Geophysical Methods

Barry J. Allred
Soil Drainage Research, U.S. Department of Agriculture—Agricultural Research Service (USDA-ARS), Columbus, Ohio, U.S.A.

Viacheslav I. Adamchuk
Bioresource Engineering, McGill University, Anne-de-Bellevue, Canada

Raphael A. Viscarra Rossel
Bruce E. Butler Laboratory, CSIRO Land and Water Flagship, Black Mountain, Queensland, Australia

Jim Doolittle
National Soil Survey Center, U.S. Department of Agriculture—Natural Resources Conservation Center (USDA-NRCC), Newtown Square, Pennsylvania, U.S.A.

Robert S. Freeland
Biosystems Engineering and Soil Science Department, University of Tennessee, Knoxville, Tennessee, U.S.A.

Katherine R. Grote
Geosciences and Geological and Petroleum Engineering Department, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

Dennis L. Corwin
U.S. Soil Salinity Laboratory, U.S. Department of Agriculture—Agricultural Research Service (USDA-ARS), Riverside, California, U.S.A.

Abstract
Near-surface geophysical methods have become an important tool for agriculture. Geophysical investigations for agriculture are most often focused on the first 2 meters directly beneath the ground surface, which includes the crop root zone and all, or at least most of the soil profile. Resistivity, electromagnetic induction, and ground-penetrating radar are the three geophysical methods most commonly employed for agricultural soil investigations; however, optical reflectance and γ-ray spectroscopy are increasingly becoming more widely utilized. Temporal and spatial variation of conditions and properties in the soil profile are important considerations when conducting a geophysical survey within an agricultural setting. Geophysical methods have been applied to soil surveys, precision farming, soil water content measurement, and soil salinity monitoring; with new agricultural geophysics applications continuing to evolve. Future development of multi-senor platforms and the use of unmanned aerial vehicles will dramatically improve geophysical soil investigation capabilities with respect to field accessibility and data interpretation.

INTRODUCTION

Agricultural geophysics as described in this entry involves the application of physical quantity measurement techniques to provide information on conditions or features within the soil environment. With the exception of borehole geophysical methods and soil probes with electrical conductivity, optical, and penetration resistance sensors, these techniques are generally non-invasive with physical quantities determined from measurements made mostly on or directly above the ground. Agricultural geophysics tends to be heavily focused on a 2 m zone directly beneath the ground surface, which includes the crop root zone and all, or at least most, of the soil profile.[1] Complexities encountered with agricultural geophysics include transient soil temperature and moisture conditions, which can appreciably alter, over a period of days or even hours, the values of measured soil physical quantities (especially electrical conductivity and dielectric constant (K)). Additionally, physical quantities measured in the soil environment with

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geophysical methods often exhibit substantial variability over very short horizontal and vertical distances. The three geophysical methods most commonly used for agricultural purposes are resistivity, electromagnetic induction (EMI), and ground-penetrating radar (GPR). However, optical reflectance and gamma (γ)-ray spectroscopy are gaining more widespread utilization. All five of these employed agricultural geophysics methods are summarized in the next section of this entry.

GEOPHYSICAL METHODS

Resistivity

The resistivity method, employed in its most conventional form, uses an external power source to supply electrical current between two "current" electrodes inserted at the ground surface. The propagation of current in the subsurface is three-dimensional, and so too is the associated electric field. Information on the electric field is obtained by measuring the voltage between a second pair of "potential" electrodes also inserted at the ground surface. The two current and two potential electrodes together comprise a single four-electrode array. The magnitude of the current applied and the measured voltage are then used in conjunction with data on electrode spacing and arrangement to determine an apparent soil electrical conductivity (EC_a), for a bulk volume of soil. The current and potential electrodes are often arranged inline, and the depth of investigation increases with increased length of the electrode array.

Continuous measurement galvanic contact resistivity systems integrated with global positioning system (GPS) receivers have been developed in the United State and Europe specifically for farm field soil investigations (Fig. 1). These resistivity systems can have more than one four-electrode array providing shallow investigation depths of 0.3–2 m, with short time or distance intervals between the continuously collected discrete EC_a measurements. The location for each EC_a measurement is determined accurately by GPS. For the system shown in Fig. 1, steel coulters (disks) that cut through the soil surface are utilized as current and potential electrodes. Maps of EC_a spatial patterns across a farm field are generated with resistivity survey data to gain insight on lateral variations in soil properties/conditions, such as water content, soil texture, organic matter content, and so on.

Fig. 2 EMI DUALEM-21 S GCM (DUALEM, Milton, Ontario, Canada) measuring soil electrical conductivity at a golf course green.

Electromagnetic Induction

Electromagnetic induction (EMI) methods also measure the EC_a for a bulk volume of soil directly beneath the surface. An instrument called a ground conductivity meter (GCM) is commonly employed for relatively shallow EMI investigations (Fig. 2). In operation, an alternating electrical current is passed through one of two small electric wire coils spaced a set distance apart and housed within the GCM, which itself is positioned at, or a short distance above, the ground surface. The applied current produces an electromagnetic field around the "transmitting" coil, with a portion of the electromagnetic field extending into the subsurface. This electromagnetic field, called the primary field, induces an alternating

Fig. 1 Example of a continuous measurement galvanic contact resistivity system, Veris 3100 Soil EC Mapping System (Veris Technologies, Salina, Kansas, United States; left) and close-up of steel coulters used for current and potential electrodes by the Veris 3100 Soil EC Mapping System (right).

electrical current within the ground, in turn producing a secondary electromagnetic field. This secondary field extends back to the surface and the air above. The second wire coil acts as a receiver measuring the resultant amplitude and phase components of both the primary and secondary fields. The amplitude and phase differences between the primary and secondary fields are then used, along with the intercoil spacing, to calculate an "apparent" value of EC_a for a bulk volume of soil. Provided low induction number conditions are satisfied, the EMI depth of investigation is dependent on the spacing distance between the electric wire coils within the GCM and the orientation (vertical, horizontal, perpendicular) of the electric wire coils.[2] As with resistivity methods, maps of EC_a spatial patterns across a farm field are generated with EMI data to gain insight on lateral variations in soil properties/conditions, such as water content, soil texture, organic matter content, etc.

Ground-Penetrating Radar

A ground-penetrating radar (GPR) system directs an electromagnetic radio energy (radar) pulse into the subsurface, followed by measurement of the elapsed time taken by the radar signal, as it travels downward from the transmitting antenna, partially reflects off subsurface boundaries or objects, and is eventually returned to the surface, where it is picked up by a receiving antenna. Reflections from different depths produce a signal trace, which is a function of radar wave amplitude vs. time. Radar waves that travel along direct and refracted paths through both air and ground from the transmitting antenna to the receiving antenna are also included as part of the signal trace. Antenna frequency, soil moisture conditions, clay content, salinity, and the amount of iron oxide present all have a substantial influence on the distance beneath the surface to which the radar signal penetrates.[3] The K of a material governs the velocity for the radar signal traveling through that material. Differences in K across a subsurface discontinuity feature control the amount of reflected radar energy, and hence radar wave amplitude, returning to the surface. GPS technologies are often integrated with GPR systems to obtain accurate and precise geographic positions of GPR measurements and to improve the efficiency of GPR field surveys (Fig. 3). As an end product, radar signal amplitude (energy) data are displayed as two-dimensional depth sections or aerial maps to gain insight on belowground conditions or to provide information on the positions and character of subsurface features. The GPR data collected can be used to measure soil volumetric water content (VWC), determine soil horizon depths/thicknesses, and map buried agricultural drainage pipe systems.

Fig. 3 GPR SIR 3000 system (Geophysical Survey Systems, Inc., Nashua, New Hampshire, United States) integrated with Topcon HiPer XT Real Time Kinematic—GPS (RTK-GPS) receiver (Topcon Positioning Systems, Inc., Livermore, California, United States).

Optical Reflectance (UV/VIS/NIR/MIR)

Optical sensors are used to determine the soil's ability to reflect light in different parts of the electromagnetic spectrum. The light can be from the sun or from an artificial source. Proximal optical sensors are fundamentally the same as optical remote sensors; the advantage of proximal sensors is that they can provide measurements at either the soil surface or within the soil. These proximal optical sensors can be used for on-the-spot or on-the-go soil measurements (Fig. 4). Optical sensing systems cover the ultraviolet (UV; 100–400 nm), visible (VIS; 400–700 nm), near infrared (NIR; 700–2500 nm), and mid-infrared (MIR; 2500–25,000 nm) portions of the electromagnetic spectrum. Typically, instruments used for soil measurements include their own light source (e.g., halogen light bulb or light-emitting diode). Photodiodes or array detectors are used to estimate the intensity of reflected light and relate this measure to the light reflected from a given set of standards. Both source and reflected light can be transmitted through the air, via fiber optics, or when feasible, through a contact window fabricated from highly resistive material, such as sapphire or quartz.

Measurements obtained using optical sensors can be related to a number of soil attributes, such as soil mineral composition, clay content, soil color, moisture, organic carbon, pH, and cation exchange capacity (CEC). Measurements can be viewed as direct, when relationships are based on a physical phenomenon that affects light reflectance in a specific part of the spectrum (e.g., predicting soil mineralogy or water content using characteristic water absorption bands); or indirect, when the relationships are deterministic for a finite domain and the combined effects of several soil attributes can be related to a given soil characteristic (e.g., predicting soil organic matter). Sensor calibration strategies

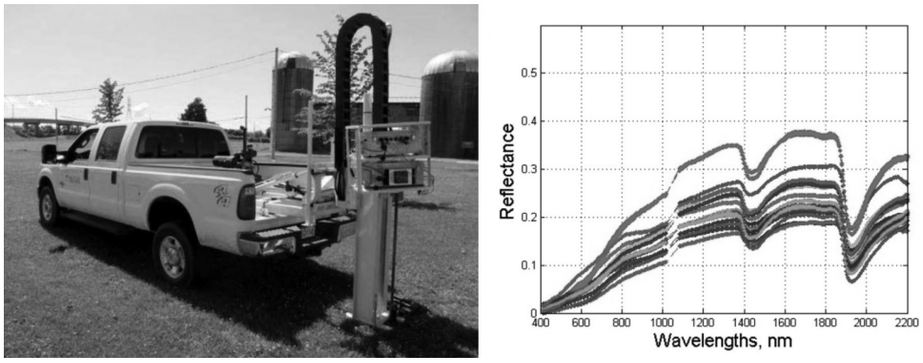

Fig. 4 Veris® P4000 (Veris Technologies, Inc.) probe equipped with two spectrometers covering VIS and NIR parts of the spectrum as well as electrical conductivity and insertion load sensors operated by McGill University (Ste-Anne-de-Bellevue, Quebec, Canada; left), and examples of soil spectra obtained by this instrument at different depths or locations (right).

ranged from a simple linear regression to multivariate methods, chemometrics, and data mining. Although some of these models may be applied to large geographic areas, most are linked to a specific range of soil and environments. UV radiation has also been used in combination with visible and infrared spectra to characterize iron oxides and organic matter.

γ-Ray Spectroscopy

γ rays contain a very large amount of energy and are the most penetrating radiation from natural or artificial sources. γ-ray spectrometers measure the distribution of the intensity of γ radiation versus the energy of each photon. Sensors may be either active or passive. Active γ-ray sensors use a radioactive source (e.g., ^{137}Cs) to emit photons of energy that can then be detected using a γ-ray spectrometer. Passive γ-ray sensors measure the energy of photons emitted from naturally occurring radioactive isotopes of the element from which they originate. As shown in Fig. 5, on-the-go measurement of soil elemental isotopes can be performed by installing a γ-ray sensor on a vehicle. Data interpretation may include analysis of measures related to the isotopes of potassium, thorium, and uranium, the total isotope count, or the entire energy spectrum. While shown to be a useful tool for predicting soil properties in different soil landscapes, a significant amount of preprocessing is often required to reveal relationships between the γ-ray spectra and the soil data. The γ-ray sensor signal can be related to soil mineralogy, particle size distribution, and the effects of attenuating materials such as water and bulk density.

Inelastic neutron scattering (INS) spectroscopy relies on the detection of γ rays that are emitted following the capture and reemission of fast neutrons, as the sample is bombarded with neutrons from a pulsed neutron generator. The emitted γ rays are characteristic of the excited nuclide, and the γ-ray intensity is directly related to the elemental content of the sample. A thorough review of these methods and other proximal soil sensing methods can be found in the work of Viscarra Rossel et al.[4]

APPLICATIONS TO SOIL SCIENCE

U.S. Department of Agriculture (USDA)/ Natural Resources Conservation Center (NRCS) Soil Surveys

Since the 1970s, GPR and EMI have been used by the National Cooperative Soil Survey (NCSS) as quality control tools to investigate, map, and interpret soils. GPR has been used principally, as shown in Fig. 6, to document the presence, depth, lateral extent, and variability of diagnostic subsurface horizons that are used to classify soils, and to name, characterize, and improve the interpretations of soil map units.[5] GPR has also been used as a research tool to assess spatial and

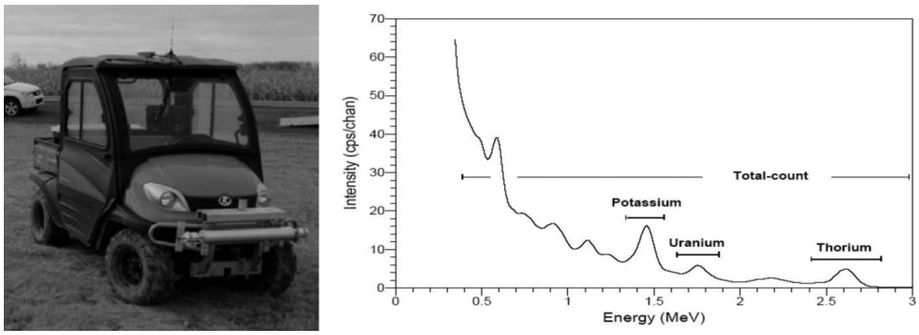

Fig. 5 The Mole γ-ray sensor (The Soil Company, Groningen, Netherlands) operated by Practical Precision, Inc. (Tavistock, Ontario, Canada; left), and an energy/intensity relationship used to define reported measurements (right).

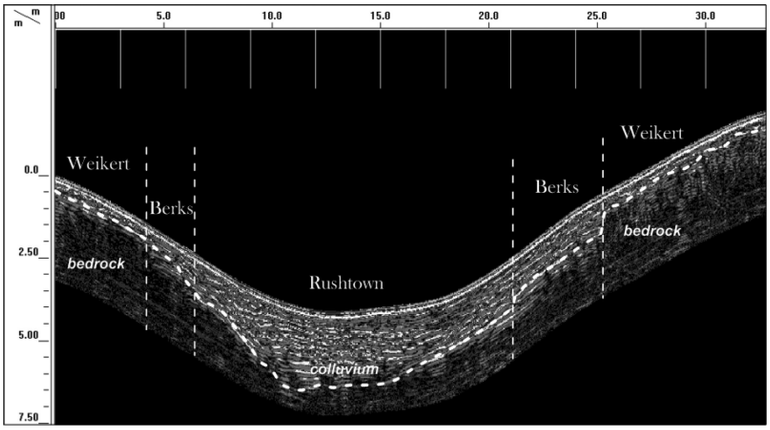

Fig. 6 Variations in the depth to shale bedrock are used to distinguish areas of shallow Weikert, moderately deep Berks and very deep Rushtown soils along this surface normalized GPR profile from the Northern Appalachian Ridges and Valley Region of central Pennsylvania.

temporal variations in soil properties. With the near completion of soil mapping in the United States, GPR is being increasingly used to support USDA conservation programs that help sustain agricultural productivity and environmental quality, address issues of soil health and soil functions, and improve the utility of soil survey data for modeling dynamic soil-hydrologic conditions and functionality at different scales.

The NCSS has used EMI to indirectly measure and map the spatial and temporal variability of soil properties at field scales. Initially used to assess soil salinity, EMI is used to map soil types; refine soil boundaries; identify contrasting soil components within soil map unit delineations; characterize soil water content and flow patterns; assess variations in soil texture, CEC, ionic composition, calcium carbonate content, organic carbon content, plant available nutrients, pH, and bulk density; and determine the depth to subsurface horizons, stratigraphic layers or bedrock, among other uses.[6] As a tool for high-intensity soil surveys, EMI has been used to assist site-specific management, characterize variability in soil physiochemical properties, and direct soil sampling.

Soil surveys require periodic maintenance and updating, as land use change and new demands require additional soil properties to be identified and interpreted. It is anticipated that, as soil surveys evolve, a greater understanding of the complexity and interaction of soil structures, processes, and functions will be needed at increasingly higher levels of resolution. In fulfilling this need, both EMI and GPR should find greater use in field-scaled research projects on representative soilscapes.

Precision Farming

The agricultural production practice, called precision farming, employs spatially mapped field variables that provide assistance to producers for cropping decisions. For example, on-board computers can reference digital maps, directing automated field machinery to vary spatially the

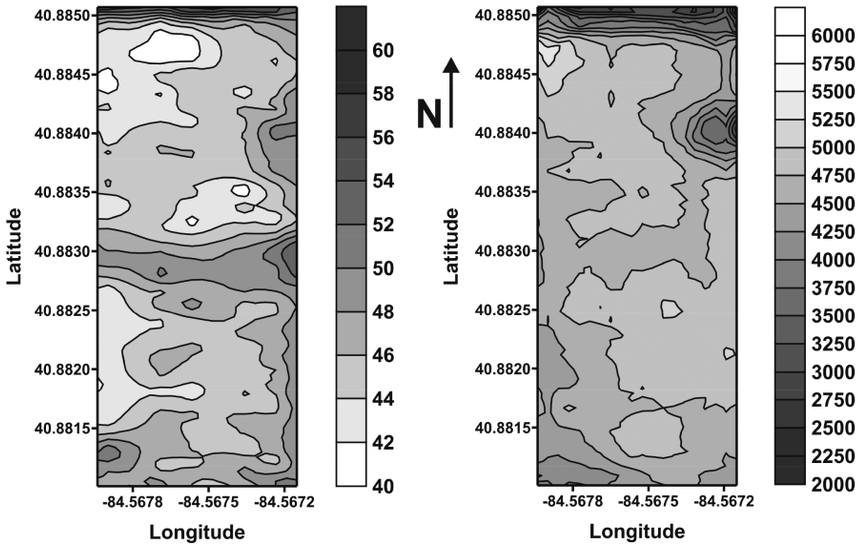

Fig. 7 Soil ECa and crop yield comparison for a 3 hectare field in northwest Ohio. The EC_a map (left) was obtained with a Veris 3100 Soil EC Mapping System, and values are in millisiemens/meter. The soybean yield map (right) has values in kilograms/hectare. The spatial correlation coefficient (r) between EC_a and soybean yield is -0.51.

application rates of fertilizers, pesticides, and seeds. As precision agriculture technologies evolve, higher spatial resolution surveys of the near subsurface will be required because some soil properties, such as soil moisture and organic matter, continually change.

GPSs were a major technology trigger for precision farming during the first decade of the 21st century. GPS is a common farm tool, and it provides accurate positioning for automated field-machine guidance and speed control and supplies the real-time positioning required for the precise placement of seeds, nutrients, and pesticides, along with the geospatial mapping of harvested yields. Global positioning integrated with massive, yet inexpensive, data storage and computational power allows for large acreages to be geospatially mapped by farmers at very high resolutions.

The relatively low-sampling data density of both on-the-go resistivity and EMI instruments, when coupled with GPS positioning, supplies an effective solution for spatially mapping any soil characteristic that can be delineated by relative resistivity/conductivity boundary shifts. For these sensors, the low-data density characteristics are their greatest advantage, as this easily allows for the generation of detailed spatial field maps for very large acreages with little visual interpretation requirements. This simplicity was a trigger for their rapid adoption by farmers and farm consultants. Field maps of EC_a from resistivity or EMI surveys, often show significant correlation with crop yield maps (Fig. 7). Consequently, EC_a maps can be employed to separate the field into different management zones and thereby increase crop production.

GPR is another geophysical tool showing great promise in precision agriculture. At the small plot scale, researchers have shown GPR's abilities to spatially map numerous soil properties essential to agricultural production. Almost any near-surface soil characteristic boundary that can be spatially delineated by sharp shifts in K can be mapped. However, the extreme amount of data generated and its variability when deployed over large acreages are too time-consuming and challenging for visual interpretations. The data computational requirements and survey data storage capacity of GPR surveys were once significant limiting factors, but they are no longer. However, efficient automated processing of the GPR data sets is lacking for large watershed-scale surveys having naturally occurring soils. In contrast with other geophysical sensors having lower data quantity requirements, this geophysical technology has not gained a following by producers using precision agriculture technologies.

Unmanned aerial vehicles (UAVs) coupled with remote geophysical sensors are projected by some experts to revolutionize precision agriculture. Rapid delivery of essential, time-critical information at very low cost is the advantage of the UAV over ground-based geophysical surveys. Aerial field surveys will become automated, inexpensive, and on-demand. For example, miniaturized and lightweight EMI sensors are being introduced for UAV surveys over large areas. The low-flying UAV will closely examine crops, pastures, and timberlands. As they should be able to detect infestations at the very outset, farmers will be able to focus precisely on containment. Cattlemen will be able to remotely monitor livestock health and pinpoint both strays and their predators while they "ride herd" overhead using UAV thermal imaging. Georeferenced nutrient and yield maps will become commonplace, advancing precision agriculture using geophysical applications even further.

Soil Water Content Measurement

GPR can be used to estimate the VWC of soil or rock, as electromagnetic velocity (v) primarily depends on the volume of water in the pore space of earthen materials. Velocity is only slightly affected by mineralogy, grain size, or temperature, so measurements of v can be converted easily to VWC. Velocity is usually converted to K before calculating VWC; several petrophysical relationships based either on empirical data or volumetric mixing models are available in the literature to convert K to VWC.[7]

The three most common techniques for estimating VWC from GPR data are reflected waves, groundwaves, and air-launched methods.[8] For reflected waves, the travel time to

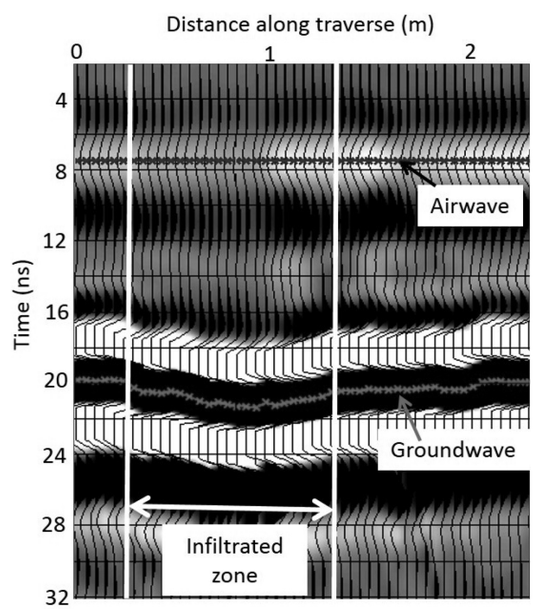

Fig. 8 GPR groundwave data acquired over an infiltrated area surrounded by dryer soil. Wetter soils have lower velocities and longer travel times, as observed over the infiltrated zone.

a subsurface interface can be measured while the GPR antennas are pulled in the common-offset mode along a traverse. If the depth to the interface is known, the travel time is used to estimate ν, which can then be related to VWC. If the depth to the interface is not known, ν can be obtained by performing a variable-offset survey, which provides information on both ν and depth to an interface at one location. Reflections from a continuous subsurface interface can be used to measure VWC to greater depths (i.e., the root zone) and to understand VWC variability across a field. If a continuous interface at a known depth is not available, reflections from isolated subsurface objects or buried pipes that create a reflection hyperbola in the GPR record can be used to estimate ν using reflection hyperbola analysis.

GPR groundwave techniques can be used to estimate VWC by measuring the travel time of this wave. Groundwaves travel in the shallow subsurface (0 cm to ~30 cm) directly between the transmitting and receiving antennas; by noting the antenna separation and the time needed for energy to travel between antennas, ν can be calculated (Fig. 8). Groundwaves do not require a reflective interface, and so can be used in many near-surface soil environments to provide continuous VWC measurements.

Air-launched GPR techniques use the magnitude of the reflection from the ground surface to estimate K. Air-launched data can be acquired and processed quickly, but have a sampling depth of less than 5 cm, and the accuracy of the data greatly diminished by vegetation, uneven soil surfaces, and vertical variations in water content, this technique can be limited in its applications.

Soil Salinity Monitoring

Soil salinity refers to the concentration of dissolved inorganic solutes in the soil solution, consisting of four major cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}) and five major anions (Cl^-, HCO_3^-, NO_3^-, SO_4^{2-}, and CO_3^{2-}). Soil salinity reduces plant growth and, in severe cases, causes crop failure by limiting plant water uptake due to an osmotic effect making it more difficult for the plant to extract water, by specific-ion toxicity, or by upsetting the nutritional balance of plants.

In the laboratory, soil salinity is most commonly determined from the measurement of the electrical conductivity of the solution extract of a saturated soil paste (EC_e), which is proportional to the concentration of ions in the solution. However, because salinity is a highly spatially and temporally variable soil property, the use of EC_e to measure salinity at field scales is impractical due to the need for hundreds or even thousands of soil samples. The use of EC_e to measure salinity at field scales is only practical when soil sampling is directed using correlated spatial information. Geospatial measurements of EC_a using geophysical techniques (i.e., electrical resistivity, EMI, or time domain reflectometry) are sources of spatial information used to direct soil sampling to characterize field-scale soil salinity variation.

EC_a measures the conductance through not only the soil solution but also through the solid soil particles and via exchangeable cations that exist at the solid–liquid interface of clay minerals. The interpretation of EC_a measurements is not trivial due to the complexity of current flow in the bulk soil through the three conductance pathways–liquid, solid, and solid–liquid interface. Because of the three pathways of

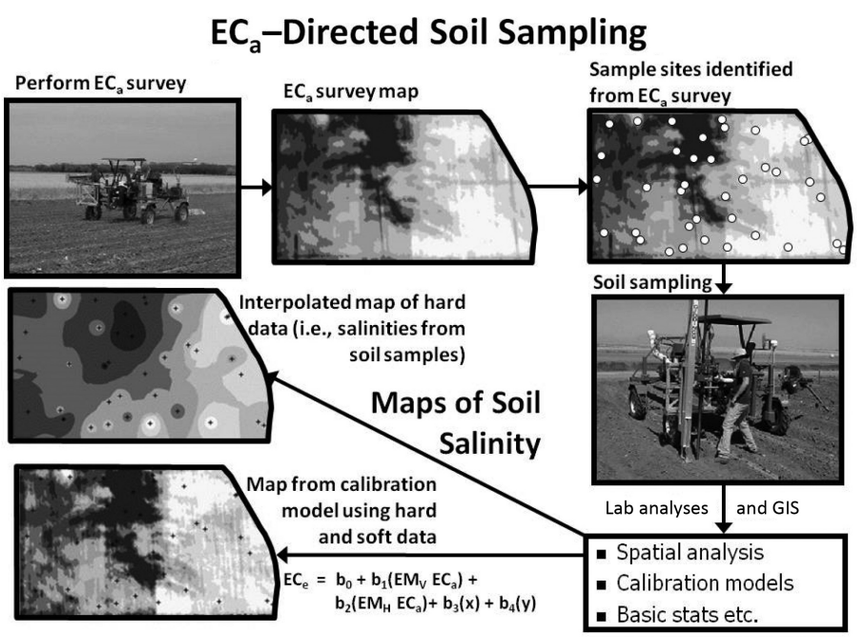

Fig. 9 Schematic of EC_a-directed soil sampling for mapping the spatial variability of soil salinity.

conductance, the EC_a measurement is influenced by several soil properties–soil salinity, texture, water content, bulk density, and temperature. Detailed protocols for conducting an EC_a survey to characterize the spatial variability of soil salinity with EC_a-directed soil sampling are provided by Corwin and Lesch.[9,10] A schematic of EC_a-directed soil sampling is shown in Fig. 9.

CONCLUSION

Near-surface geophysical methods have become an increasingly important tool for soil investigations in agricultural settings. The methods predominantly employed are resistivity, EMI, and GPR; however, optical reflectance and γ-ray spectroscopy are beginning to find more widespread utilization. Furthermore, research indicates that other geophysical methods, such as cosmic-ray neutron probes, seismic, self-potential, magnetometry, nuclear magnetic resonance, etc., all exhibit potential for measurement of soil properties or conditions. The application to soil surveys, precision farming, soil water content measurement, and soil salinity monitoring has been described in this entry, but geophysical methods have also been used for soil investigations in forested areas, confined animal feeding facilities, and golf courses, with new applications continuing to evolve. Development of multisenor platforms and sensors mounted on UAVs will dramatically improve geophysical soil investigation capabilities with respect to field accessibility and data interpretation. Consequently, the future of near-surface geophysics in soil science appears very promising.

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