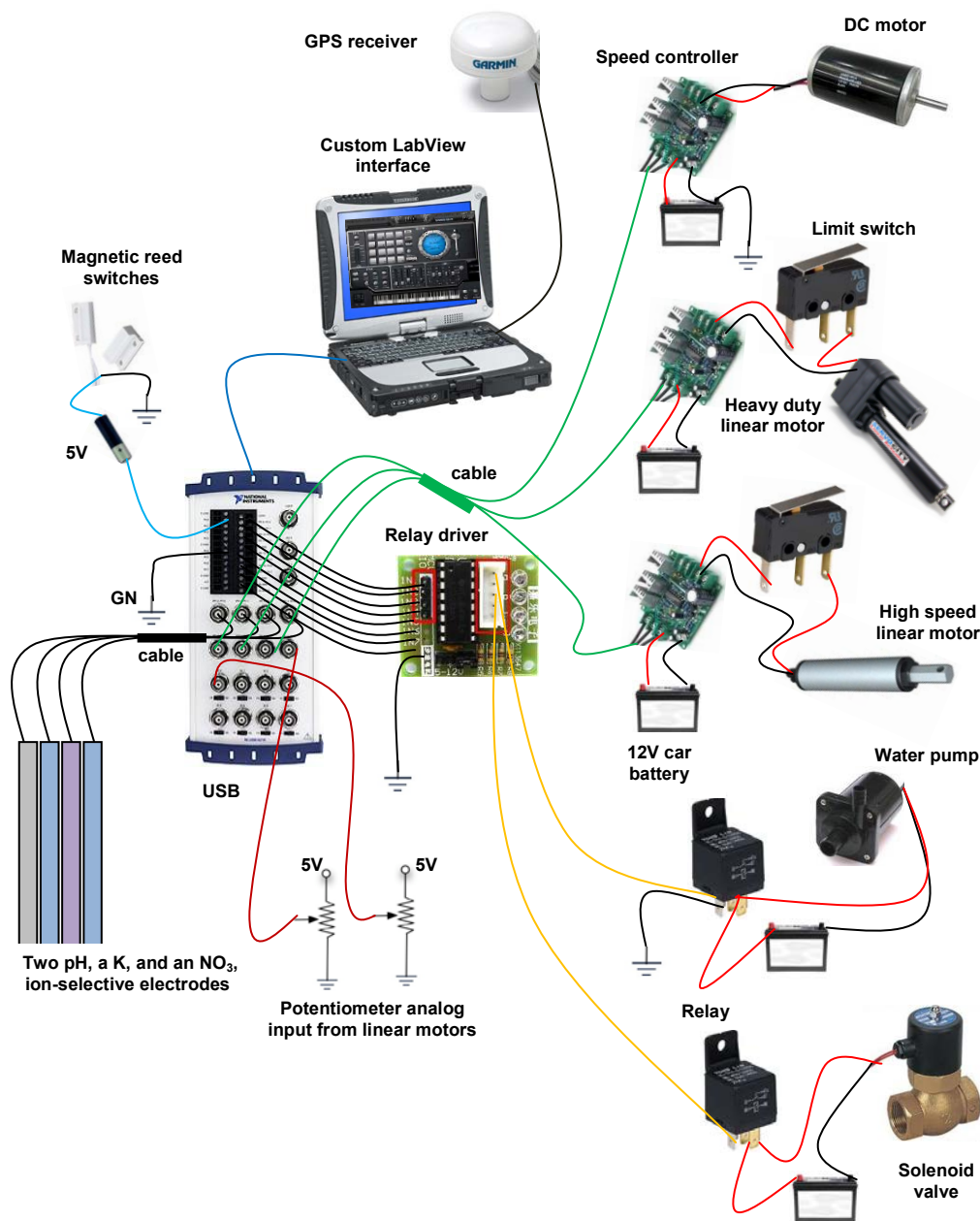


Figure 6. Key electronic components of the prototype OSA.

A special control application was developed, using LabView 12.0 (National Instruments Corp., Austin, Texas, USA), to allow the electric motor and the linear actuator to rapidly remove soil and expose the soil measurement surface at a predefined depth (about 10 cm below surface). Two magnetic switches were used to assure proper motor stop position to present an opening in the middle of the soil preparation unit where the electrodes were to be deployed. Then, a high speed linear actuator (45 cm stroke, Progressive Automations, Inc., Richmond, British Columbia, Canada) was used to place the ISEs into contact with the soil. The “gentle” action required to preserve the fragile sensor membranes was achieved

using a spring mounting. After the measurements were obtained, the electrodes were retracted, the pivoted bracket returned to a transportation position, and jet water nozzles were used to rinse the electrodes. Water from a 50-L storage tank was delivered using a 12 VDC power pump. All data acquisition and control functions were performed through a USB-6216 data acquisition card (National Instruments Corp., Austin, Texas, USA).

### System Evaluation

A preliminary system evaluation was conducted to assess the system's control functionalities. It was impossible to make quality comparisons of the measurements obtained with the OSA and in the laboratory due to a relatively early start of the subfreezing season. While constructing the prototype, two quick tests were performed using the manual probe (Figure 2) equipped with a FieldScout pH 100 meter (Spectrum Technologies Inc., Aurora, Illinois, USA) at various Macdonald Farm research plots (McGill University, Ste-Anne-de-Bellevue, QC, Canada).

To assess performance of a nitrate detectION™ 3021BN (Nico Scientific, Inc., Huntingdon Valley, Pennsylvania, USA) ISE, measurements were performed in an experimental canola field divided into sixteen plots, treated with different levels of urea (0, 50, 100 and 150 kg N ha<sup>-1</sup>). Two months after planting, random *in-situ* measurements were taken 2-3 cm below the soil surface using the manual probe. The electrode was calibrated using standard potassium nitrate (KNO<sub>3</sub>) solutions with known nitrate (NO<sub>3</sub><sup>-</sup>) concentrations. A simple linear regression method was applied to determine the relationship between the per plot averages of the electrode outputs and the NO<sub>3</sub><sup>-</sup> concentrations measured using corresponding composite (five cores) 15-cm deep soil samples. These samples were analyzed to quantify NO<sub>3</sub><sup>-</sup> concentrations in the laboratory, using a potassium chloride (KCl) extraction procedure and a cadmium reduction colorimetric technique. Estimates of soil water content, sampling depth and soil bulk density were used to bring all the measurement to mg L<sup>-1</sup> units.

Seven research plots with suspected variability in soil pH were used to test an antimony combination pH electrode (Veris Technologies, Inc., Salina, Kansas, USA). The manual probe was used to make measurements 8 cm deep. The electrode was calibrated using standard buffer solutions (pH 4 and 7). A simple linear regression was performed to compare results with those from a commercial soil laboratory performed on soil samples obtained as close to the manual probe measurements as possible.

## RESULTS AND DISCUSSION

As shown in Figure 7, the system was able to remove approximately 8 cm (3.1 in.) of topsoil under various field conditions, which provided a suitable surface for electrode deployment. The electrodes could be brought into contact with the soil and rinsed well afterwards. The entire cycle could be performed within a 60-s timeframe.

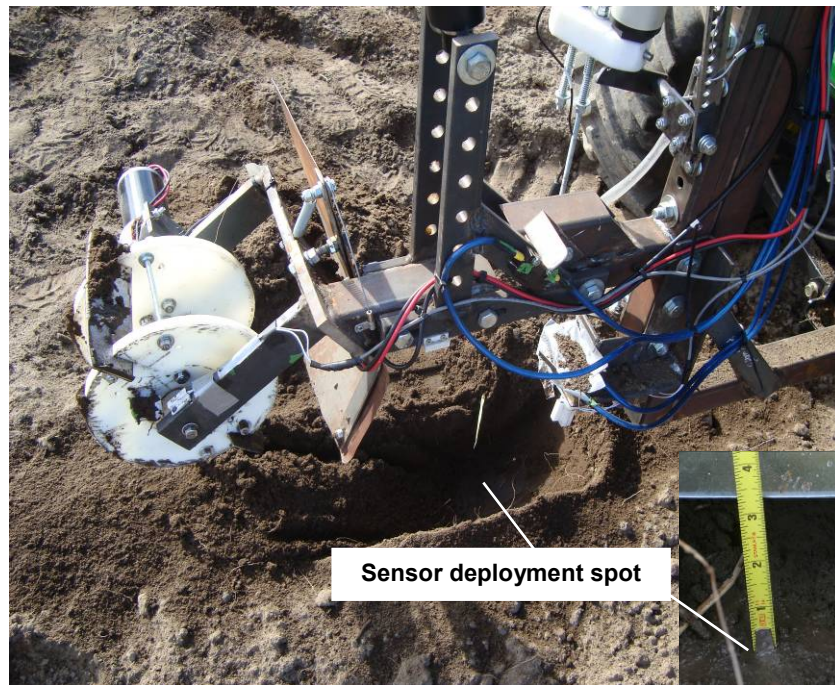


Figure 7. Test of the soil preparation mechanism.

According to Figure 8, both  $\text{NO}_3^-$  and pH electrodes revealed major differences in corresponding soil properties between different research plots and should be suitable for deployment using the developed OSA. Other sensors, including an array of portable optical and radiometric instruments, should also be appropriate to be used with this system.

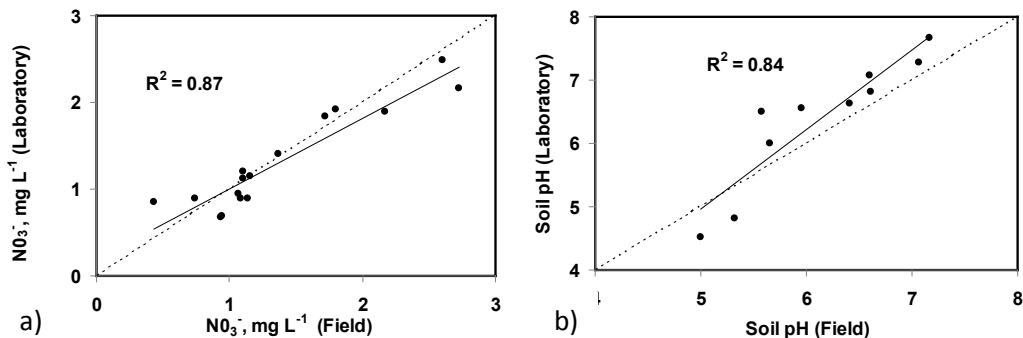


Figure 8. Results of the soil  $\text{NO}_3^-$  and pH measurements test.

The system was designed in such a way that it can be operated from the standard hitch of a pickup, an all-terrain vehicle, or another platform. If such a platform is autonomous, measurements are conducted without an operator's involvement. Measurement locations and density can be either predefined or adjusted in real time to respond to the quality and variability of the measurements already obtained at a given site. The system can be used by individuals and organizations involved in small-scale soil mapping. Relatively inexpensive and easy to use, the system will be attractive to agribusinesses involved in soil fertility management.



The low destruction approach will make this method applicable to specialty and permanent crop environments. An option to conduct measurements automatically can assist in obtaining data in hazardous areas without the need for a human presence.

## SUMMARY

Measurement of soil spatial variability provides important information used for soil cultivation, reclamation, remediation and other practices. Soil sampling and *ex-situ* analysis is the most popular approach currently in use. Proximal soil sensing is an emerging technology resulting in on-the-go mapping of soil characteristics. Lower costs have been one of the main advantages for on-the-go sensing methods when compared to on-the-spot solutions. The latter approach has a number of technical advantages and the use of robots can make on-the-spot measurements even more attractive. Technology for mapping soil pH on-the-go and manually activated on-the-spot measurements of soil pH are both commercially available. The on-the-spot soil analyzer presented in this study pertains to a new mechanism that enables rapid and reliable soil manipulation to facilitate the necessary interface between sensors and soil in an automated mode. Furthermore, when compared to existing solutions, this method is applicable in difficult soil conditions and enables sufficient opening of a subsurface soil area to engage an array of proximal soil sensors. For example, this system can carry several ion-selective electrodes (pH, nitrate, potassium, phosphorus, etc.), along with a miniature camera for machine vision analysis and a spectroradiometer for colorimetric analysis. During each measurement, this mechanism removes a predefined layer of soil and crop residue and gently brings the sensors into contact with the prepared soil surface. When all measurements are stabilized, they are stored along with geographic coordinates and time of each measurement. After retrieving and rinsing the sensor surfaces, the system can be moved to a different location for new measurements.

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