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

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CONTENTS

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.

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* 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, $\omega\ m^{-1}$):

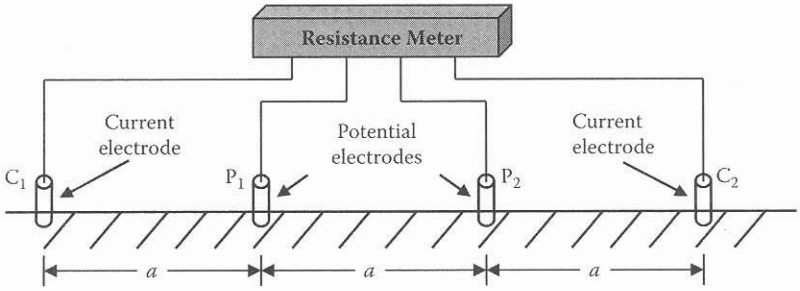

FIGURE 2.1 Wenner array electrodes: C_1 and C_2 represent the current electrodes, P_1 and P_2 represent the potential electrodes, and a represents the interelectrode spacing. (From Rhoades, J.D., and Halvorson, A.D., Electrical conductivity methods for detecting and delineating saline seeps and measuring salinity in Northern Great Plains soils, ARS W-42, USDA-ARS Western Region, Berkeley, CA, pp. 1–45, 1977. With permission.)

$$R = \rho\left(\frac{l}{a}\right) \tag{2.5}$$

The conductance (C, ω^{-1} or Siemens, S) is the inverse of resistance, and the EC_a (dS m^{-1}) is the inverse of the resistivity:

$$EC_a = \frac{1}{\rho} = \frac{1}{R}\left(\frac{l}{a}\right) = C\left(\frac{l}{a}\right) \tag{2.6}$$

When the four electrodes are equidistantly spaced in a straight line at the soil surface, the electrode configuration is referred to as the Wenner array (Figure 2.1). The resistivity measured with the Wenner array is shown in Equation (2.7):

$$\rho = \frac{2\pi a \Delta V}{i} = 2\pi a R \tag{2.7}$$

and the measured EC_a is as shown in Equation (2.8):

$$EC_a = \frac{1}{2\pi a R} \tag{2.8}$$

where a is the interelectrode spacing (m). The equations for other electrode configurations can be found in Dobrin (1960), Telford et al. (1990), and Burger (1992).

The volume of measurement of the Wenner array is relatively large and includes all the soil between the inner pair of electrodes from the soil surface to a depth equal to roughly the interelectrode spacing. Figure 2.2 illustrates the volume of measurement. For a homogeneous soil, the volume of measurement is approximately πa^3. The depth of penetration of the electrical current and the volume of measurement increase as the interelectrode spacing, a, increases.

Apparent soil electrical conductivity for a discrete depth interval of soil, EC_x, can be obtained with the Wenner array by measuring the EC_a of successive layers by increasing the interelectrode spacings (a_{i-1} and a_i) and using Equation (2.9) for parallel resistors (Barnes, 1952):

$$EC_x = EC_{a_i} - EC_{a_{i-1}} = \frac{\left(EC_{a_i} a_i - EC_{a_{i-1}} a_{i-1}\right)}{a_i - a_{i-1}} \tag{2.9}$$

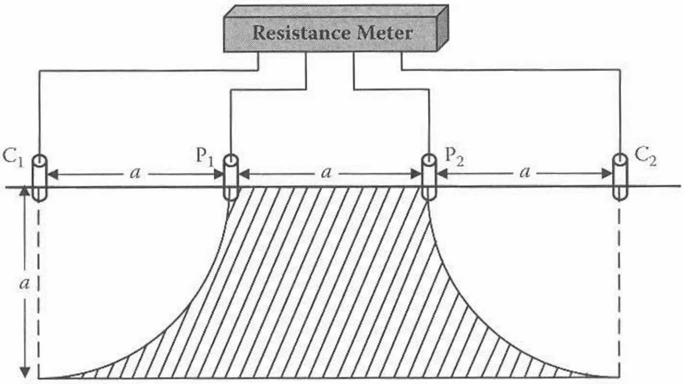

FIGURE 2.2 The volume of measurement for a Wenner-array electrode configuration. The shaded area represents measurement volume. C_1 and C_2 represent the current electrodes, P_1 and P_2 represent the potential electrodes, and a represents the interelectrode spacing. (From Rhoades, J.D., and Halvorson, A.D., Electrical conductivity methods for detecting and delineating saline seeps and measuring salinity in Northern Great Plains soils, ARS W-42, USDA-ARS Western Region, Berkeley, CA, pp. 1–45, 1977. With permission.)

where a_i is the interelectrode spacing, which equals the depth of sampling; a_{i-1} is the previous interelectrode spacing, which equals the depth of previous sampling; and EC_x is the conductivity for a specific depth interval. This is often referred to as vertical profiling.

Electrical resistivity is an invasive technique that requires good contact between the soil and electrodes inserted into the soil; consequently, it produces less reliable measurements in frozen, dry, or stony soils than noninvasive EMI measurement. Furthermore, depending upon the manner in which the ER electrodes are mounted onto the mobile fixed-array platform, microtopography, such as a bed-furrow surface, may cause contact problems between the electrodes and soil. Even so, ER is widely used in agriculture and has been adapted for commercial field-scale applications primarily because the ease of calibration is appealing and the linear relationship of EC_a with depth, which makes the application of Equation (2.9) possible, is simple and readily understood.

2.2.1.2 Electromagnetic Induction

In the late 1970s and early 1980s, de Jong et al. (1979), Rhoades and Corwin (1981), and Williams and Baker (1982) began investigating the use of EMI to measure soil salinity. de Jong et al. (1979) published the first use of EMI for measuring soil salinity. The early studies with EMI by Rhoades and Corwin were efforts to profile soil salinity through the root zone (Corwin and Rhoades, 1982; Rhoades and Corwin, 1981). Unlike ER, vertical profiling with EMI is not a trivial task, because a relatively simple linear model can be used for low conductivity media, but for higher conductivity values, a nonlinear model is required. Williams and Baker (1982) sought to use EMI as a means of surveying soil salinity at landscape scales and larger with the first use of AEM to map geologic sources of salinity having agricultural impacts.

Through the 1980s and early 1990s, the focus of EMI work in agriculture was on vertical profiling (Cook and Walker, 1992; Corwin and Rhoades, 1982, 1990; Rhoades and Corwin, 1981; Rhoades et al., 1989; Slavich, 1990; Wollenhaupt et al., 1986). Vertical profiling of soil salinity with EMI involves raising the EMI conductivity meter to various heights at or above the soil surface (i.e., 0, 30, 60, 90, 120, and 150 cm) to measure the EC_a corresponding to incremental depths below the soil surface (i.e., 0 to 150, 0 to 120, 0 to 90, 0 to 60, and 0 to 30, respectively). Site-specific empirical relationships were developed, which were not widely used because they could not be extrapolated to other sites without calibration. It was not until the work of Borchers and colleagues (1997) that inverse procedures for the linear and nonlinear models (Hendrickx et al., 2002) were developed to profile soil salinity with above-ground EMI measurements. Vertical profiling of EC_a

with EMI is mathematically complex and a difficult quantitative undertaking (Borchers et al., 1997; Hendrickx et al., 2002; McBratney et al., 2000). As a result, qualitative evaluations of EC_a at shallow and deep depths with EMI are generally used by positioning the EMI instrument at the soil surface in the vertical (EM_v) and then the horizontal (EM_h) dipole mode (i.e., receiver and transmitter coils are oriented perpendicular or parallel with the soil surface, respectively), which measures to depths of 0.75 and 1.5 m, respectively. This provides measurements of EC_a at shallow and deeper depths, which enables the qualitative determination of whether an EC_a profile is uniform with depth ($EM_h \approx EM_v$), inverted ($EM_h > EM_v$), or normal ($EM_h < EM_v$).

The depth-weighted nonlinear response of EMI is shown in Equation (2.10) and Equation (2.11) from McNeill (1980) for the vertical and horizontal dipoles, respectively:

$$R_v(z) = \frac{1}{(4z^2+1)^{1/2}} \tag{2.10}$$

$$R_h(z) = (4z^2+1)^{1/2} - 2z \tag{2.11}$$

where $R_v(z)$ and $R_h(z)$ are the cumulative relative contributions of all soil electrical conductivity with the vertical and horizontal EMI dipoles, respectively, for a homogeneously conductive media below a depth of z (m).

At low conductivity values (EC_a < 100 mS m^{-1}), McNeill (1980) showed that the measured EC_a when the EMI instrument is located at the soil surface is given by Equation (2.12):

$$EC_a = \left[\frac{4}{2\pi\mu_0 f s^2}\right]\left(\frac{H_s}{H_p}\right) \tag{2.12}$$

where EC_a is measured in S m^{-1}; H_p and H_s are the intensities of the primary and secondary magnetic fields at the receiver coil (A m^{-1}), respectively; f is the frequency of the current (Hz); μ_0 is the magnetic permeability of air ($4\pi 10^{-7}$ H m^{-1}); and s is the intercoil spacing (m).

The calibration of EMI equipment (e.g., Geonics EM38[1]), which can be difficult and time consuming, is another dissimilarity with ER. However, the DUALEM-2 does not appear to suffer from the same calibration difficulties as the EM38 due to the increased distance between the transmitter and receiver coils. Complexity of the EMI measurement and difficulties in calibration are distinct disadvantages of the EMI approach that have reduced its use in agriculture. These limitations are the most likely reasons that there are no commercially available EMI mobile platforms. This has caused the use of EMI in agriculture, even today, to be principally as a research tool.

Following the early vertical profiling efforts, research with EMI, and concomitantly with ER, drifted away from salinity and concentrated more on observed associations between ER and EMI measurements of EC_a and other soil properties. This research trend significantly contributed to the base of knowledge compiled in Table 2.1.

2.2.2 Measurement of Water Content with EC_a

Several geophysical techniques have been adapted for agriculture to measure θ within the root zone including TDR, GPR, CP, AM, PM, EMI, neutron thermalization, NMR, gamma ray attenuation, and ER. Aside from ER and EMI, neutron thermalization, CP, TDR, and GPR have received the greatest use for laboratory and field-scale agricultural applications. The history of the agricultural application of CP and neutron thermalization predates all other geophysical-based approaches for measuring θ except ER. Gamma ray attenuation has been in use in agriculture since the 1950s, but it

TABLE 2.1
Compilation of Literature Measuring EC_a with Geophysical Techniques (ER or EMI) Categorized According to the Soil-Related Properties Directly or Indirectly Measured by EC_a

Soil Property	References
Directly Measured Soil Properties	
Salinity (and nutrients, e.g., NO_3^-)	Bennett and George (1995); Cameron et al. (1981); Cannon et al. (1994); Corwin and Rhoades (1982, 1984, 1990); de Jong et al. (1979); Diaz and Herrero (1992); Drommerhausen et al. (1995); Eigenberg and Nienaber (1998, 1999, 2001); Eigenberg et al. (1998, 2002); Greenhouse and Slaine (1983); Halvorson and Rhoades (1976); Hanson and Kaita (1997); Hendrickx et al. (1992); Herrero et al. (2003); Johnston et al. (1997); Kaffka et al. (2005); Lesch et al. (1992, 1995a, 1995b,1998); Mankin and Karthikeyan (2002); Mankin et al. (1997); Nettleton et al. (1994); Paine (2003); Ranjan et al. (1995); Rhoades (1992, 1993); Rhoades and Corwin (1981, 1990); Rhoades and Halvorson (1977); Rhoades et al. (1976, 1989, 1990, 1999a, 1999b); Slavich and Petterson (1990); van der Lelij (1983); Williams and Baker (1982); Williams and Hoey (1987); Wollenhaupt et al. (1986)
Water content	Brevik and Fenton (2002); Farahani et al. (2005); Fitterman and Stewart (1986); Freeland et al. (2001); Hanson and Kaita (1997); Kachanoski et al. (1988, 1990); Kaffka et al. (2005); Kean et al. (1987); Khakural et al. (1998); Morgan et al. (2000); Sheets and Hendrickx (1995); Vaughan et al. (1995); Wilson et al. (2002)
Texture related (e.g., sand, clay, depth to claypans or sand layers)	Anderson-Cook et al. (2002); Banton et al. (1997); Boettinger et al. (1997); Brevik and Fenton (2002); Brus et al. (1992); Doolittle et al. (1994, 2002); Inman et al. (2001); Jaynes et al. (1993); Kitchen et al. (1996); Rhoades et al. (1999a); Scanlon et al. (1999); Stroh et al. (1993); Sudduth and Kitchen (1993); Triantafilis et al. (2001); Williams and Hoey (1987)
Bulk density related (e.g., compaction)	Gorucu et al. (2001); Rhoades et al. (1999a)
Indirectly Measured Soil Properties	
Organic matter related (including soil, organic carbon, and organic chemical plumes)	Benson et al. (1997); Bowling et al. (1997); Brune and Doolittle (1990); Brune et al. (1999); Farahani et al. (2005); Greenhouse and Slaine (1983, 1986); Jaynes (1996); Nobes et al. (2000); Nyquist and Blair (1991)
Cation exchange capacity	Farahani et al. (2005); McBride et al. (1990); Triantafilis et al. (2002)
Leaching	Corwin et al. (1999); Rhoades et al. (1999a); Slavich and Yang (1990)
Groundwater recharge	Cook and Kilty (1992), Cook et al. (1992); Salama et al. (1994)
Herbicide partition coefficients	Jaynes et al. (1995a)
Soil map unit boundaries	Fenton and Lauterbach (1999); Stroh et al. (2001)
Corn rootworm distributions	Ellsbury et al. (1999)
Soil drainage classes	Kravchenko et al. (2002)

Source: From Corwin, D.L., and Lesch, S.M., *Comput. Electron. Agric.*, 46, 11–43, 2005a. With permission.

relies on disturbed soil samples rather than an in situ measurement or noninvasive surface measurement like the other geophysical techniques. The remaining techniques for measuring θ (i.e., TDR, GPR, AM, PM, EMI, NMR, and near seismic reflection) are geophysical adaptations to agriculture that have principally developed since the 1980s and 1990s.

Unlike the electromagnetic approaches (e.g., CP, ER, TDR, and GPR), neutron thermalization relies on a radioactive source of high-energy, epithermal neutrons that collide with H nuclei in soil as a means of inferring volumetric water content. Because the H nucleus is similar in mass to a neutron, H atoms will thermalize the neutrons upon collision. The thermalized neutrons returning to a detector give a measure of the saturation of H atoms in the soil, which is related to volumetric water content as most H atoms in common soils are associated with water. Neutron thermalization first appeared in agriculture in the early 1950s.

Even though capacitance was introduced in the 1930s as a means of measuring θ (Smith-Rose, 1933), its greatest development occurred in the 1990s as a result of advances in microelectronics. Numerous papers and reviews are available in the literature that detail historical developments in capacitance probes (Chernyak, 1964; Dean et al., 1987; Gardner et al., 1991, 1998; Kuràz et al., 1970; Paltineanu and Starr, 1997; Robinson et al., 1998; Schmugge et al., 1980; Thomas, 1966; Wobschall, 1978).

Ground penetrating radar is an area of geophysical instrumentation where electromagnetic signals that propagate as waves are used to map subsurface structure. It has great potential for rapid, noninvasive soil water content measurements over large areas (Basson et al., 1993; Chanzy et al., 1996; van Overmeeren et al., 1997). Agricultural applications in GPR began in the early 1990s and are still in their infancy. Nevertheless, GPR technology has rapidly advanced due to (1) tremendous reduction in the cost of GPR instrumentation over the past decade, (2) advances in instrumentation, and (3) advances in data processing that make it practical and reliable for non-GPR experts to operate and use the instrumentation (Annan and Davis, 1997; Annan et al., 1997).

The underlying principles of GPR and TDR are identical (Davis and Annan, 2002; Weiler et al., 1998). As pointed out by Davis and Annan (2002), TDR is effectively a two-dimensional radar system where radio frequency signals are guided along a transmission line formed from metal conductors embedded in the soil, while GPR radiates the signals from a transmitting antenna through soil to the receiver antenna, which makes it better for rapid bulk measurements over large areas because the signal path is less constrained. Both methods measure the travel time and amplitude of electromagnetic wave fields to determine θ.

Spatial θ information is of particular value in light of the fact that distributions of soil moisture are often the single most important factor influencing within-field variation in crop yield, particularly in irrigated agriculture (Corwin et al., 2003a). Reliable noninvasive techniques that can be mobilized, such as GPR and EMI, where θ within the root zone can be quickly measured, offer a tremendous source of spatial data at field extents and larger, regardless of the dryness or condition of the field (e.g., frozen, rocky). In contrast, invasive techniques, such as ER and TDR, need good contact between the sensor and the soil. Nevertheless, invasive techniques such as TDR still have their place in agriculture outside the controlled conditions of the laboratory.

2.2.2.1 Time Domain Reflectometry

Time domain reflectometry was initially adapted in the early 1980s by Topp and colleagues as a point source technique for measuring θ in the laboratory and for obtaining field θ profiles (Topp and Davis, 1981; Topp et al., 1980, 1982a, 1982b). Over the past 25 years, TDR has become a standard method for measuring θ, which is second only to thermogravimetric methods. Great strides have been taken in the past decade to mobilize TDR and improve its use at field extents (Wraith et al., 2005).

Dalton et al. (1984) demonstrated the utility of TDR to also measure EC_a, based on the attenuation of the applied signal voltage as it traverses through soil. The ability to measure both θ and EC_a makes TDR a versatile geophysical technique in agriculture. The monitoring of the dynamics and spatial patterns of θ and EC_a with TDR was bolstered with the advent of automating and multiplexing capability (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Herkelrath et al., 1991). Noborio (2001) provides a review of TDR with a thorough discussion of the theory for the measurement of θ and EC_a; probe configuration, construction, and installation; and strengths and limitations. Wraith (2002) provides an excellent overview of the principles, equipment, procedures, range and precision of measurement, and calibration of TDR. More recently, Wraith et al. (2005) provided an excellent review of TDR with emphasis given to the spatial characterization of θ and EC_a with TDR.

The TDR technique is based on the time for a voltage pulse to travel down a soil probe and back, which is a function of the dielectric constant (ε) of the porous media being measured. By measuring ε, θ can be determined through calibration (Dalton, 1992). The ε is calculated with Equation (2.13) from Topp et al. (1980):

$$\varepsilon = \left(\frac{ct}{2l_p}\right)^2 = \left(\frac{l_a}{l_p v_p}\right)^2 \tag{2.13}$$

where c is the propagation velocity of an electromagnetic wave in free space (2.997×10^8 m s^{-1}), t is the travel time (s), l_p is the real length of the soil probe (m), l_a is the apparent length (m) as measured by a cable tester, and v_p is the relative velocity setting of the instrument. The relationship between θ and ε is approximately linear and is influenced by soil type, ρ_b, clay content, and OM (Jacobsen and Schjønning, 1993).

By measuring the resistive load impedance across the probe (Z_L), EC_a can be calculated with Equation (2.14) from Giese and Tiemann (1975):

$$EC_a = \frac{\varepsilon_0 c}{l} \frac{Z_0}{Z_L} \tag{2.14}$$

where ε_0 is the permittivity of free space (8.854×10^{-12} F m^{-1}), Z_0 is the probe impedance (Ω), and $Z_L = Z_u\,[2V_0/V_f - 1]^{-1}$, where Z_u is the characteristic impedance of the cable tester, V_0 is the voltage of the pulse generator or zero-reference voltage, and V_f is the final reflected voltage at a very long time. To reference EC_a to 25°C, Equation (2.15) is used:

$$EC_a = K_c f_t Z_L^{-1} \tag{2.15}$$

where K_c is the TDR probe cell constant (K_c [m^{-1}] = $\varepsilon_0 c Z_0/l$), which is determined empirically.

The advantages of TDR for measuring EC_a include (1) a relatively noninvasive nature, (2) an ability to measure both θ and EC_a, (3) an ability to detect small changes in EC_a under representative soil conditions, (4) the capability of obtaining continuous unattended measurements, and (5) a lack of a calibration requirement for θ measurements in many cases (Wraith, 2002). However, because TDR is a stationary instrument with which measurements are taken from point-to-point, thereby preventing it from mapping at the spatial resolution of ER and EM approaches, it is currently impractical for developing detailed geo-referenced EC_a maps for large areas.

Although TDR has been demonstrated to compare closely with other accepted methods of EC_a measurement (Heimovaara et al., 1995; Mallants et al., 1996; Reece, 1998; Spaans and Baker, 1993), it is still not sufficiently simple, robust, and fast enough for the general needs of field-scale soil salinity assessment (Rhoades et al., 1999a, 1999b). Currently, the use of TDR for field-scale spatial characterization of θ and EC_a distributions is largely limited. Even though TDR has been adapted to fit on mobile platforms such as ATVs, tractors, and spray rigs (Inoue et al., 2001; Long et al., 2002; Western et al., 1998), vehicle-based TDR monitoring is in its infancy, and only ER and EMI have been widely adapted for detailed spatial surveys consisting of intensive geo-referenced measurements of EC_a at field extents and larger (Rhoades et al., 1999a, 1999b).

2.2.3 From Observed Associations to EC_a-Directed Soil Sampling

Much of the early observational work with EC_a correlated EC_a to soil properties measured from soil samples taken on a grid, which required considerable time and effort. This early work noted the spatial correlation between EC_a and soil properties and subsequently between EC_a and crop yield. However, some of these observational studies were not solidly based on an understanding of the principles and theories encompassing EC_a measurements, which led to presentations and even publications with misinterpretations. To ground researchers in the basic theories and principles of EC_a, guidelines for EC_a surveys and their interpretation were developed by Corwin and Lesch (2003).

After the research associating EC_a to soil properties and to crop yield, the direction of research gradually shifted to mapping within-field variation of EC_a as a means of directing soil sampling to characterize the spatial distribution and variability of properties that statistically correlate with EC_a. The early observational studies compiled in Table 2.1 served as a precursor to the mapping of edaphic (e.g., salinity, clay content, organic matter, etc.) and anthropogenic (e.g., leaching fraction, compaction, etc.) properties using EC_a-directed soil sampling.

Soil sampling directed by geospatial EC_a measurements is the current trend and direction for characterizing spatial variability. The use of EC_a-directed sampling has significantly reduced intensive grid sampling from tens of samples or even a hundred or more samples to eight to twelve sample locations for the characterization of spatial variability in a given field. The earliest work in the soil science literature for the application of geospatial EC_a measurements to direct soil sampling for the purpose of characterizing the spatial variability of a soil property (i.e., salinity) was by Lesch et al. (1992).

2.3 CURRENT STATE-OF-THE-SCIENCE OF EC_a APPLICATIONS IN AGRICULTURE—THE PRESENT

The current status of geophysical techniques in agriculture is reflected in ongoing research of the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) laboratories at Ames, IA; Columbia, MO (Kitchen, Lund, and Sudduth); Columbus, OH (Allred); Fort Collins, CO (Buchleiter and Farahani); and Riverside; CA (Corwin and Lesch). Researchers at these facilities have been instrumental in organizing and contributing to symposia and special issues of journals that demonstrate the current role of geophysical techniques, particularly the measurement of EC_a, in agriculture: Soil Electrical Conductivity in Precision Agriculture Symposium at the 2000 American Society of Agronomy-Crop Science Society of America-Soil Science Society of America Annual Meetings, Applications of Geophysical Methods in Agriculture Symposium at the 2003 Annual American Society of Agricultural Engineers International Meeting, special symposium issue of *Agronomy Journal* (2003, vol. 95, number 3) on Soil Electrical Conductivity in Precision Agriculture, and special issue of *Computers and Electronics in Agriculture* (Corwin and Plant, 2005) on Applications of Apparent Soil Electrical Conductivity in Precision Agriculture. The most up-to-date review of EC_a measurements in agriculture is provided by Corwin and Lesch (2005a).

2.3.1 Factors Driving EC_a-Directed Soil Sampling

Three essential factors have driven the development of EC_a-directed soil sampling as a tool to characterize the spatial variability of soil properties: (1) the mobilization of EC_a measurement equipment, (2) the commercialization and widespread availability of a Global Positioning System (GPS), and (3) the development or adaptation of a statistical sampling approach to select sample sites from spatial EC_a data. All of these came to fruition in the 1990s.

The development of mobile EC_a measurement equipment coupled to a GPS (Cannon et al., 1994; Carter et al., 1993; Freeland et al., 2002; Jaynes et al., 1993; Kitchen et al., 1996; McNeill, 1992; Rhoades, 1993) has made it possible to produce EC_a maps with measurements taken every few meters. Mobile EC_a measurement equipment has been developed for both ER and EMI geophysical approaches. In the case of ER, by mounting the electrodes to "fix" their spacing, considerable time for a measurement is saved. Veris Technologies* developed a commercial mobile system for

* Veris Technologies, Salinas, KS. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

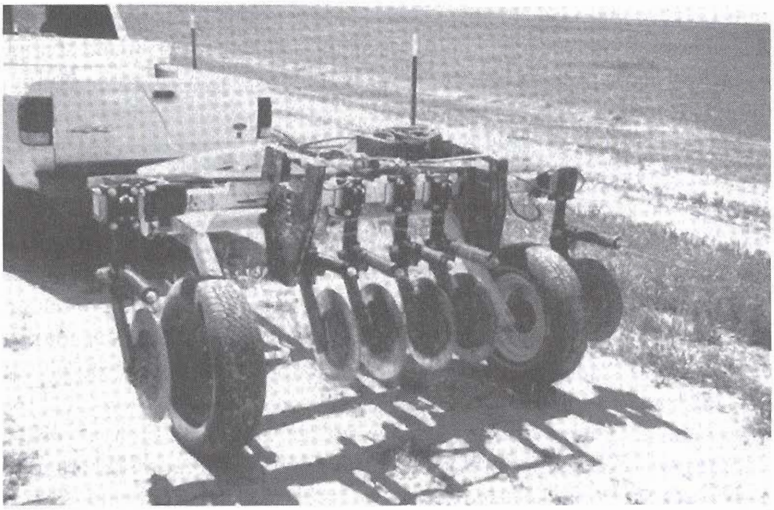

FIGURE 2.3 Veris 3100 mobile electrical resistivity equipment. (From Corwin, D.L., and Lesch, S.M., *Comput. Electron. Agric.*, 46, 11–43, 2005a. With permission.

measuring EC_a using the principles of ER (Figure 2.3). In the case of EMI, the EMI conductivity meter is carried on a sled or nonmetallic cart pulled by a pickup, ATV, or four-wheel-drive spray rig (Cannon et al., 1994; Carter et al., 1993; Corwin and Lesch, 2005a; Freeland et al., 2002; Jaynes et al., 1993; Kitchen et al., 1996; Rhoades, 1992, 1993). Both mobile ER and EMI platforms permit the logging of continuous EC_a measurements with associated GPS locations at time intervals of just a few seconds between readings, which results in readings every few meters. The mobile EMI platform permits simultaneous EC_a measurements in both the horizontal (EM_h) and vertical (EM_v) dipole configurations, and the mobile ER platform (i.e., Veris 3100) permits simultaneous measurements of EC_a at 0 to 30 and 0 to 90 cm depths. No commercial mobile system has been developed for EMI, but several fabricated mobile EMI rigs have been developed (e.g., see Figure 2.4).

To establish where soil sample sites are to be located based on the spatial EC_a data, the third essential component of EC_a-directed sampling is needed (i.e., statistical sample design). Currently, two EC_a-directed soil sampling designs are used: (1) design-based sampling and (2) model-based

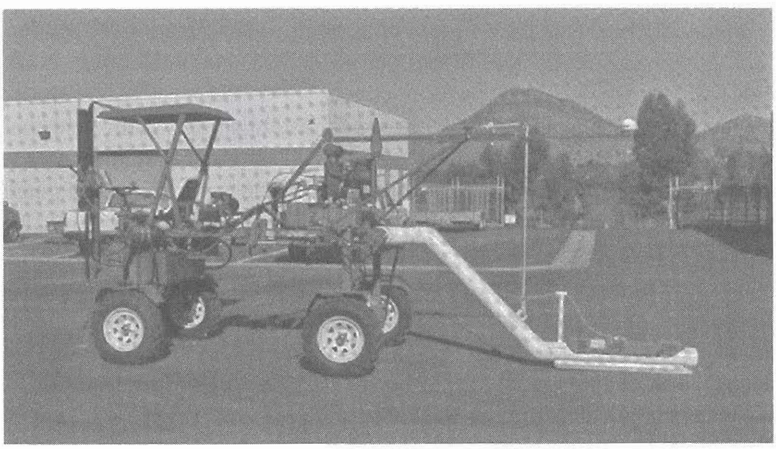

FIGURE 2.4 Mobile dual-dipole electromagnetic induction equipment developed at the United States Salinity Laboratory. (From Corwin, D.L., and Lesch, S.M., *Comput. Electron. Agric.*, 46, 11–43, 2005a. With permission.)

sampling. Design-based sampling primarily consists of the use of unsupervised classification (Johnson et al., 2001), whereas model-based sampling typically relies on optimized spatial response surface sampling (SRSS) design (Corwin and Lesch, 2005b). Design-based sampling also includes simple random and stratified random sampling. Lesch and colleagues (Lesch, 2005; Lesch et al., 1995a, 1995b, 2000) developed a model-based SRSS software package (ESAP) that is specifically designed for use with ground-based soil EC_a data. The ESAP software package identifies the optimal locations for soil sample sites from the EC_a survey data. These sites are selected based on spatial statistics to reflect the observed spatial variability in EC_a survey measurements. Generally, eight to twelve sites are selected depending on the level of variability of the EC_a measurements for a site. The optimal locations of a minimal subset of EC_a survey sites are identified to obtain soil samples. Protocols are currently available to maintain reliability, consistency, accuracy, and compatibility of EC_a surveys and their interpretation for characterizing spatial variability of soil physical and chemical properties (Corwin and Lesch, 2005b).

There are two main advantages to the response-surface approach. First, a substantial reduction in the number of samples required for effectively estimating a calibration function can be achieved in comparison to more traditional design-based sampling schemes. Second, this approach lends itself naturally to the analysis of remotely sensed EC_a data. Many types of ground-, airborne-, and satellite-based remotely sensed data are often collected specifically because one expects this data to correlate strongly with some parameter of interest (e.g., crop stress, soil type, soil salinity, etc.), but the exact parameter estimates (associated with the calibration model) may still need to be determined via some type of site-specific sampling design. The response-surface approach explicitly optimizes this site-selection process.

2.3.2 Characterization of Soil Spatial Variability with EC_a

The shift in the emphasis of field-related EC_a research from observed associations to directed-sampling design has gained momentum, resulting in the accepted use of geospatial measurements of EC_a as a reliable directed-sampling tool for characterizing spatial variability at field and landscape extents (Corwin and Lesch, 2003, 2005a, 2005b). At present, no other measurement provides a greater level of spatial soil information than that of geospatial measurements of EC_a when used to direct soil sampling to characterize spatial variability (Corwin and Lesch, 2005a). The characterization of spatial variability using EC_a measurements is based on the hypothesis that spatial EC_a information can be used to develop a directed soil sampling plan that identifies sites that adequately reflect the range and variability of soil salinity and other soil properties correlated with EC_a. This hypothesis has repeatedly held true for a variety of agricultural applications (Corwin, 2005; Corwin and Lesch, 2003, 2005a, 2005c, 2005d; Corwin et al., 2003a, 2003b; Johnson et al., 2001; Lesch et al., 1992, 2005).

The EC_a measurement is particularly well suited for establishing within-field spatial variability of soil properties because it is a quick and dependable measurement that integrates within its measurement the influence of several soil properties that contribute to the electrical conductance of the bulk soil. The EC_a measurement serves as a means of defining spatial patterns that indicate differences in electrical conductance due to the combined conductance influences of salinity, θ, texture, and ρ_b. Therefore, maps of the variability of EC_a provide the spatial information to direct the selection of soil sample sites to characterize the spatial variability of those soil properties correlating, either for direct or indirect reasons, to EC_a.

The characterization of the spatial variability of various soil properties with EC_a is a consequence of the physicochemical nature of the EC_a measurement. Three pathways of current flow contribute to the EC_a of a soil: (1) a liquid phase pathway via dissolved solids contained in the soil water occupying the large pores, (2) a solid–liquid phase pathway primarily via exchangeable cations associated with clay minerals, and (3) a solid pathway via soil particles that are in direct and continuous contact with one another (Rhoades et al., 1989, 1999a). These three pathways of current

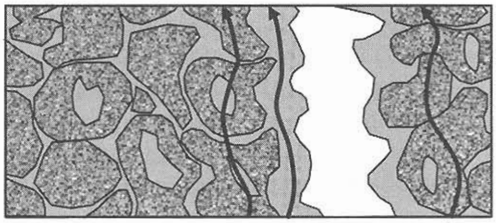

FIGURE 2.5 The three conductance pathways for the ECa measurement. (Modified from Rhoades, J.D., Manteghi, N.A., Shouse, P.J., and Alves, W.J., *Soil Sci. Soc. Am. J.*, 53, 433–439, 1989. With permission.

flow are illustrated in Figure 2.5. Rhoades et al. (1989) formulated an electrical conductance model that describes the three conductance pathways of EC_a:

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{\theta_{ss} \cdot EC_{ws} + \theta_{ws} \cdot EC_s}\right] + (\theta_{sc} \cdot EC_{sc}) + (\theta_{wc} \cdot EC_{wc}) \tag{2.16}$$

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the soil–water pathway (cm^3 cm^{-3}) and in the continuous liquid pathway (cm^3 cm^{-3}), respectively; θ_{ss} and θ_{sc} are the volumetric contents of the surface-conductance (cm^3 cm^{-3}) and indurated solid phases of the soil (cm^3 cm^{-3}), respectively; EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil–water pathway (dS m^{-1}) and continuous-liquid pathway (dS m^{-1}); and EC_{ss} and EC_{sc} are the electrical conductivities of the surface-conductance (dS m^{-1}) and indurated solid phases (dS m^{-1}), respectively. Equation (2.16) was reformulated by Rhoades et al. (1989) into Equation (2.17):

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{(\theta_{ss} \cdot EC_{ws}) + (\theta_{ws} \cdot EC_s)}\right] + (\theta_w - \theta_{ws}) \cdot EC_{wc} \tag{2.17}$$

where $\theta_w = \theta_{ws} + \theta_{wc}$ = total volumetric water content (cm^3 cm^{-3}), and $\theta_{sc} \cdot EC_{sc}$ was assumed to be negligible. The following simplifying approximations are also known:

$$\theta_w = \frac{(PW \cdot \rho_b)}{100} \tag{2.18}$$

$$\theta_{ws} = 0.639\theta_w + 0.011 \tag{2.19}$$

$$\theta_{ss} = \frac{\rho_b}{2.65} \tag{2.20}$$

$$EC_{ss} = 0.019(SP) - 0.434 \tag{2.21}$$

$$EC_w = \left[\frac{EC_e \cdot \rho_b \cdot SP}{100 \cdot \theta_w}\right] \tag{2.22}$$

where PW is the percent water on a gravimetric basis, ρ_b is the bulk density (Mg m^{-3}), SP is the saturation percentage, EC_w is average electrical conductivity of the soil water assuming equilibrium (i.e., $EC_w = EC_{sw} = EC_{wc}$), and EC_e is the electrical conductivity of the saturation extract (dS m^{-1}).

The reliability of Equation (2.17) through Equation (2.22) has been evaluated by Corwin and Lesch (2003). These equations are reliable except under extremely dry soil conditions. However, Lesch and Corwin (2003) developed a means of extending equations for extremely dry soil conditions by dynamically adjusting the assumed water content function.

Because of the three pathways of electrical conductance, EC_a is influenced by several soil physical and chemical properties: (1) soil salinity, (2) saturation percentage, (3) water content, (4) bulk density, and (5) temperature. The quantitative influence of each factor is reflected in Equation (2.17) through Equation (2.22). The SP and ρ_b are both directly influenced by clay content and organic matter (OM). Furthermore, the exchange surfaces on clays and OM provide a solid–liquid phase pathway primarily via exchangeable cations; consequently, clay content and mineralogy, cation exchange capacity (CEC), and OM are recognized as additional factors influencing EC_a measurements. Apparent soil electrical conductivity is a complex property that must be interpreted with these influencing factors in mind.

Field measurements of EC_a are the product of both static and dynamic factors, which include soil salinity, clay content and mineralogy, θ, ρ_b, and temperature. Johnson et al. (2003) described the observed dynamics of the general interaction of these factors. In general, the magnitude and spatial heterogeneity of EC_a in a field are dominated by one or two of these factors, which will vary from one field to the next, making the interpretation of EC_a measurements highly site specific. In instances where dynamic soil properties (e.g., salinity) dominate the EC_a measurement, temporal changes in spatial patterns exhibit more fluidity than systems that are dominated by static factors (e.g., texture). In texture-driven systems, spatial patterns remain consistent because variations in dynamic soil properties affect only the magnitude of measured EC_a (Johnson et al., 2003). For this reason, Johnson et al. (2003) warn that EC_a maps of static-driven systems convey very different information from those of less-stable dynamic-driven systems.

Numerous EC_a studies have been conducted that revealed the site specificity and complexity of spatial EC_a measurements with respect to the particular property influencing the EC_a measurement at that study site. Table 2.1 is a compilation of various laboratory and field studies and the associated dominant soil property measured.

The complex nature of EC_a has a positive benefit. Because of its complexity, geospatial measurements of EC_a provide a means of potentially characterizing the spatial variability of those soil properties influencing EC_a or even soil properties correlated to EC_a without a direct cause-and-effect relationship. The characterization of spatial variability of soil properties correlated with EC_a at a specific field has been achieved through EC_a-directed soil sampling (Corwin and Lesch, 2005c; Lesch et al., 1995b).

2.3.3 Agricultural Applications of EC_a-Directed Soil Sampling

The characterization of soil spatial variability using EC_a-directed soil sampling has been applied to a variety of landscape-scale agricultural applications: (1) spatial input for solute transport models of the vadose zone, (2) mapping edaphic and anthropogenic properties, (3) characterizing and assessing soil quality, (4) delineating site-specific management units (SSMUs) and productivity zones, and (5) monitoring management-induced spatiotemporal change in soil condition.

To date, the only study to use EC_a-directed soil sampling to characterize soil variability for use in the modeling of solute transport in the vadose zone is by Corwin et al. (1999). In a landscape-scale study modeling salt loading to tile drains in California's San Joaquin Valley, Corwin et al. (1999) used EC_a-directed soil sampling to define spatial domains of similar solute transport capacity in the vadose zone. These spatial domains, referred to as stream tubes, were volumes of soil that are assumed to be isolated from adjacent stream tubes in the field (i.e., no solute exchange) so that a one-dimensional, vertical solute transport model can be applied to each stream tube without concern for lateral flow of water and transport of solute. The application of a functional, tipping-bucket, layer-equilibrium model to each stream tube resulted in the prediction of salt loading to within 30% over a five-year study period.

Mapping soil properties with EC_a-directed soil sampling has been conducted by a limited number of researchers because this approach is comparatively new. The earliest work was conducted by Lesch et al. (1995b) mapping soil salinity. Johnson et al. (2001, 2004) used an EC_a-directed stratified sampling approach to delineate within-field variability of physical, chemical, and biological properties and to relate observations made at different experimental scales. Corwin and Lesch (2005c) used EC_a-directed soil sampling to map a variety of properties for a saline-sodic soil, including salinity, clay content, and sodium adsorption ratio. Triantafilis and Lesch (2005) mapped clay content over a 300 km^2 area. Lesch et al. (2005) used EC_a-directed soil sampling (1) to map and monitor salinity during the reclamation of a field by leaching, (2) to map soil texture and soil type classification, and (3) to identify and locate buried tile lines of a drainage system. Sudduth et al. (2005) provide the most comprehensive compilation relating EC_a to soil properties covering the north-central United States.

An extension of the ability to map individual soil properties is the ability to characterize and assess soil condition based on a compilation of spatial data for individual soil properties influencing the intended function of a soil. The application of EC_a-directed soil sampling to characterize and assess soil condition has been largely found in the Great Plains area and the southwestern United States. Using EC_a maps to direct soil sampling, Johnson et al. (2001) and Corwin et al. (2003b) spatially characterized the overall soil quality of physical and chemical properties thought to affect yield potential. To characterize the soil quality, Johnson et al. (2001) used a stratified soil sampling design with allocation into four geo-referenced EC_a ranges. Correlations were performed between EC_a and the minimum data set of physical, chemical, and biological soil attributes proposed by Doran and Parkin (1996). Their results showed a positive correlation of EC_a with percentage clay, ρ_b, pH, and $EC_{1:1}$ over a soil depth of 0 to 30 cm, and a negative correlation with soil moisture, total and particulate organic matter, total C and N, microbial biomass C, and microbial biomass N. No relationship of the soil properties to crop yield was determined. Corwin et al. (2003b) characterized the soil quality of a saline-sodic soil using a SRSS design. A positive correlation was found between EC_a and the properties of volumetric water content; electrical conductivity of the saturation extract (EC_e); Cl^-, NO_3^-, SO_4^-, Na^+, K^+, and Mg^{+2} in the saturation extract; SAR (sodium adsorption ratio), exchangeable sodium percentage (ESP); B; Se; Mo; $CaCO_3$; and inorganic and organic C. The positive correlation indicated that the spatial variability of soil properties would be accurately characterized. Most of these properties are associated with soil quality for arid zone soils. A number of soil properties (i.e., ρ_b; percentage clay; pH_e; SP; HCO_3^- and Ca^{+2} in the saturation extract; exchangeable Na^+, K^+, and Mg^{+2}; As; CEC; gypsum; and total N) did not correlate well with EC_a measurements, indicating that the SRSS sample design would not accurately characterize the spatial variability of these particular properties. Johnson et al. (2001) and Corwin et al. (2003b) did not actually relate the spatial variation in the measured soil physical and chemical properties to crop yield variations.

To a varying extent from one field to the next, crop patterns are influenced by the spatial variability of edaphic properties. Conventional farming does not address these variations because it manages a field uniformly; as a result, within-field variations in soil properties cause less than optimal crop yields. Site-specific crop management (SSCM) seeks to address variations in crop yield by managing edaphic, anthropogenic, biological, meteorological, and topographic factors to optimize yield and economic return. Bullock and Bullock (2000) point out the importance to SSCM of developing efficient methods for accurately measuring within-field variations in soil physical and chemical properties that influence spatial variation in crop yield. The geospatial measurement of EC_a is a technology that has become an invaluable tool for identifying the soil physical and chemical properties influencing crop yield patterns and for establishing the spatial variation of these soil properties (Corwin et al., 2003a).

The application of EC_a to the SSCM arena is largely due to the past and current research efforts of Kitchen and colleagues (2003, 2005), Lund and colleagues (1999, 2001), and Jaynes and colleagues (1995b, 2003, 2005) in the Midwest using EC_a to delineate productivity zones. Productivity zones refer to areas of similar productivity potential and are of interest to producers, because some key management decisions depend upon reliable estimates of expected yield. Productivity zones associate productivity with a soil property or condition but do not provide the producer with site-specific information for optimizing yield in low-yield portions of a field. For instance, the productivity zones of dryland agriculture have been primarily related to available water as affected by soil and topography (Jaynes et al., 2003; MacMillan et al., 1998). In contrast, SSMUs are units of soil that can be managed similarly to optimize yield.

Corwin et al. (2003a) carried the EC_a-directed soil sampling approach to the next level in SSCM by integrating crop yield to delineate SSMUs with associated recommendations. This work was based on the hypothesis that in the field where yield spatially correlates with EC_a, then geospatial measurements of EC_a can be used to identify edaphic and anthropogenic properties that influence yield. Through spatial statistical analysis, Corwin et al. (2003a) were able to show the influence of salinity, leaching fraction, θ, and pH on the spatial variation of cotton yield for a 32.4 ha field in the Broadview Water District of central California. With this information, a crop yield response model was developed and management recommendations were made that spatially prescribed what could be done to increase cotton yield at those locations with less than optimal yield. Subsequently, Corwin and Lesch (2005a) delineated SSMUs. Highly leached zones were delineated where the leaching fraction (LF) needed to be reduced to <0.5; high salinity areas were defined where the salinity needed to be reduced below the salinity threshold for cotton, which was established at $EC_e = 7.17$ dS m^{-1} for this field; areas of coarse texture were defined that needed more frequent irrigations; and areas were pinpointed where the pH needed to be lowered below a pH of 8 with a soil amendment such as OM. This work brought an added dimension because it delineated within-field units where associated site-specific management recommendations would optimize the yield, but it still falls short of integrating biological, meteorological, economic, and environmental impacts on within-field crop-yield variation. However, prior to the work by Corwin and colleagues, SSCM applications of EC_a had been restricted to the identification of productivity zones (Boydell and McBratney, 1999; Jaynes et al., 2003, 2005; Kitchen et al., 2005; Ping and Dobermann, 2003) rather than management zones that vary in some management input or practice.

Because of its ability to spatially characterize soil properties, EC_a-directed soil sampling easily transitions into a means of monitoring management-induced spatiotemporal changes through the interjection of a temporal component (Corwin et al., 2006). However, even though EC_a-directed soil sampling is far more efficient and less costly than conventional grid sampling, it is still limited in the frequency with which spatio-temporal changes can be studied. Highly dynamic changes, such as those occurring between irrigation or precipitation events or within a crop growing season, are probably too dynamic to monitor effectively. Gradual changes that occur during the course of soil reclamation (Lesch et al., 2005) or due to changes in management, such as drainage water reuse (Corwin et al., 2006), are well suited for EC_a-directed soil sampling. These typically require monitoring at annual intervals or longer.

2.4 PROGNOSIS OF GEOPHYSICAL TECHNIQUES IN AGRICULTURE—FUTURE TRENDS AND NEEDS

The use of geospatial measurements of EC_a for directing soil sampling to characterize soil spatial variability will continue to be a useful approach for field and larger spatial extents. There is considerable potential impact because the characterization of spatial variability is a fundamental component of a variety of field- and landscape-scale issues, including soil quality assessment, solute transport modeling in the vadose zone, SSCM, assessing management-induced changes, and mapping and inventorying soil properties.

When geospatial measurements of EC_a are spatially correlated with geo-referenced yield data, their combined use provides an excellent tool for identifying edaphic and anthropogenic factors that influence yield, which can be used to delineate SSMUs (Corwin and Lesch, 2005a; Corwin et al., 2003a). The delineation of productivity zones from geospatial measurements of EC_a provides another approach to SSCM (Jaynes et al., 2005; Kitchen et al., 2005). Even so, an understanding of the soil-related factors influencing yield or the identification of productivity zones does not provide the whole picture for SSCM because crop systems are affected by a complex interaction of edaphic, biological, meteorological, anthropogenic, and topographic factors. Moreover, the precise manner in which these factors influence the dynamic process of plant growth and reproduction is not always well understood. Geo-referenced EC_a will only help to provide a spatial understanding of edaphic and anthropogenic influences. To be able to manage within-field variation in yield, it is necessary to have an understanding within a spatial context of the relationship of all dominant factors causing the variation.

Current applications of geophysical techniques in agriculture have made it evident that the temporal and spatial complexity of soil–plant systems at field and larger spatial extents will require a combined use of multiple geophysical sensors to obtain the full spectrum of spatial data necessary to identify and characterize the factors influencing yield. Of these, the use of hyperspectral imagery, EMI, real-time kinematic GPS, and GPR probably have the greatest potential from a cost-benefit perspective for providing the greatest information impact. The fruition of EC_a in SSCM will likely come from future plant indicator approaches where combinations of geo-referenced data are used (Corwin and Lesch, 2003). These geo-referenced data will likely include airborne multi- and hyperspectral imagery, EMI, GPR, and real-time kinetic GPS. Plant and soil sampling with model- or design-based sampling strategies will be based on the combined data inputs. Manipulation, organization, and display of these inputs and outputs will be performed with a geographic information system, image analysis, and spatial statistical analysis.

Remotely sensed imagery and EMI measurements of EC_a provide complementary information. Remotely sensed imagery is generally best suited for spatially characterizing dynamic properties associated directly with plant vegetative development, and EC_a measurements are best suited for spatially characterizing static soil properties such as texture, water table depth, and steady-state salinity. Remotely sensed imagery is particularly well suited for obtaining spatial crop information during the maturation of a crop. Furthermore, hyperspectral imagery may hold the key for identifying the spatial effects of nonedaphic factors (e.g., disease, climate, humankind, etc.) on crops. Geospatial measurements of EC_a are most reliable for measuring static soil properties that may influence crop yield because of the associated soil sampling required for ground truth to establish what soil property or properties are influencing EC_a at a given point of measurement. Soil sampling and analysis is time and labor intensive, making the measurement of dynamic soil properties using EC_a generally untenable. Ground truth for remotely sensed imagery is also necessary, but (1) wide-coverage real-time remote images are generally easier to obtain than spatially comparable real-time EC_a data unless EC_a is measured from an airborne platform and (2) calibrations are often faster because soil sampling for EC_a can involve several depth increments and numerous soil properties. Conventional mobilized ground-based EC_a platforms cannot begin to compete with satellite or airborne imagery from the perspective of extent of coverage of real-time data. Nonetheless, ground-based EC_a surveys at field scales have their place because they allow greater control and potentially increased spatial resolution.

There is no question that geospatial measurements of EC_a have found a niche in agricultural research and will likely continue to serve a significant role in the future. However, additional spatial information is needed to fill gaps in the database necessary for SSCM, including (1) the need for integrated spatial data of topographical, meteorological, biological, anthropogenic, and edaphic factors influencing yield; (2) the need for real-time data and rapid processing and analysis to enable temporal as well as spatial management decisions; and (3) the need for sensors that can measure dynamic soil properties and crop responses to those properties. Furthermore, no single study has been conducted that evaluates SSCM from a holistic perspective of environmental, productivity, and economic impacts. This task remains as a future goal for agronomists and soil and environmental scientists. Geophysical techniques will play a crucial role in any future holistic evaluations.

The integrated use of multiple remote and ground-based sensors is the future direction that agriculture will likely take to obtain the extensive spatial data that will be needed to direct variable-rate technologies. Variable-rate technologies driven by a network-centric system of multiple sensors will ultimately take SSCM from a drawing board concept to a reality.

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