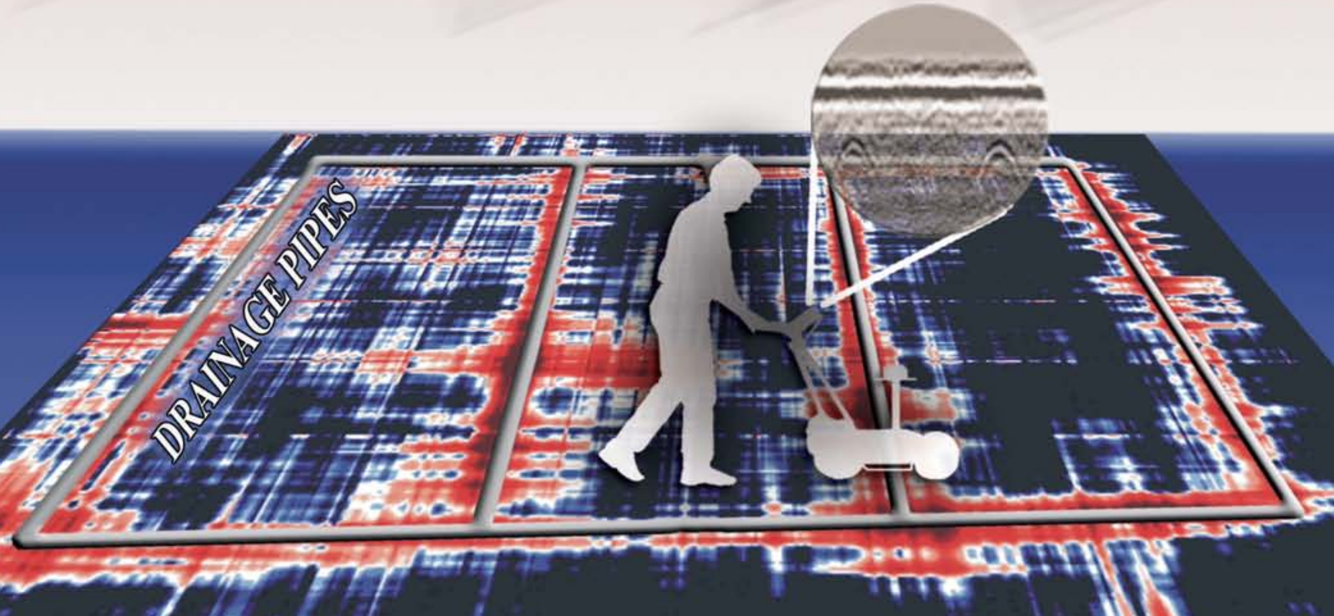
Handbook *of* Agricultural Geophysics

Edited by

Barry J. Allred • Jeffrey J. Daniels
M. Reza Ehsani



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Preface

Geophysical methods continue to show great promise for use in agriculture. The term "agricultural geophysics" denotes a subdiscipline of geophysics that is focused only on agricultural applications. As this geophysics subdiscipline becomes better established, there may come a time when a contracted name becomes appropriate, such as "agrigeophysics;" however, for this book, the more recognized term, "agricultural geophysics" will be used predominantly. Potential agricultural applications for geophysical methods are widespread and include precision agriculture, site infrastructure assessment, hydrologic monitoring, and environmental investigations. For example, changes in soil electrical conductivity measured across a farm field using geophysical methods may reflect spatial variability in soil properties, and this information can in turn be used along with precision agriculture techniques to ensure that the right quantity of fertilizer is applied to different parts of the field. In cases where placement records have been lost, ground-penetrating radar can be employed to locate and map buried agricultural drainage pipes. Geophysical measurements can be affected by the amount of water within soil, thereby allowing assessment of shallow hydrologic conditions. Geophysical methods could also be used in an environmental investigation to determine if there are leaks present in animal waste storage ponds or treatment lagoons.

The *Handbook of Agricultural Geophysics* was compiled to include a concise overview of the geophysical methods that can be utilized in agriculture and provides detailed descriptions of situations in which these techniques have been employed. The book is divided into four sections, with the first section devoted to both a general introduction of agricultural geophysics (Chapter 1) and a summary of past applications of geophysical methods to agriculture (Chapters 2 and 3). The second section systematically describes the three geophysical methods now most commonly employed: resistivity (Chapter 5), electromagnetic induction (Chapter 6), and ground-penetrating radar (Chapter 7). The second section also presents some theoretical insight on soil electrical conductivity measurement (Chapter 4) and describes, although in limited detail, three geophysical methods not typically used for agriculture but possibly having more widespread future application: magnetometry, self-potential, and seismic (Chapter 8). The Global Positioning System (GPS) and geographic information systems (GISs) are revolutionizing the way geophysical data are acquired and analyzed, and therefore warrant separate discussion in the third section of the book (Chapters 9 and 10). Agricultural geophysics case histories comprise roughly half the book. The resistivity and electromagnetic induction method case histories are included in Section IV (Chapters 11–22). The ground-penetrating radar method case histories are found in Section V (Chapters 23–30). The value of these case histories is that they document a wide range of scenarios in which geophysical methods have been successfully employed, thereby giving the reader an indication as to the potential effectiveness of using agricultural geophysics for their particular purpose.

Geophysicists will undoubtedly be very knowledgeable regarding most of the material presented within the first two, and probably, the third sections of this book. Although not the intended audience, geophysicists who are unfamiliar with geophysical applications to agriculture may have an interest in the case histories presented within the last two sections of the book. The primary audience for the *Handbook of Agricultural Geophysics* is expected to be quite diverse and include government agency personnel, university agricultural researchers, and agricultural and environmental consultants. To meet the growing demands of the intended audience, the book has been written specifically for those working in agriculture who need to use geophysical tools for gathering valuable information to solve problems. The reader of this book is therefore not expected to have a strong background in geophysics, and as such, when theoretical aspects are introduced, they are described, as much as possible, in an easy to understand manner. Furthermore, throughout the book, emphasis is placed on practical considerations regarding the application of geophysical methods to agriculture.*

Barry J. Allred
M. Reza Ehsani
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* Note: The use of product names throughout the book is for informational purposes only and does not imply endorsement by the editors or the organizations they represent.

Editors

Barry Allred is an agricultural engineer with the U.S. Department of Agriculture – Agricultural Research Service – Soil Drainage Research Unit, Columbus, Ohio. He is also an adjunct assistant professor in the Food, Agricultural, and Biological Engineering Department at Ohio State University. He has a B.S. degree in geology and two M.S. degrees, the first M.S. with emphasis in geophysics and the second M.S. with emphasis in hydrogeology. He earned his Ph.D. in Biosystems Engineering from Oklahoma State University. Prior employment experience includes working as a geophysicist in the petroleum industry (ConocoPhillips Inc.) and as a hydrogeologist with both an environmental consulting firm (ERM-Southwest, Inc.) and a state government agency (New Mexico Bureau of Geology and Mineral Resources). His research interests involve application of near-surface geophysical methods to agriculture; agricultural drainage and drainage water recycling systems; and laboratory hydraulic/mechanical property, solute transport, and environmental remediation studies. His agricultural geophysics investigations have focused largely on drainage pipe detection and golf course infrastructure assessment using ground-penetrating radar. He has also studied aspects of soil electrical conductivity mapping using both resistivity and electromagnetic induction methods. He is the lead author or coauthor of over 50 journal, technical, or book chapter publications.

Jeffrey Daniels is a professor in the School of Earth Sciences at The Ohio State University. He received his Ph.D. degree from the Colorado School of Mines and M.S. and B.S. degrees from Michigan State University. Daniels is an applied geophysicist, with a broad base of experience in surface and borehole geophysical methods applied to subsurface science. Prior to 1985, he was a research scientist for the U.S. Geological Survey in Denver, Colorado, working on surface electrical methods and borehole geophysical methods (electrical, nuclear, and acoustic) for characterizing physical properties near the borehole in the uranium (exploration and nuclear waste disposal) and coal exploration and development programs. He is an experienced computer programmer, and his personal research focuses on forward and inverse computer modeling applied to geophysical imaging. In addition to his current work on agricultural problems, he has research projects and interests in the areas of subsurface void detection and environmental problems related to energy development and sustainability.

Reza Ehsani is an assistant professor of Agricultural and Biological Engineering at the University of Florida/Institute of Food and Agricultural Sciences (UF/IFAS) Citrus Research and Education Center (CREC). His current areas of research include precision technology for fruit and vegetable production, application of Global Positioning System/Geographic Information System (GPS/GIS) for orchard management, development of soil and plant sensors, and machine enhancement for citrus mechanical harvesters. He also develops educational materials on the application of GPS/GIS and sensor technology for fruit and vegetable growers and organizes grower conferences on precision agriculture and mechanical harvesting for citrus. Ehsani has a Ph.D. in Biological and Agricultural Engineering from the University of California, Davis. He also obtained a B.S. and M.S. in Agricultural Engineering from Tehran University, Iran. He was an assistant professor and a precision agriculture specialist at the Department of Food, Agricultural, and Biological Engineering at The Ohio State University before joining the University of Florida. He has authored or coauthored more than 65 journal and technical papers.

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List of Important Agricultural and Geophysical Quantities

Quantity	Acronym or Symbol	Commonly Reported Measurement Units	Abbreviated Measurement Units
Apparent soil electrical conductivity	EC_a, σ_a	millisiemens/meter	mS/m
Apparent soil electrical resistivity	ER_a, ρ_a	ohm-meter	Ωm
Bulk modulus	k	gigapascals	GPa
Cation exchange capacity	CEC	milliequivalents/100 grams	meq/100 g
Crop yield	Y	kilograms/hectare	kg/ha
Density	ρ	grams/cubic centimeter	g/cm^3
Dielectric constant (or relative permittivity)	κ, ε_r	dimensionless ratio value	dimensionless
Electric current	I	amperes	A
Electric potential	V	volts	V
Electric potential difference	ΔV	volts	V
Electric Field electric potential gradient	E	volts/meter	V/m
Electromagnetic wave skin depth	δ, $\frac{1}{\alpha}$	meters	m
Hydraulic conductivity	K	centimeters/second	cm/s
Frequency (wave)	f	hertz	Hz
Magnetic field strength	B	nanoteslas	nT
Magnetic permeability	μ	henrys/meter	H/m
Magnetic susceptibility	κ	dimensionless quantity	dimensionless
Pesticide partition coefficient	K_d	liters/kilogram	L/kg
Porosity	n, ϕ	fraction by volume	dimensionless
Rigidity (shear) modulus	μ	gigapascals	GPa
Seismic adsorption coefficient	α	1/kilometers	1/km
Degree of saturation (soil)	S	fraction by volume	dimensionless
Salinity (electrical conductivity of saturated soil paste)	EC_e	decisiemens/meter	dS/m
Sodium adsorption ratio	SAR	fraction based on concentration	dimensionless
Soil dry bulk density	ρ_b	grams/cubic centimeter	g/cm^3
Soil particle size distribution	sand, silt, and clay	percentage by weight	%
Soil gravimetric water content	w	fraction by weight	dimensionless
Soil organic matter content	SOM	fraction by weight	dimensionless
Soil organic carbon content	SOC	fraction by weight	dimensionless
Soil pH	pH	dimensionless quantity	dimensionless
Soil volumetric water content	θ	fraction by volume	dimensionless
Soil solution concentration	Cc	moles/liter, milligrams/liter, or parts/million	mol/L, mg/L, or ppm
Pore water pressure potential	H_p, Ψ	centimeters of water	cm
Specific surface	S_S	meters squared/gram	m^2/g
Temperature	T	degrees celsius	°C

(continued on next page)

Quantity	Acronym or Symbol	Commonly Reported Measurement Units	Abbreviated Measurement Units
Velocity (seismic and radar)	seismic P-wave (V_P), seismic S-wave (V_S), radar (v)	V_P: kilometers/second V_S: kilometers/second v: meters/nanosecond	V_P: km/s V_S: km/s v: m/ns
Wavelength	λ	meters	m

Note: The same symbol is often utilized for more than one quantity.

Section I

Agricultural Geophysics Overview

1 General Considerations for Geophysical Methods Applied to Agriculture

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1.1 INTRODUCTION: GEOPHYSICS DEFINITIONS, DEVELOPMENT CHRONOLOGY, INVESTIGATION SCALE

Geophysics can be defined several ways. In the broadest sense, geophysics is the application of physical principles to studies of the Earth (Sheriff, 2002). This general definition of geophysics encompasses a wide range of disciplines, such as hydrology, meteorology, physical oceanography, seismology, tectonophysics, etc. Geophysics, as it is used in this book, has a much more focused definition. Specifically, geophysics is the application of physical quantity measurement techniques to provide information on conditions or features beneath the Earth's surface. With the exception of borehole geophysical methods and soil probes like a cone penetrometer, these techniques are generally noninvasive, with physical quantities determined from measurements made mostly at or near the ground surface. (Note: Some large-scale airborne surveys are carried out with geophysical measurements collected by airplanes and helicopters positioned well above the surface, but these types of surveys are not within the scope of this book.) The geophysical methods employed to obtain subsurface information from surface-based measurements include resistivity, electromagnetic induction, ground-penetrating radar, magnetometry, self-potential, seismic, gravity, radioactivity, nuclear magnetic resonance, induced polarization, etc.

One of the first known instruments for geophysical measurement is a seismoscope invented in A.D. 132 by the Chinese philosopher, Chang Hêng (Needham, 1959). This seismoscope reportedly had the capability to not only detect earthquakes, but could also determine the direction from which the earthquake originated. Many of the geophysical methods employed today originated or were more fully developed based on the needs of the mining and petroleum industries. In fact, present levels of worldwide production for minerals, oil, and natural gas could not have been achieved without the use of geophysics as an exploration tool.

The magnetic compass was used to find iron ore as early as 1640 (Dobrin and Savit, 1988). Robert Fox devised the self-potential method using copper-plated electrodes and a galvanometer to find copper sulfide ore bodies in Cornwall, England, during 1830 (Reynolds, 1997). Robert Thalén wrote *On the Examination of Iron Ore Deposits by Magnetic Methods* in 1879 and contributed to the invention of some of the first magnetometers (Telford et al., 1976). These Thalén–Tiberg and Thomson–Thalén magnetometers proved very successful for mineral prospecting in Sweden during the late 1800s. Initial development of resistivity and electromagnetic induction methods for the mining industry occurred between 1910 and 1930. Airborne magnetometers refined for submarine detection during the Second World War were employed shortly afterward to quickly prospect for minerals over large areas (Dobrin and Savit, 1988). The introduction of airborne electromagnetic surveys for mineral exploration also occurred shortly after the Second World War ended.

Dobrin and Savit (1988) and Lawyer et al. (2001) detail some of the early history involving initial applications of geophysical methods for the petroleum industry. A torsion balance field device for measuring anomalies in the Earth's gravitational field was refined by Baron Roland von Eötvös of Hungary in the late 1800s. Crude seismic methods were developed by the French, British, Germans, and Americans during the First World War as a means to locate enemy artillery positions. Torsion balance gravity measurements and fan-pattern seismic refraction surveys were then used to find oil fields associated with Texas Gulf Coast salt domes in the 1920s. Conventional seismic refraction methods introduced in 1928 to the Middle East were soon found to be particularly effective within Iran for locating limestone structures containing substantial oil reserves. J. C. Karcher conducted the first seismic reflection experiments from 1919 to 1921 and then demonstrated the potential of this geophysical method for oil exploration by mapping a shallow rock unit in central Oklahoma during 1921. The first oil discovery attributed to seismic reflection occurred during 1927 with the Maud Field in Oklahoma. Seismic reflection is the predominant geophysical method used for petroleum exploration today.

Although radar technologies were introduced during the Second World War, it was not until the early 1960s that ground-penetrating radar was first employed as a geophysical tool, initially to investigate the subsurface characteristics of polar ice sheets (Bailey et al., 1964). Archeological, environmental, geotechnical engineering, and hydrological geophysical surveys became more and more common in the latter half of the past century. There was some agricultural research activity in the 1930s and 1940s related to soil moisture measurement with resistivity methods (Edlefsen and Anderson, 1941; Kirkham and Taylor, 1949; McCorkle, 1931), but for the most part, the application of geophysical methods to agriculture did not gain momentum until the 1960s, and to a greater extent in the 1970s, with the use of resistivity methods for soil salinity assessment (Halvorson and Rhodes, 1974; Rhoades and Ingvalson, 1971; Rhoades et al., 1976; Shea and Luthin, 1961). Greater historical detail on the application of geophysical methods to agriculture is provided in Chapters 2 and 3 of this book.

Geophysical surveys conducted for petroleum, mining, hydrological, environmental, geotechnical engineering, archeological, and agricultural applications vary dramatically in scale with respect to the investigation depth of interest. Petroleum industry oil and gas wells have been drilled to levels 8 km beneath the surface based on information obtained from seismic reflection surveys. Most geophysical surveys conducted in the mining industry have an investigation depth of interest that is less than 1 km. There are, however, some deep mining operations extending more than 3 km below ground, and therefore mining geophysical surveys can occasionally require greater investigation depths down to 3 or 4 km. A geophysical survey conducted as part of a hydrological investigation to determine groundwater resources usually has an investigation depth no greater than 300 m. Geophysical investigation depths for environmental, geotechnical engineering, and archeological applications typically do not exceed 30 m. 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.

With regard to the application of geophysics to agriculture, this extremely shallow 2 m depth of interest is certainly an advantage, in one sense because most geophysical methods have investigation depth capabilities that far exceed 2 m. However, there are complexities associated with agriculture geophysics not typically encountered with the application of geophysical methods to other industries or disciplines. One such complexity involves transient soil temperature and moisture conditions that can appreciably alter the values of measured geophysical quantities over a period of days or even hours. Additionally, physical quantities measured in the soil environment with geophysical methods often exhibit substantial variability over very short horizontal and vertical distances.

1.2 GEOPHYSICAL METHODS APPLICABLE TO AGRICULTURE

Geophysical methods can be classified as passive or active. There is no artificial application of energy with passive geophysical methods. On the other hand, active geophysical methods do require the artificial application of some form of energy. The three geophysical methods predominantly used for agricultural purposes are resistivity, electromagnetic induction, and ground-penetrating radar. All three of these predominantly employed methods are active, and each is summarized within this book; resistivity in Chapter 5, electromagnetic induction in Chapter 6, and ground-penetrating radar in Chapter 7. Chapter 8 provides shorter descriptions of three additional geophysical methods: magnetrometry (passive), self-potential (passive), and seismic (active), all of which have the potential for substantial future use in agriculture, but at present are being employed sparingly or not at all for agricultural purposes. To provide an introduction, the six geophysical methods—resistivity, electromagnetic induction, ground-penetrating radar, magnetometry, self-potential, and seismic—are all concisely defined as follows.

1.2.1 Resistivity Methods

Resistivity methods measure the electrical resistivity, or its inverse, electrical conductivity, for a bulk volume of soil directly beneath the surface. Resistivity methods basically gather data on the subsurface electric field produced by the artificial application of electric current into the ground. With the conventional resistivity method, an electrical current is supplied between two metal electrode stakes partially inserted at the ground surface, while voltage is concurrently measured between a separate pair of metal electrode stakes also inserted at the surface. The current, voltage, electrode spacing, and electrode configuration are then used to calculate a bulk soil electrical resistivity (or conductivity) value.

1.2.2 Electromagnetic Induction Methods

Electromagnetic induction methods also measure the electrical conductivity (or resistivity) for a bulk volume of soil directly beneath the surface. An instrument called a ground conductivity meter is commonly employed for relatively shallow electromagnetic induction investigations. 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 ground conductivity meter that 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 electrical current within the ground, in turn producing a secondary electromagnetic field. Part of the secondary field spreads 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 resultant fields are then used, along with the intercoil spacing, to calculate an "apparent" value for soil electrical conductivity (or resistivity).

1.2.3 Ground-Penetrating Radar Methods

With the ground-penetrating radar (GPR) method, an electromagnetic radio energy (radar) pulse is directed 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 a buried feature, and eventually returns 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 versus 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 have a substantial influence on the distance beneath the surface to which the radar signal penetrates. The dielectric constant of a material governs the velocity for the radar signal traveling through that material. Differences in the dielectric constant across a subsurface discontinuity feature control the amount of reflected radar energy, and hence radar wave amplitude, returning to the surface. As an end product, radar signal amplitude data are plotted on depth sections or areal maps to gain insight on below-ground conditions or to provide information on the position and character of a subsurface feature.

1.2.4 Magnetometry Methods

This geophysical method employs a sensor, called a magnetometer, to measure the strength of the Earth's magnetic field. Anomalies in the Earth's magnetic field indicate the presence of subsurface features. An anomaly is produced when a subsurface feature has a remanent magnetism or magnetic susceptibility that is different from its surroundings. A gradiometer is an instrument setup composed of two magnetometer sensors mounted a set distance apart. Gradiometers are typically used to measure the vertical gradient of the magnetic field, which is not affected by transient magnetic field changes. In comparison to a single magnetometer sensor, the gradiometer has the additional advantage of being better adapted for emphasizing magnetic field anomalies from shallow sources.

1.2.5 Self-Potential Methods

Self-potential methods collect information on a naturally occurring electric field associated with nonartificial electric currents moving through the ground. Unlike resistivity methods, no electric power source is required. Naturally occurring electric potential gradients can arise a number of different ways, including the subsurface flow of water containing dissolved ions, spatial concentration differences of dissolved ions present in subsurface waters, and electrochemical interactions between mineral ore bodies and dissolved ions in subsurface waters. Self-potential methods are fairly simple operationally. All that is required to obtain information on a natural electric field below ground is the voltage measurement between two nonpolarizing electrodes placed or inserted at the ground surface.

1.2.6 Seismic Methods

Seismic methods employ explosive, impact, vibratory, and acoustic energy sources to introduce elastic (or seismic) waves into the ground. These seismic waves are essentially elastic vibrations that propagate through soil and rock materials. The seismic waves are timed as they travel through the subsurface from the source to the sensors, called "geophones." The energy source is positioned at the surface or at a shallow depth. Geophones are typically inserted at the ground surface. Seismic waves move through the subsurface from source to geophone along a variety of direct, refracted, and reflected travel paths. The velocity of a seismic wave as it travels through a material is determined by the density and elastic properties for that particular material. Differences in the density and elastic properties across a subsurface discontinuity feature control the amount of reflected or refracted seismic energy, and hence the seismic wave amplitudes returning to the surface. Information on the timed arrivals and amplitudes of the direct, refracted, and reflected seismic waves measured by the geophones are then used to gain insight on below-ground conditions or to locate and characterize subsurface features.

1.3 ASPECTS OF AGRICULTURAL GEOPHYSICS DATA COLLECTION AND ANALYSIS

1.3.1 Selecting the Proper Geophysical Method

A clear goal must be defined in the initial planning stage of a geophysical survey regarding the soil condition or subsurface feature information that needs to be acquired. In order to choose the proper geophysical method for monitoring changing soil conditions, consideration must first be given to the different physical properties responded to by the various geophysical methods and then whether any of these physical properties are influenced by the soil condition of interest. Delineating a subsurface feature with geophysics requires there to be a contrast between the feature and its surroundings with respect to some physical property responded to by a geophysical method. To summarize, the geophysical method selected must respond to a physical property that is in turn affected by temporal changes in soil conditions or the spatial patterns of subsurface features; otherwise, useful information cannot be obtained on these soil conditions or subsurface features of interest. For example, soil cation exchange capacity (CEC) will often have a substantial impact on soil electrical conductivity (or resistivity); therefore, resistivity or electromagnetic induction methods that measure soil electrical conductivity may be useful for delineating spatial patterns in CEC. On the other hand, magnetometry methods respond to anomalies in remanent magnetism or magnetic susceptibility, properties that are not likely to be affected by CEC, and consequently, magnetometry methods would not be a good choice for delineating spatial patterns in CEC.

1.3.2 Investigation Depth and Feature Resolution Issues

Once a geophysical method is chosen, there are usually options with respect to the equipment and its setup. The investigation depth required and the size of the feature to be detected are two important issues that should be taken into account when deciding on the equipment to use and its setup. There is normally a trade-off between the investigation depth and the minimum size a feature must have to be detected. Finding a large, deeply buried object or a small, shallow object with geophysical methods is much easier than locating a small, deeply buried object. One potential example is the use of GPR to locate buried plastic or clay tile agricultural drainage pipe. The radar signal penetration depth and minimum size at which an object can be detected are both inversely related to GPR antenna frequency. Low-frequency GPR antennas are better for locating larger deeply buried objects, and high-frequency GPR antennas are more applicable for small, shallow objects. Therefore, a GPR unit with 100 MHz transmitting and receiving antennas might work well at finding a 30 cm diameter drainage pipe 2 m beneath the surface in a clay soil, and a GPR unit with 250 MHz transmitting and receiving antennas is likely capable of finding a 10 cm diameter drainage pipe 0.5 m beneath the surface in a clay soil. But, finding a 10 cm diameter drainage pipe 2 m beneath the surface in a clay soil is probably an extremely difficult undertaking regardless of the GPR antenna frequency employed.

An important implication with respect to the issues of investigation depth and feature resolution (detection) is to use equipment with the proper setup that provides an investigation depth similar to the investigation depth of interest. Using an equipment setup with an investigation depth substantially greater than the investigation depth of interest results in the minimal size for feature resolution being increased over what would be the case if the equipment investigation depth coincided with the investigation depth of interest. Additionally, by using an equipment setup with an investigation depth substantially greater than the investigation depth of interest, a problem could arise of not being able to determine whether a detected feature is located within the investigation depth of interest or at a deeper level. An equipment setup investigation depth substantially less than the investigation depth of interest means that features positioned between the equipment setup investigation depth and the depth of interest will not be detected. For example, when a resistivity survey is employed to map lateral changes within a well-developed soil profile, a specific electrode array length might be chosen to provide an approximate 2 m investigation depth. Significantly shorter or longer electrode array lengths than that selected for a 2 m investigation depth would respectively produce investigation depths much less or much greater than 2 m, thereby producing information that does not include the entire soil profile (short electrode array length problem) or information where it is difficult to determine whether resistivity changes occurred within the soil profile or at a greater depth (long electrode array problem). Finally, there are instances where small, deeply buried features are unlikely to be detected, and therefore, time and expense should not be wasted conducting a geophysical survey.

1.3.3 Field Operations: Station Interval, Stacking, Survey Line/Grid Setup, and Global Positioning System (GPS) Integration

The distance is usually fixed or at least fairly consistent from one geophysical measurement location to the next along a transect, and this distance between measurement locations is referred to as the station interval. A short station interval provides a better chance for finding the smaller features that are capable of being resolved with the geophysical equipment used. Reducing the station interval has the downside of increasing the time needed to conduct a geophysical survey. Consequently, it makes sense to use the shortest station interval possible that still allows the geophysical survey to be carried out in the time allotted.

Often, several measurements are collected at each measurement location and then are added or averaged. This overall process is called stacking. Unwanted signals referred to as noise tend to be random and can thus be cancelled out by adding or averaging multiple geophysical measurements obtained at the same location. Although data quality is improved, increased stacking can slow the geophysical survey. Data collection procedures should be optimized to provide the greatest amount of stacking possible within the time frame during which the geophysical survey needs to be conducted.

For a larger subsurface feature where the general directional trend is known, a sufficient number of geophysical measurement transects should be oriented perpendicular to the feature's trend so as to better delineate the feature. A measurement transect parallel to a linear subsurface feature, but offset from it by sufficient distance, will in all probability not detect the feature. A geophysical survey grid covering a study area is commonly composed of either one set of parallel measurement transects or two sets of parallel measurement transects oriented perpendicular to one another. Setting up a geophysical survey grid composed of two sets of parallel measurement transects oriented perpendicular to one another reduces the risk of not finding long, narrow subsurface features, such as agricultural drainage pipes, whose trend prior to the survey is unknown. The spacing distance between adjacent transects is usually fixed at some constant or fairly consistent value for a particular set of parallel transects. This spacing distance should be set small enough, within reasonable limits, to avoid missing important features.

The integration of Global Positioning System (GPS) receivers with geophysical equipment is becoming more and more common, particularly with regard to agricultural applications. GPSs can provide accurate determinations of measurement locations while the geophysical survey is in progress. As a result of GPS integration, marking off a well-defined grid in the field is no longer required, thereby allowing rapid geophysical data collection over large areas, especially in regard to horizontal soil electrical conductivity mapping with resistivity or electromagnetic induction methods. The importance of GPS to agricultural geophysics will undoubtedly continue to experience growth in the near future; therefore, a detailed discussion on aspects related to GPS is certainly warranted and can be found in Chapter 9.

1.3.4 Analysis of Geophysical Data

Depth sections and contour maps are two of the most common geophysical data analysis end products. Two-dimensional depth sections characterize the distribution of some geophysically measured property beneath a measurement transect along the surface. Different geophysical methods employ different computer processing steps to produce these depth sections. Contour maps are typically used to show the horizontal spatial pattern of some geophysically measured property. Various spatial interpolation algorithms are employed by the computer software used to generate these contour maps. Where there is a choice, careful consideration is needed in selecting the interpolation algorithm so as not to introduce features on the contour map that do not truly exist or to remove features that are actually present.

Rather than focusing just on a single geophysical data set at a time, the integration of several geophysical data sets along with other spatial information is an approach that can potentially improve agricultural data interpretation for a particular farm site. Integration of multiple geophysical and nongeophysical spatial data sets is accomplished using a geographic information system (GIS). A GIS is a powerful data analysis tool that is just beginning to find widespread use in agricultural geophysics. Because GIS is expected to become essential to agricultural geophysics in the future, a detailed discussion on some important GIS elements is definitely relevant and is presented in Chapter 10.

1.4 POTENTIAL AGRICULTURAL USES FOR GEOPHYSICAL METHODS

Past research indicates a wide range of potential uses for the three geophysical methods predominantly employed in agriculture (resistivity, electromagnetic induction, and ground-penetrating radar). Table 1.1 serves to emphasize the variety of possible applications by listing just a few of the numerous ways that these three geophysical methods can provide valuable information for agriculture purposes. The resistivity and electromagnetic induction case histories in Chapter 11 and the ground-penetrating radar case histories in Chapter 12 provide in-depth descriptions for many of the agricultural geophysics applications listed in Table 1.1. However, some aspects regarding the last four agricultural geophysics applications listed in Table 1.1 warrant further mention at this juncture.

Figure 1.1 provides two examples of GPR drainage pipe detection. Figure 1.1a and Figure 1.1b are GPR time-slice amplitude maps. Each map represents the reflected radar amplitudes (and radar energy) returning to the surface from a particular depth interval. Lighter shaded elements on grayscale GPR time-slice amplitude maps typically denote subsurface features that reflect significant amounts of radar energy. The lighter shaded elements with linear trends found in Figure 1.1 are indicative of buried drain lines. Shown in Figure 1.1a is the subsurface drainage pipe system in a northwest Ohio agricultural field, and depicted in Figure 1.1b is the subsurface drainage pipe system for a central Ohio golf course green. In addition to GPR, magnetometry methods have exhibited some success in locating buried drainage pipes (Rogers et al., 2005, 2006). An example regarding the application of magnetometry methods to locate subsurface drain lines at a dairy operation in Oregon is included in Chapter 8.

TABLE 1.1
Potential Agricultural Applications for Resistivity, Electromagnetic Induction, and Ground-Penetrating Radar Methods

Geophysical Method	Agricultural Application	Literature Source
Resistivity	Soil drainage class mapping	Kravchenko et al., 2002
Electromagnetic induction	Determining clay-pan depth	Doolittle et al., 1994
Electromagnetic induction	Estimation of herbicide partition coefficients in soil	Jaynes et al., 1995a
Electromagnetic induction	Mapping of flood deposited sand depths on farmland adjacent to the Missouri River	Kitchen et al., 1996
Electromagnetic induction	Soil nutrient monitoring from manure applications	Eigenberg and Nienaber, 1998
Ground-penetrating radar	Quality/efficiency improvement and updating of U.S. Department of Agriculture/Natural Resources Conservation Service (USDA/NRCS) soil surveys	Doolittle, 1987; Schellentrager et al., 1988
Ground-penetrating radar	Measurement of microvariability in soil profile horizon depths	Collins and Doolittle, 1987
Ground-penetrating radar	Bedrock depth determination in glaciated landscape with thin soil cover	Collins et al., 1989
Ground-penetrating radar	Plant root biomass surveying	Butnor et al., 2003; Konstantinovic et al., 2007; Wöckel, et al., 2006
Ground-penetrating radar	Identification of subsurface flow pathways	Freeland et al., 2006; Gish et al., 2002
Ground-penetrating radar	Farm field and golf course drainage pipe detection	Allred et al., 2005a; Boniak et al., 2002; Chow and Rees, 1989
Resistivity and electromagnetic induction	Soil salinity assessment	Doolittle et al., 2001; Hendrickx et al., 1992; Rhoades and Ingvalson, 1971; Rhoades et al., 1989; Shea and Luthin, 1961
Resistivity and electromagnetic induction	Delineation of spatial changes in soil properties	Allred et al., 2005b; Banton et al., 1997; Carroll and Oliver, 2005; Johnson et al., 2001; Lund et al., 1999
Resistivity, electromagnetic induction, and ground-penetrating radar	Soil water content determination	Grote at al., 2003; Huisman et al., 2003; Kirkham and Taylor, 1949; Lunt et al., 2005; McCorkle, 1931; Sheets and Hendrickx, 1995

Substantial efforts have been devoted toward evaluating the capabilities of resistivity and electromagnetic induction methods for soil salinity assessment. The standard laboratory technique for determining salinity involves measuring the electrical conductivity of water extracted from a soil sample saturated paste (Smedema et al., 2004). The soil salinity obtained by the electrical conductivity of a saturated paste extract is designated EC_e. Resistivity and electromagnetic induction methods are used in the field to measure an "apparent" electrical conductivity for a bulk volume of soil beneath the surface, and this apparent electrical conductivity is designated EC_a. By incorporating various soil moisture, soil density, and soil textural parameters, EC_e can be calculated from EC_a (Rhoades et al., 1989, 1990). Discussions regarding the impact of soil conditions and soil properties on EC_a can be found in Chapters 2, 4, and 5. With the protocols now available for calculating EC_e from EC_a, resistivity and electromagnetic induction methods are indeed valuable tools for monitoring soil salinity levels in an agricultural field.

Precision agriculture is a growing trend combining geospatial data sets, state-of-the-art farm equipment technology, GIS, and GPS receivers to support spatially variable field application of

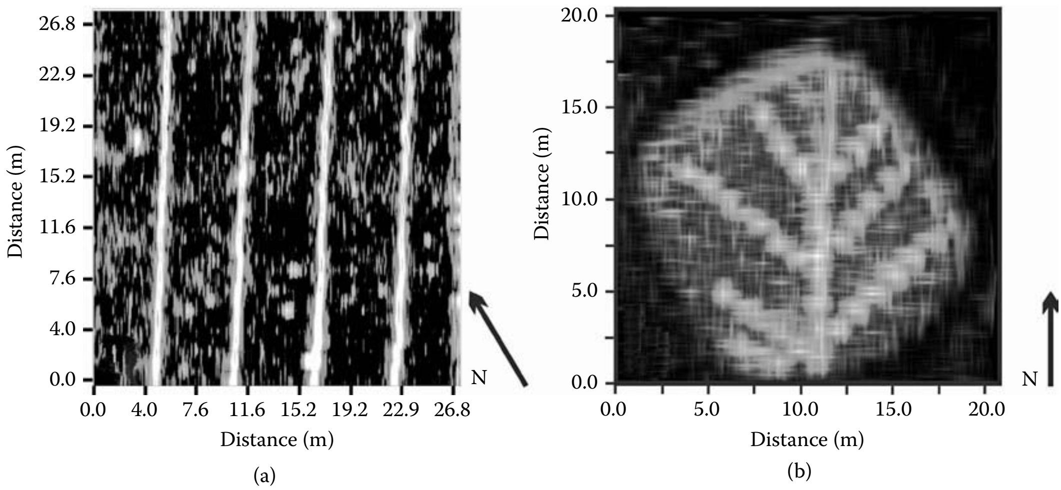

FIGURE 1.1 Ground-penetrating radar drainage pipe detection examples: (a) agricultural test plot in northwest Ohio and (b) golf course green in central Ohio.

fertilizer, soil amendments, pesticides, and even tillage effort (Morgan and Ess, 1997; National Research Council, 1997). The benefits of precision agriculture to farmers are maximized crop yields and reduced input costs. There is an important environmental benefit as well. Overapplication of agrochemicals and soil tillage is fairly common. Because precision agriculture operations result in optimal amounts of fertilizer, soil amendments, pesticides, and tillage applied on different parts of the field, there are potentially less agrochemicals and sediment released offsite via subsurface drainage and surface runoff. With reduced offsite discharge of agrochemicals and sediment, adverse environmental impacts on local waterways are diminished. In essence, precision agriculture techniques allow a farm field to be divided into different management zones for the overall purpose of optimizing economic benefits and environmental protection.

Geophysical surveys can have an important role in precision agriculture. The apparent soil electrical conductivity (EC_a) map of a farm field, obtained from resistivity or electromagnetic induction measurements, is often significantly correlated with the crop yield map for the same field. Presented in Figure 1.2 is an example comparing EC_a and soybean yield for a 3 ha field in northwest Ohio. The spatial correlation coefficient (r) between EC_a and soybean yield is −0.51 for the field shown in Figure 1.2. Over a two-year period for three different fields, Jaynes et al. (1995b) found r values between EC_a and corn/soybean yield of −0.73, −0.63, −0.55, −0.50, −0.09, and 0.45, so in five out of six cases for this study, there was substantial correlation.

Furthermore, the mapped horizontal EC_a patterns for a farm field often tend to remain consistent over time, which implies that the horizontal EC_a pattern is governed by lateral variations in soil properties (Allred et al., 2005b, 2006; Lund et al., 1999). The EC_a can be affected in a complex manner by a number of different soil properties; therefore, a limited soil sampling and analysis program is typically required to determine which soil property or properties have the greatest influence on the horizontal EC_a field pattern. Again, discussions regarding the effect of soil conditions and soil properties on soil electrical conductivity can be found in Chapters 2, 4, and 5. Soil property information based on EC_a measurement is useful for formulating management practices (strategies for fertilizer, soil amendment, and pesticide application along with tillage effort) that will improve crop yields while limiting the offsite release of agrochemicals and sediment. Consequently, because the spatial pattern for crop yield commonly exhibits a strong correlation with the horizontal EC_a pattern, which is in turn governed by lateral changes in soil properties, it becomes apparent that EC_a maps generated from resistivity and electromagnetic induction surveys can be a valuable precision agriculture tool providing insight on how to best divide a field into zones based on soil property

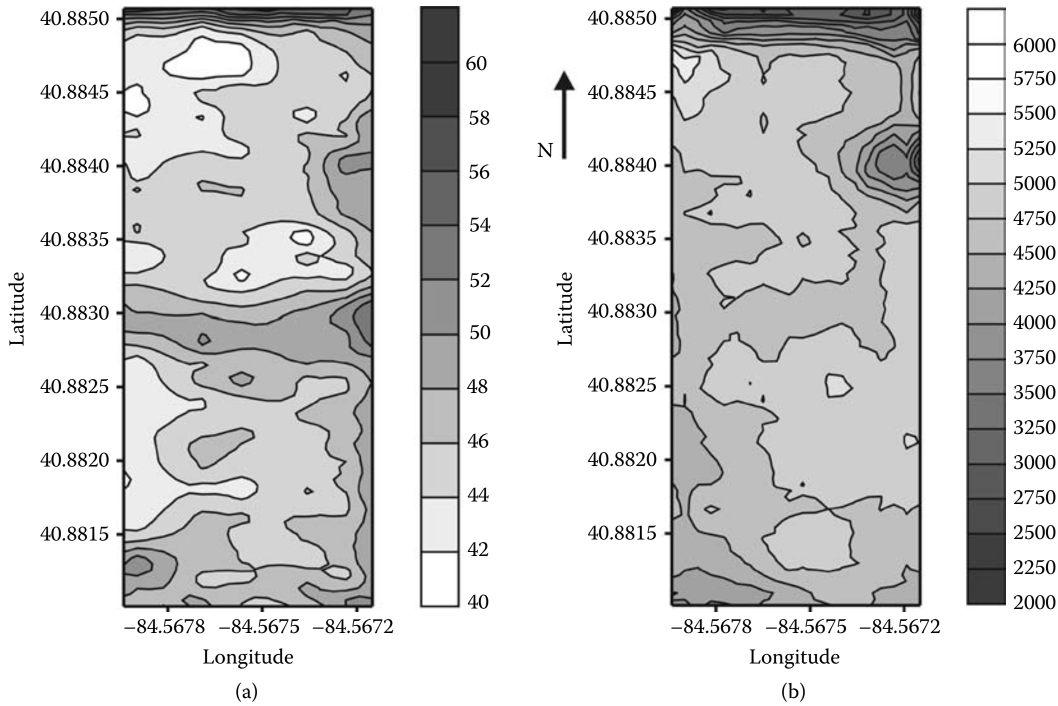

FIGURE 1.2 Soil electrical conductivity and crop yield comparison for a 3 ha field in northwest Ohio: (a) apparent soil electrical conductivity map obtained with a Veris 3100 Soil EC Mapping System (values are in millisiemens/meter) and (b) soybean yield map (values are in kilograms/hectare).

differences. These field zones can then be separately managed in an effective and efficient manner so as to maximize economic benefits while protecting the environment.

McCorkle (1931) conducted one of the first agricultural geophysics studies that focused on the use of resistivity methods to determine the soil gravimetric water content. There have been a number of research investigations since that have quantified the bulk soil volumetric water content (θ) level in soil using EC_a measured with resistivity or electromagnetic induction methods. There are, however, certain drawbacks regarding the use of resistivity and electromagnetic induction methods to determine θ. One drawback is that soil properties in which affect EC_a differ from one location to the next, and as a consequence, the EC_a versus θ relationship must be developed at each particular field site. In addition, temperature effects on EC_a values need to be taken into account before accurate θ estimates can be obtained.

GPR has recently proven to be an effective tool for rapidly measuring soil volumetric water content (θ) over large areas (Grote et al., 2003; Huisman et al., 2003; Lunt et al., 2005). The GPR methods employed for θ measurement are all based on the determination of a soil's dielectric constant, also called the relative permittivity (ε_r). The value of ε_r is strongly correlated to θ. For mapping θ, a couple of approaches are used to determine a soil's ε_r value. One approach is to calculate ε_r directly from the radar signal velocity in a soil. The soil radar signal velocity is easily computed by dividing the length of the direct or reflected signal travel path through the soil by the elapsed time taken by the signal to travel along the path from the transmitting antenna to the receiving antenna (velocity equals distance divided by time). The second approach involves positioning the transmitting and receiving antennas a short distance above the ground surface and then measuring the reflection coefficient at the ground surface. The reflection coefficient in this case equals the ratio of the radar signal amplitude reflected from the ground surface to the radar signal amplitude incident at the ground surface. With the ε_r of air known (equal to 1), the ε_r at the soil surface can be calculated from the ground surface reflection coefficient in a straightforward manner. Theoretically based site-specific calibrated equations or empirically derived relationships are used in the final step to calculate θ values from soil ε_r values. The empirical relationship most commonly used to calculate θ from ε_r for soils was developed by Topp et al. (1980) and is given by:

$$\theta = -0.053 + 0.0292\varepsilon_r - 0.00055\varepsilon_r^2 + 0.0000043\varepsilon_r^3 \quad (1.1)$$

Additional information on the application of GPR to soil volumetric water content determination can be found in three of the Chapter 12 case studies.

1.5 AGRICULTURAL GEOPHYSICS OUTLOOK

New developments in the overall discipline of geophysics are ongoing, with innovative methods, equipment, and field procedures continuing to be introduced. The same is particularly true for agricultural geophysics. Many concepts being tested and initiated at present will eventually become commonplace for agricultural geophysics. In this regard, the following is a list summarizing the probable future trends (some previously mentioned) for agricultural geophysics.

1. New agricultural applications will continue to be discovered for the geophysical methods already used in agriculture (resistivity, electromagnetic induction, and GPR).
2. Geophysical methods not traditionally employed in the past for agricultural purposes will find significant use in the future. The geophysical methods likely to make inroads into agriculture include magnetometry, self-potential, and seismic. Agricultural opportunities for other geophysical methods, such as nuclear magnetic resonance, induced polarization, and seismoelectric, may also exist.
3. The incorporation of GPS receivers will become the norm, especially with regard to real-time kinematic (RTK) GPS, which will allow geophysical measurement positions to be determined with horizontal and vertical accuracies of a few centimeters or less. Guidance devices, video display tracking systems, or even simple on-the-go guesstimates of the spacing distance between transects, when used with an accurate GPS, can provide the capability of efficiently conducting geophysical surveys over large agricultural field areas without the need to mark out a well-defined grid at the ground surface. For some geophysical methods, the computer processing procedures used for horizontal mapping of measurements may require some modification for input of data collected along a set of transects with somewhat irregular orientations and spacing distances.
4. Geophysical surveying with more than one sensor will become a standard approach because of the variety of field information required to make correct agricultural management decisions. Multisensor systems based on a single geophysical technique have already been produced, and these systems are certainly beneficial to agriculture. Examples include GPR systems having more than one transmitter and receiver antenna pair (the individual transmitter and receiver antenna pairs can have the same frequency or different frequencies), or continuously pulled resistivity electrode arrangements containing more than one four-electrode array. However, multisensor systems based on more than one geophysical technique still need to be developed for agricultural purposes, something likely to happen in the near future. For reference, the physical properties responded to by the different geophysical methods are reviewed in Table 1.2.
5. Multiple geophysical data sets integrated and analyzed together along with other geospatial information can provide agricultural insight not available when analyzing each geophysical data set separately. Geostatistical analysis techniques can be especially useful in this regard. GISs are particularly well adapted for integration and geostatistical analysis of

TABLE 1.2
Physical Properties Responded to by Geophysical Methods

Geophysical Method	Physical Property
Resistivity	Electrical resistivity (or electrical conductivity)
Electromagnetic induction	Electrical conductivity (or electrical resistivity)
Ground-penetrating radar	Dielectric constant and electrical conductivity
Magnetometry	Magnetic susceptibility and remanent magnetism
Self-potential	Electric potential gradient
Seismic	Density and elastic moduli (bulk modulus, shear modulus, etc.)

multiple geophysical and nongeophysical spatial data sets. Consequently, GIS will play a greater role in the analysis of geophysical data collected in agricultural settings. Furthermore, as the practice of precision agriculture continues to grow, there is expected to be an increasing need to input geophysical data into the GIS used to make proper management decisions in regard to different areas of a farm field.

6. Expert system computer software and learning-capable computer software incorporating neural networks will be developed for specific agricultural applications to automatically analyze and interpret geophysical data.
7. Tomographic procedures will be employed to obtain geophysical data in agricultural settings when the situation is warranted. It is usually not possible to conduct geophysical surveys in an agricultural field during the growing season, once the crop emerges and begins to develop. Tomographic data collection and analysis procedures are a potential solution to this field access problem, allowing the within field horizontal spatial pattern of a physical property to be determined without actually having to obtain geophysical measurements inside the field. Tomographic data collection and analysis procedures can also provide valuable geophysical information even for circumstances when field access is not a problem. For the geophysical field measurement tomographic approach, geophysical energy source and sensor locations are moved along the perimeter of the field. They will typically involve multiple source and sensor positionings in which the geophysical sensor locations are always on opposite or adjacent sides of the field with respect to the side of the field where the geophysical energy source is located. A map of the horizontal spatial pattern for some physical property within an agricultural field is then generated with measurement data from a sufficient number of geophysical source and sensor positionings used as input for image reconstruction computer software employing inversion techniques.
8. The application of geophysical methods to agriculture will eventually become a well-recognized subdiscipline of geophysics, at which time it may become appropriate to use the contracted term "agrigeophysics" instead of the longer term "agricultural geophysics."

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2 Past, Present, and Future Trends of Soil Electrical Conductivity Measurement Using Geophysical Methods

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2.1 INTRODUCTION

Arguably, the beginnings of geophysics can be traced to Gilbert's discovery that the world behaves like a massive magnet and Newton's theory of gravitation. Since that time, researchers in geophysics have developed a broad array of measurement tools involving magnetic, seismic, electromagnetic, resistivity, induced polarization, radioactivity, and gravity methods. Although at times a formidable technological feat, the adaptation of geophysical techniques from the measurement of geologic strata to the measurement of surface and near-surface soils for agricultural applications was the next logical step.

Geophysical techniques currently used in agricultural research include electrical resistivity (ER), time domain reflectometry (TDR), ground-penetrating radar (GPR), capacitance probes (CPs), radar scatterometry or active microwaves (AM), passive microwaves (PM), electromagnetic induction (EMI), neutron thermalization, nuclear magnetic resonance (NMR), gamma ray attenuation, and near-surface seismic reflection. Several of the geophysical techniques fall into the category of electromagnetic (EM) methods because they rely on an EM source, including TDR, GPR, CP, AM, PM, and EMI. Each varies from the other in a subtle way. For TDR, the applied electromagnetic pulse is guided along a transmission line embedded in the soil. The time delay between the reflections of the pulse from the beginning and the end of the transmission line is used to determine the velocity of propagation through soil, which is controlled by the relative dielectric permittivity or dielectric constant. Both TDR and GPR are based on the fact that electrical properties of soils are primarily determined by the water content (θ) in the frequency range from 10 to 1000 MHz (Topp et al., 1980). For GPR, however, radio frequency signals are radiated from an antenna at the soil surface into the ground, while a separate antenna receives both reflected and transmitted signals. Signals arriving at the receiving antenna come from three pathways: (1) through the air, (2) through the near surface soil, and (3) reflected from objects or layers below the soil surface. Signal velocity and attenuation are used, like TDR, to infer both θ and soil apparent electrical conductivity (EC_a), which is the electrical conductivity through the bulk soil. Capacitance probes for measuring θ are placed in the soil so that the soil acts like the dielectric of a capacitor in a capacitive-inductive resonant circuit, where the inductance is fixed. Active microwaves or radar scatterometry are similar to GPR, except that the antennae are located above the soil surface. The signal penetrates to a shallow depth, generally <100 mm below the soil surface, for the transmitted frequencies used. Analysis of the reflected signal results in a measure of θ and electrical conductivity at the near surface. Passive microwaves are unique in that no signal is applied, rather the surface soil is the EM source and a sensitive receiver located at the soil surface measures temperature and dielectric properties of the surface soil from which θ and EC_a are inferred. Finally, EMI, unlike GPR, employs lower-frequency signals and primarily measures the signal loss to determine EC_a. The common operating frequency ranges of instrumentation for these electromagnetic techniques are EMI (0.4 to 40 kHz), CP (38 to 150 MHz), GPR (1 to 2,000 MHz), TDR (50 to 5,000 MHz), AM (0.2 to 300 GHz), and PM (0.3 to 30 GHz).

Of these geophysical techniques, the agricultural application of geospatial measurements of EC_a, as measured by EMI, ER, and TDR, has had tremendous impact over the past two decades. Currently, EC_a is recognized as the most valuable geophysical measurement in agriculture for characterizing soil spatial variability at field and landscape spatial extents (Corwin, 2005, Corwin and Lesch, 2003, 2005a). It is the objective of this chapter to present a historical perspective of the adaptation of geophysical techniques for use in agriculture with a primary focus on trends in the adaptation of EC_a to agriculture, as well as the practical and theoretical factors that have forged these trends.

2.2 HISTORICAL PERSPECTIVE OF APPARENT SOIL ELECTRICAL CONDUCTIVITY (EC_a) TECHNIQUES IN AGRICULTURE—THE PAST

The adaptation of geophysical EC_a measurement techniques to agriculture was largely motivated by the need for reliable, quick, and easy measurements of soil salinity at field and landscape spatial extents. However, it became quickly apparent that EC_a was influenced not only by salinity, but also by a variety of other soil properties that influenced electrical conductivity in the bulk soil, including θ, clay content and mineralogy, organic matter, bulk density (ρ_b), and temperature. The EC_a measurement is a complex physicochemical property resulting from the interrelationship and interaction of these soil properties. Researchers subsequently realized that geospatial measurements of EC_a can potentially provide spatial distributions of any or all of these properties. This realization resulted in the evolution of EC_a in agriculture from a tool for measuring, profiling, and mapping soil salinity into a present-day tool for characterizing the spatial variability of any soil property that correlates with EC_a.

The impetus behind the evolution of EC_a in agriculture stems from several factors that make it well suited for characterizing spatial variability at field and larger spatial extents. Most importantly, measurements of EC_a are reliable, quick, and easy to take. This factor was instrumental in the initial adaptation of EC_a for agricultural use. Historically, considerable research was conducted using

EC_a measurements of soils. Consequently, there is a reasonable understanding of what is being measured, even though the measurement is complicated by the interaction of several soil properties that influence the conductive pathways through the bulk soil. Another factor is that the mobilization of EC_a measurement equipment is comparatively easy and can be accomplished at a reasonable cost. Tractor- and all-terrain vehicle (ATV)-mounted platforms have made intensive field-scale measurements commonplace (Cannon et al., 1994; Carter et al., 1993; Freeland et al., 2002; Jaynes et al., 1993; Kitchen et al., 1996; McNeill, 1992; Rhoades, 1993). Basin- and landscape-scale assessments are possible with airborne electromagnetic (AEM) systems (Cook and Kilty, 1992; George and Woodgate, 2002; George et al., 1998; Munday, 2004; Spies and Woodgate, 2004; Williams and Baker, 1982). However, AEM applications in agriculture have been primarily used to identify geological sources of salinity, because AEM penetrates well below the root zone to depths of tens of meters, whereas surface EMI for agricultural applications, such as the Geonics EM38* or DUALEM-2† electrical conductivity meters, generally penetrates to depths confined mainly to the root zone (i.e., 1.5 to 2 m). Mobilization made it possible to create maps of EC_a variation at field scales, making EC_a a practical field measurement. Finally, because EC_a is influenced by a variety of soil properties, the spatial variability of these properties can be potentially established, providing a wealth of spatial soil-related information.

2.2.1 Measurement of Soil Salinity with EC_a

The measurement of soil salinity has a long history prior to its measurement with EC_a. Soil salinity refers to the presence of major dissolved inorganic solutes in the soil aqueous phase, which consist of soluble and readily dissolvable salts including charged species (e.g., Na^+, K^+, Mg^{+2}, Ca^{+2}, Cl^-, HCO_3^-, NO_3^-, SO_4^{-2}, and CO_3^{-2}), nonionic solutes, and ions that combine to form ion pairs. The need to measure soil salinity stems from its detrimental impact on plant growth. Effects of soil salinity are manifested in loss of stand, reduced plant growth, reduced yields, and, in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential making it more difficult for the plant to extract water. Salinity may also cause specific-ion toxicity or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth.

Six methods have been developed for determining soil salinity at field scales: (1) visual crop observations, (2) the electrical conductance of soil solution extracts or extracts at higher than normal water contents, (3) in situ measurement of ER, (4) noninvasive measurement of electrical conductance with EMI, (5) in situ measurement of electrical conductance with TDR, and (6) multi- and hyperspectral imagery.

Visual crop observation is the oldest method of determining the presence of soil salinity. It is a quick method, but it has the disadvantage that salinity development is detected after crop damage has occurred. For obvious reasons, the least desirable method is visual observation because crop yields are reduced to obtain soil salinity information. However, remote imagery is increasingly becoming a part of agriculture and represents a quantitative approach to the antiquated method of visual observation that may offer a potential for early detection of the onset of salinity damage to plants. Even so, multi- and hyperspectral remote imagery are still in their infancy with an inability at the present time to differentiate osmotic from matric or other stresses, which is key to the successful application of remote imagery as a tool to map salinity and water content.

* Geonics Limited, Inc., Mississaugua, Ontario, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

† DUALEM, Inc., Milton, Ontario, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

The determination of salinity through the measurement of electrical conductance has been well established for decades (U.S. Salinity Laboratory Staff, 1954). It is known that the electrical conductivity of water is a function of its chemical composition. McNeal et al. (1970) were among the first to establish the relationship between electrical conductivity and molar concentrations of ions in the soil solution. Soil salinity is quantified in terms of the total concentration of the soluble salts as measured by the electrical conductivity (EC) of the solution in dS m^{-1}. To determine EC, the soil solution is placed between two electrodes of constant geometry and distance of separation (Bohn et al., 1979). At constant potential, the current is inversely proportional to the solution's resistance. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. The electrical conductance is a reciprocal of the resistance as shown in Equation (2.1):

$$\mathrm{EC}_T = k/\mathrm{R}_T \tag{2.1}$$

where EC_T is the electrical conductivity of the solution in dS m^{-1} at temperature T (°C), k is the cell constant, and R_T is the measured resistance at temperature T.

Electrolytic conductivity increases at a rate of approximately 1.9 percent per degree centigrade increase in temperature. Customarily, EC is expressed at a reference temperature of 25°C for purposes of comparison. The EC measured at a particular temperature T (°C), EC_T, can be adjusted to a reference EC at 25°C, EC_{25}, using the below equations from Handbook 60 (U.S. Salinity Laboratory staff, 1954):

$$\mathrm{EC}_{25} = f_T \bullet \mathrm{EC}_T \tag{2.2}$$

where f_T is a temperature conversion factor. Approximations for the temperature conversion factor are available in polynomial form (Rhoades et al., 1999a; Stogryn, 1971; Wraith and Or, 1999) or other equations can be used such as Equation (2.3) by Sheets and Hendrickx (1995):

$$f_T = 0.4470 + 1.4034e^{-T/26.815} \tag{2.3}$$

Customarily, soil salinity is defined in terms of laboratory measurements of the EC of the saturation extract (EC_e) because it is impractical for routine purposes to extract soil water from samples at typical field water contents. Partitioning of solutes over the three soil phases (i.e., gas, liquid, solid) is influenced by the soil:water ratio at which the extract is made, so the ratio must be standardized to obtain results that can be applied and interpreted universally. Commonly used extract ratios other than a saturated soil paste are 1:1, 1:2, and 1:5 soil:water mixtures.

Soil salinity can also be determined from the measurement of the EC of a soil solution (EC_w). Theoretically, EC_w is the best index of soil salinity because this is the salinity actually experienced by the plant root. Nevertheless, EC_w has not been widely used to express soil salinity for two reasons: (1) it varies over the irrigation cycle as θ changes, and (2) methods for obtaining soil solution samples are too labor and cost intensive at typical field water contents to be practical for field-scale applications (Rhoades et al., 1999a). For disturbed samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum- or pressure-extraction methods. For undisturbed samples, EC_w can be determined either in the laboratory on a soil solution sample collected with a soil-solution extractor or directly in the field using in situ, imbibing-type porous-matrix salinity sensors. Briggs and McCall (1904) devised the first extractor system. Kohnke et al. (1940) provide a review of early extractor construction and performance.

The ability of soil solution extractors and porous-matrix salinity sensors (also known as soil salinity sensors) to provide representative soil water samples is doubtful (England, 1974; Raulund- Rasmussen, 1989; Smith et al., 1990). Because of their small sphere of measurement, neither extractors nor salt sensors adequately integrate spatial variability (Amoozegar-Fard et al., 1982; Haines et al., 1982; Hart and Lowery, 1997); consequently, Biggar and Nielsen (1976) suggested that soil solution samples are qualitative point-sample measurements of soil solutions that are not representative quantitative measurements because of the effect of local-scale variability on small sample volumes. Furthermore, salinity sensors demonstrate a lag in response time that is dependent upon the diffusion of ions between the soil solution and solution in the porous ceramic, which is affected by (1) the thickness of the ceramic conductivity cell, (2) the diffusion coefficients in soil and ceramic, and (3) the fraction of the ceramic surface in contact with soil (Wesseling and Oster, 1973). The salinity sensor is generally considered the least desirable method for measuring EC_w because of its low sample volume, unstable calibration over time, and slow response time (Corwin, 2002).

Developments in the measurement of soil EC to determine soil salinity shifted away from extractions to the measurement of EC_a because the time and cost of obtaining soil solution extracts prohibited their practical use at field scales, and the high local-scale variability of soil rendered salinity sensors and small volume soil core samples of limited quantitative value. Rhoades and colleagues at the U.S. Salinity Laboratory led the shift in the early 1970s to the use of EC_a as a measure of soil salinity (Rhoades and Ingvalson, 1971). The use of EC_a to measure salinity has the advantage of increased volume of measurement and quickness of measurement, but suffers from the complexity of measuring EC for the bulk soil rather than restricted to the solution phase. Furthermore, EC_a measurement techniques, such as ER and EMI, are easily mobilized and are well suited for field-scale applications because of the ease and low cost of measurement with a volume of measurement that is sufficiently large (>1 m^3) to reduce the influence of local-scale variability. Developments in agricultural applications of ER and EMI have occurred along parallel paths with each filling a needed niche based upon inherent strengths and limitations.

2.2.1.1 Electrical Resistivity

Electrical resistivity was developed in the second decade of the 1900s by Conrad Schlumberger in France and Frank Wenner in the United States for the evaluation of ground ER (Telford et al., 1990; Burger, 1992). The earliest application of ER in agriculture was to measure θ (Edlefsen and Anderson, 1941; Kirkham and Taylor, 1950). This adaptation was later eclipsed by the use of ER to measure soil salinity (Rhoades and Ingvalson, 1971). Electrical resistivity has been most widely used in agriculture as a means of measuring soil salinity. A review of this early body of salinity research can be found in Rhoades et al. (1999). Arguably, the early salinity research with ER provided the initial momentum to the subdiscipline of agricultural geophysics.

Electrical resistivity methods involve the measurement of the resistance to current flow across four electrodes inserted in a line on the soil surface at a specified distance between the electrodes (Figure 2.1). The resistance to current flow is measured between a pair of inner electrodes while electrical current is caused to flow through the soil between a pair of outer electrodes. Although two electrodes (i.e., a single current electrode and a single potential electrode) can also be used, this configuration is highly unstable, and the introduction of four electrodes helped to stabilize the resistance measurement. According to Ohm's Law, the measured resistance is directly proportional to the voltage (V) and inversely proportional to the electrical current (i):

$$R = \frac{V}{i} \tag{2.4}$$

where resistance (R) is defined as one ohm (ω) of resistance that allows a current of one ampere to flow when one volt of electromotive force is applied. The resistance of a given volume of soil depends on its length (l, m), its cross-sectional area (a, m^2), and a fundamental soil property called resistivity (ρ, ω m^{-1}):