4 Theoretical Insight on the Measurement of Soil Electrical Conductivity

Dennis L. Corwin, Scott M. Lesch, and Hamid J. Farahani

CONTENTS

4.1 INTRODUCTION

Due in large measure to the research that has been conducted at the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) United States Salinity Laboratory over the past 50 years, the measurement of electrical conductivity (EC) has become a standard soil physicochemical measurement both in the laboratory and in the field to address agricultural and environmental concerns. In particular, the geospatial measurement of EC with geophysical techniques, including electrical resistivity (ER), electromagnetic induction (EMI), and time domain reflectometry (TDR), has burgeoned into one of the most useful field agricultural measurements, particularly for spatially characterizing the variability of soil properties such as salinity, water content, and texture (Corwin, 2005).

The value of spatial measurements of soil EC to agriculture is widely acknowledged due to its ability to characterize spatial variability, with applications in solute transport modeling at field and landscape scales (Corwin et al., 1999), salinity mapping and assessment (Corwin et al., 2003a), mapping soil texture (Doolittle et al., 2002) and soil type (Anderson-Cook et al., 2002; Jaynes et al., 1993), location of claypans and depth of depositional sand (Doolittle et al., 1994; Kitchen et al., 1996; Sudduth et al., 1995), soil quality assessment (Corwin et al., 2003a; Johnson et al., 2001; McBride et al., 1990), monitoring of management-induced spatiotemporal changes in soil condition (Corwin et al., 2006), delineation of site-specific crop management units (Corwin et al., 2003b, 2008) and zones of productivity (Jaynes et al., 2003, 2005; Kitchen et al., 2005), and measuring other soil properties such as soil moisture (Kachanoski et al., 1988; Sheets and Hendrickx, 1995), clay content (Sudduth et al., 2005; Triantafilis and Lesch, 2005; Williams and Hoey, 1987), shallow subsurface available soil N (Eigenberg et al., 2002), and cation exchange capacity (Sudduth et al., 2005). The above studies mostly used the noncontact electromagnetic induction (EMI) method to measure soil EC, with a few using the four-electrode contact methods that induce electrical current into the soil through insulated metal electrodes. A complete review of EC measurements in agriculture is provided by Corwin and Lesch (2005a).

As evident from the above studies, there are significant innovations in developing useful applications of soil EC measurements in agriculture. Nearly all experimental observations similar to those listed above are based on soil EC being regarded as a surrogate measure of one or more soil properties of interest. Results are dictated by the physical and chemical properties of the soil at the time of the EC measurements. However, it is not evident that the basic principles of soil EC have been adequately examined. That is particularly the case in examining the recent interests in various applications of soil EC mapping in precision agriculture. An understanding of the spatial and temporal variability of soil EC and an appreciation for its highly complex interactions with static and dynamic soil properties, particularly at low-salt concentrations, is needed. It is the intent of this chapter to highlight the important aspects of spatial EC measurements in agriculture by providing basic principles and theory of soil EC measurement and what it actually measures, standard operating procedures for conducting a field-scale EC survey, including an outlined set of EC-directed soil sampling protocols, and examples of spatial EC surveys and their interpretation.

4.1.1 BACKGROUND: DEFINITION AND BRIEF HISTORY OF SOIL ELECTRICAL CONDUCTIVITY

Soil EC has its historical roots in the measurement of soil salinity. In situ measurement of soil resistivity dates back to at least the latter part of the nineteenth century when Whitney et al. (1897) attempted to infer soil water content and salinity from measurements of soil resistivity using two-probe electrodes. Gardner (1898) and Briggs (1899) reported additional measurements as part of the early group of USDA scientists investigating soil temperature, salinity, and water content effects on soil resistivity. To minimize the difficulties with the unstable two-probe method, Frank Wenner (1915) introduced the theory of utilizing four equally spaced electrodes to measure earth resistivity and wrote "A knowledge of earth resistivity (or specific resistance) may be of value in determining something of the composition of earth."

Soil salinity refers to the presence of major dissolved inorganic solutes in the aqueous phase consisting of soluble and readily dissolvable salts in soil and can be determined by measuring the total solute concentration in the soil aqueous phase, more commonly referred to as the soil solution. The determination of total solute concentration (i.e., salinity) through the measurement of EC has been well established for half a century (U.S. Salinity Laboratory Staff, 1954). Soil salinity is quantified in terms of the total concentration of soluble salts as measured by the EC of the solution in dS m^{-1}.

It is known that the EC of a pure solution (σ_w) is a function of its chemical composition and is characterized by Equation (4.1):

$$\sigma_w = k\sum_{i=1}^{n} \lambda_i M_i |v_i| \tag{4.1}$$

where k is the cell constant accounting for electrode geometry, λ is the molar limiting ion conductivity (S m^2 mol^{-1}), M is the molar concentration (mol m^{-3}), v is the absolute value of the ion charge, and i denotes the ion species in solution. Marion and Babcock (1976), among others, have confirmed the existence of the relationship between EC and molar concentrations of ions in the soil solution.

To determine soil EC, the soil solution is placed between two electrodes of constant geometry and distance of separation (Bohn et al., 1979). The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. Electrical conductance was considered more suitable for salinity measurements than resistance because it increases with salt content, which simplifies the interpretation of readings. At constant potential, the electrical conductance is a reciprocal of the measured resistance as shown in Equation (4.2):

$$EC_T = k/R_T \tag{4.2}$$

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 approximately 1.9 percent per degree centigrade increase in T. Customarily, EC is adjusted to a reference temperature of 25°C using Equation (4.3) from Handbook 60 (U.S. Salinity Laboratory Staff, 1954):

$$EC_{25} = f_T \cdot EC_T \tag{4.3}$$

where f_T is a temperature conversion factor that has been approximated by a polynomial form (Rhoades et al., 1999a; Stogryn, 1971; Wraith and Or, 1999) and by Equation (4.4) from Sheets and Hendrickx (1995):

$$f_T = 0.4470 + 1.4034e^{-T/26.815} \tag{4.4}$$

Soil EC is determined for an aqueous extract of a soil sample. Ideally, the EC of an extract of the soil solution (EC_w) is the most desirable, because this is the water content to which plant roots are exposed, but this is usually difficult and time consuming to obtain. The soil sample from which the extract is taken can either be disturbed or undisturbed. For disturbed samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum- or pressure-extraction methods. Because of the difficulty in extracting soil solution from soil samples at typical field water contents, soil solution extracts are most commonly from higher than normal water contents. The most common extract obtained is that from a saturated soil paste (EC_e), but other commonly used extract ratios include 1:1 ($EC_{1:1}$), 1:2 ($EC_{1:2}$), and 1:5 ($EC_{1:5}$) soil-to-water mixtures. Unfortunately, the partitioning of solutes over the three soil phases (i.e., gas, liquid, and solid) is influenced by the soil-to-water ratio at which the extract is made, which confounds comparisons between ratios and interpretations; consequently, standardization is needed for comparison of EC measurements. For undisturbed soil samples, EC_w can be determined either in the laboratory on a soil solution sample collected with a soil-solution extractor installed in the field or directly in the field using in situ, imbibing-type, porous-matrix, salinity sensors. All of these approaches for measuring soil EC are time and labor intensive; as a result, they are not practical for the characterization of the spatial variability of soil salinity at field extents and larger.

Because of the time, labor, and cost of obtaining soil solution extracts, developments in soil salinity measurement at field and landscape scales over the past 30 years have shifted to EC measurement of the bulk soil, referred to as the apparent soil electrical conductivity (EC_a). The measurement of EC_a is an indirect method for the determination of soil salinity because EC_a measures conductance not only through the soil solution, but also through solid soil particles and via exchangeable cations that exist at the solid–liquid interface of clay minerals. The shift away from extracts to the measurement of EC_a occurred 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. Historically, the utility of EC_a has been in identifying geological features in geophysical sciences and explorations (McNeill, 1980; Zalasiewicz, et al., 1985) and in agricultural soil salinity surveys for diagnostics, leaching, and salt loading (Corwin et al., 1996; Rhoades and Ingvalson, 1971; Rhoades et al., 1990). During the past decade, there has been an increased interest in using EC_a maps to infer the spatial variability of soil properties important to crop production. In particular, there is an emerging interest in utilizing the spatial variability in EC_a for the purposes of guiding soil sampling (as opposed to systematic grid sampling) and developing management zones to vary agricultural inputs.

The measurement of soil EC_a is primarily through the use of the geophysical techniques of ER, EMI, and TDR. Among the many advanced sensors recently introduced in precision agriculture, EMI and ER EC_a measuring devices provide the simplest and least expensive soil variability measurement. Electrical resistivity introduces an electrical current into the soil through current electrodes at the soil surface, and the difference in current flow potential is measured at potential electrodes that are placed in the vicinity of the current flow. Generally, there are four electrodes inserted in the soil in a straight line at the soil surface, with the two outer electrodes serving as the current electrodes and the two inner electrodes serving as the potential electrodes (Figure 4.1). A resistance meter is used to measure the potential gradient. For a homogeneous soil, the volume of measurement with ER is roughly πa^3, where a is the interelectrode spacing when the electrodes are equally spaced. The most commonly used ER equipment is the Veris Soil EC Mapping System (Veris Technologies, Salina, KS). The Veris 3100 unit has six coulter electrodes mounted on a platform that can be pulled by a pickup truck. It uses a modified Wenner configuration to measure EC_a by inducing current in the soil through two coulter electrodes and measuring the voltage drop across the two pairs of coulters that are spaced to measure EC_a for the top 0.3 m (shallow) and 0.9 m (deep) of soil (Lund et al., 2000). The shallow and deep EC_a readings at each measurement point in the field are useful in examining soil profile changes. Although soil compaction affects EC_a due to the reduced porosity and increased soil particle-to-particle contact, compaction is not easily identified from a Veris EC_a map, as the compacted layer represents only a small percentage of the domain of EC_a measurements.

The Veris unit interfaces with a differential Global Positioning System (GPS) and provides simultaneous and geo-referenced readings of EC_a. The Veris unit is designed to operate in tilled or untilled conditions, where the coulters penetrate the soil 20 to 50 mm (more penetration for drier

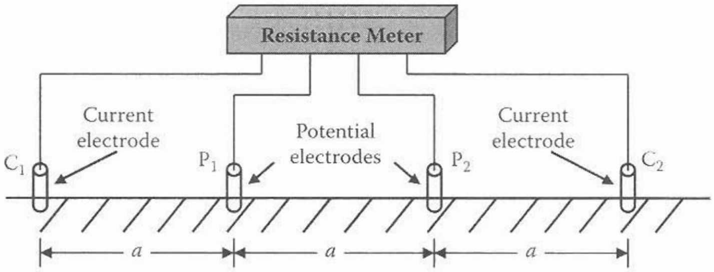

FIGURE 4.1 Electrical resistivity with a Wenner array electrode configuration where the interelectrode spacing is equal between current and potential electrodes: C_1 and C_2 represent the current electrodes, P_1 and P_2 represent the potential electrodes, and a represents the interelectrode spacing. (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.)

and looser soil surface conditions). It is good practice to map fields when they are not very dry. Soil EC_a mapping with the Veris unit should not be attempted when the soil is frozen, or in the presence of any frost layers. Frozen soil has significantly different conductive properties, and the EC_a data collected will not be valid. The Veris unit is a rugged and reliable system with no known difficulties in mapping fields in the spring prior to tillage and planting operations or in the fall after harvest with heavy standing and flat-lying surface residue conditions (Farahani and Buchleiter, 2004). For ease of maneuvering, fields are normally traversed in the direction of crop rows, but the resulting map is not affected by the direction of travel. On average, travel speeds through the field range between 7 and 16 km h^{-1} with measurements taken every second, corresponding to 2 to 4 m spacing between measurements in the direction of travel, respectively. A parallel swather (such as AgGPS Parallel Swathing Option, Trimble Navigation Ltd., Sunnyvale, CA) mounted inside the vehicle pulling the Veris unit may be used to guide parallel passes through the field at desired (i.e., 12 to 18 m) swath widths.

The direct contact method used by EC_a equipment like Veris has a distinct advantage over the EMI method in that there is no possibility of ambient electrical (for instance from power lines), metallic (operator's belt buckle), or engine noise interferences. Other important advantages of ER-type methods over EMI are that there is no calibration or nulling procedures required prior to mapping, and there is no known report of any observed drift in the measured soil EC_a by ER. Regular "drift runs" that involve traversing the same location in a field are needed for EMI in order to determine the drift resulting from air temperature effects on the instrument throughout the day. Because the electrodes in the ER method directly inject the signal into the soil, changes in air temperature have virtually no effect on the readings. It is noted that EC_a data collected with either method are affected by soil temperature. The most obvious disadvantage of direct ER methods is their intrusiveness as compared to the nonintrusive EMI methods. The invasive ER method requires solid contact between the coulters and soil; consequently, dry conditions or irregular microtopography can prevent contact. Although the distinction between the two differing EC_a measuring methods of ER and EMI is important, side-by-side measurements of soil EC_a by contact electrodes and EMI methods has given highly correlated values (Sudduth et al., 2003) and has provided similar maps (Doolittle et al., 2002).

In the case of EMI, EC is measured remotely using a frequency signal in the range of 0.4 to 40 kHz and primarily measures signal loss to determine EC_a. The EMI measurement is made with the instrument at or above the soil surface. An EMI transmitter coil located at one end of the instrument induces circular eddy-current loops in the soil (Figure 4.2). The magnitude of these loops is directly proportional to the EC_a of the soil in the vicinity of that loop. Each current loop generates a secondary electromagnetic field that is proportional to the current flowing within the loop. A portion of the secondary-induced electromagnetic field from each loop is intercepted by the receiver coil, and the sum of these signals is related to a depth-weighted EC_a.

For TDR, an 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

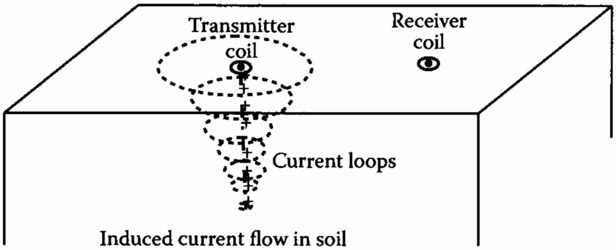

FIGURE 4.2 The principle of operation electromagnetic induction. (From Corwin, D.L., and Lesch, S.M., *Agron. J.*, 95, 455–471, 2003. With permission.)

transmission line is used to determine the velocity of propagation through soil, which is controlled by the relative dielectric permittivity or dielectric constant. By measuring the resistive load impedance across the probe, EC_a can be determined. 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 has not been widely used for geospatial measurements of EC_a at field and larger spatial extents. Only ER and EMI are commonly used at these spatial extents (Rhoades et al., 1999a, 1999b).

Field measurements of EC_a to determine soil salinity began in the early 1970s with the use of ER (Halvorson and Rhoades, 1976; Rhoades and Halvorson, 1977; Rhoades and Ingvalson, 1971). However, geospatial measurements of EC_a in the field did not occur in earnest until the 1980s, primarily with the use of EMI, which had definite advantages over ER because it was noninvasive. Observational research through the 1980s and early 1990s largely correlated EC_a measurements to soil properties in an effort to sort out what soil properties were measured by EC_a (Table 4.1). From the late 1990s to the present, the complex spatial relationship between EC_a, edaphic properties, and within-field variations in crop yield for site-specific crop management has increasingly become the focus of EC_a research. However, over the past three decades and even today, measurements of EC_a are often misunderstood and misinterpreted. The misconceptions regarding EC_a are the consequence of incomplete knowledge of the basic principles and theory of the EC_a measurement.

4.1.2 MISCONCEPTIONS SURROUNDING THE APPARENT SOIL ELECTRICAL CONDUCTIVITY (EC_a) MEASUREMENT

When scientists began to take EC_a measurements in the field and correlate them to soil properties, there were preconceived notions about what was being measured. Those scientists in the arid southwestern United States felt that salinity was being measured, and those in the Midwest felt water content and texture were being measured. In reality, both were correct, but each failed to acknowledge that EC_a is a complex physicochemical measurement influenced by any soil property that influences electrical conductance pathways in soil. Additional research produced correlations between EC_a and soil properties that were not directly measured but indirectly related to properties that were measured by EC_a (Table 4.1).

With a few exceptions, the EC_a related observations suggest salinity, soil water content, clay content, exchange cations, temperature, and organic matter content are the dominating soil properties affecting EC_a, but the strength of the reported correlations varies widely with coefficients ranging from below 0.4 to above 0.8. Contrasting findings are evident in literature; for example, Dalgaard et al. (2001) reported a higher correlation between EC_a and clay at higher water contents, and Banton et al. (1997), in a detailed study on an experimental farm near Quebec City, found texture parameters to have a stronger correlation with EC_a for dry than wet soil conditions. Johnson et al. (2001), on the other hand, found no strong correlations between EC_a and a host of soil properties in a 250 ha dryland no-till field in eastern Colorado, concluding that EC_a delineations were useful in identifying overall soil variability but not in producing specific maps of any individual soil property. In nonsaline fields in Missouri, depth to claypans (a sublayer with 50 to 60 percent in clay and varying in depth from 0.1 to 1 m) was found highly correlated to EC_a (Doolittle et al., 1994). As EC_a increased, depth to claypan decreased. A more extensive study on the Missouri claypan, however, produced EC_a maps that exhibited little resemblance to the maps of measured depth to claypans (Sudduth et al., 1995), concluding that the EC_a data were strongly influenced by the crop and farming system, soil water, and crop biomass at the time of EC_a measurements. Additional difficulties with interpreting literature are that most of the identified soil properties that dominate EC_a variability exhibit significant codependency and thus provide overlapping (or redundant), but confusing, information about EC_a. Generally speaking, the degree of EC_a association with a given soil property

TABLE 4.1
Compilation of Literature Measuring ECa with Geophysical Techniques (ER or EMI) Categorized According to the Soil-Related Properties Directly or Indirectly Measured by ECa

Soil Property	References
Directly measured soil properties:salinity (and nutrients, e.g., NO3-)	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, 2005); 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); Sudduth et al. (2005); 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); Sudduth et al. (2005); 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); Lesch et al. (2005); Rhoades et al. (1999a); Scanlon et al. (1999); Stroh et al. (1993); Sudduth and Kitchen (1993); Sudduth et al. (2005); Triantafilis and Lesch (2005); 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); Sudduth et al. (2005)
Cation exchange capacity	Farahani et al. (2005); McBride et al. (1990); Sudduth et al. (2005); Triantafilis et al. (2002)
Leaching	Corwin et al. (1999); Lesch et al. (2005); 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. (1995)
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, 2005. With permission.

is time-of-measurement dependent. That dependency is mainly due to the dynamic nature of some soil properties (such as soil water content, solution concentration, and temperature).

Although there was nothing technically unsound concerning the research relating EC_a to directly or indirectly measured soil properties, an impression was created that EC_a was a vague, ethereal measurement that was less than robust due to the spatially heterogeneous and complex nature of soil. There is some truth to this notion, because electrical conductance through soil is complex due to the complex nature of soil. As a result, without a scientific understanding and explanation for what was being measured, geospatial EC_a readings and their correlations with soil properties are easily misinterpreted and misused to spatially characterize properties that are only loosely related or completely unrelated to actual properties being measured. This fact became evident in the early application of spatial EC_a measurements to site-specific crop management when correlations between EC_a and crop yields were found that were positive, negative, and unrelated. If, in fact, EC_a was measuring just water content and texture, or just salinity, then why were correlations with crop yield so erratic? The answer lies in the principles and theory behind the EC_a measurement.

4.2 BASIC PRINCIPLES AND THEORY OF EC_a

Electrical conduction through soil is due to the presence of free salts in the soil solution and exchangeable ions at the surfaces of solid particles. The soil equivalent resistance model (Sauer et al., 1955) provides the basis for the formulation of a mechanistic soil EC_a model applicable to the entire range of soil solution concentrations (Rhoades et al., 1989; Shainberg et al., 1980). Three pathways of current flow contribute to the EC_a of a soil: (1) a conductance pathway traveling through alternating layers of soil particles and soil solution, (2) a conductance pathway traveling through the continuous soil solution, and (3) a conductance pathway traveling through or along the surface of soil particles in direct and continuous contact (Rhoades et al., 1989, 1999a). These three pathways of current flow are illustrated in Figure 4.3. Conceptually, the first pathway can be thought of as a solid–liquid, series-coupled element, and the second and third pathways represent continuous liquid and solid elements, respectively.

Rhoades et al. (1989) introduced a model for EC_a describing the three separate current-flow pathways acting in parallel:

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{\theta_{ss} \cdot EC_{ws} + \theta_{ws} \cdot EC_{ss}}\right] + (\theta_{sc} \cdot EC_{sc}) + (\theta_{wc} \cdot EC_{wc}) \tag{4.5}$$

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the series-coupled 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 series-coupled 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 (4.5) was reformulated by Rhoades et al. (1989) into Equation (4.6):

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{w} \cdot EC_{ss}}{(\theta_{ss} \cdot EC_{ws}) + (\theta_{ws} \cdot EC_{ss})}\right] + (\theta_{w} - \theta_{ws}) \cdot EC_{w} \tag{4.6}$$

where $\theta_w = \theta_{ws} + \theta_{wc}$ = total volumetric water content ($cm^3\ cm^{-3}$), $\theta_{sc} \cdot EC_{sc}$ was assumed to be negligible, and solution conductivity equilibrium was assumed (i.e., $EC_w = EC_{ws} = EC_{wc}$, where EC_w is average electrical conductivity of the soil water assuming equilibrium). According to Equation (4.6), EC_a is determined by the following five parameters: θ_w, θ_{ws}, θ_{ss}, EC_{ss}, and EC_w. Using the following empirical approximations, Rhoades et al. (1989) showed that these five parameters are related to four measurable soil properties, which include soil salinity (EC_e; $dS\ m^{-1}$), saturation percentage (SP; SP is the gravimetric soil water content at saturation), bulk density (ρ_b; $Mg\ m^{-3}$), and gravimetric water content (θ_g; $kg\ kg^{-1}$):

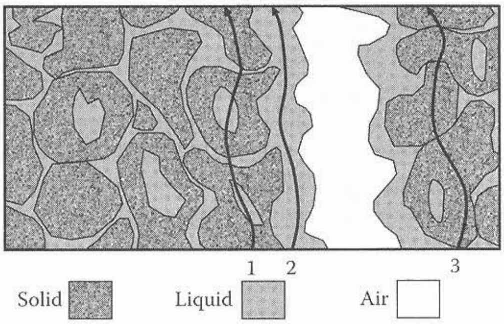
Pathways of Electrical Conductance
Soil Cross Section

FIGURE 4.3 The three conductance pathways for the EC_a 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.)

$$\theta_w = \theta_g \cdot \rho_b \tag{4.7}$$

$$\theta_{ws} = 0.639\theta_w + 0.011 \tag{4.8}$$

$$\theta_{ss} = \frac{\rho_b}{2.65} \tag{4.9}$$

$$EC_{ss} = 0.019(SP) - 0.434 \tag{4.10}$$

$$EC_w = \left[\frac{EC_e \cdot \rho_b \cdot SP}{100 \cdot \theta_w}\right] = EC_e \cdot \left(\frac{SP}{\theta_g}\right) \tag{4.11}$$

The reliability of Equation (4.6) through Equation (4.11) 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. Using the above theory, Farahani et al. (2005) deduced the importance of various soil properties to explain EC_a variability in nonsaline soils of three Colorado fields. Their examination of the above theoretically based EC_a model was useful in highlighting the general complexity of EC_a, its major pathways in the soil, and the concept as a whole, even though crude assumptions were made in approximating the parameters in Equation (4.6) through Equation (4.11).

Equation (4.3) and Equation (4.6) through Equation (4.11) indicate that EC_a is influenced by EC_e, SP, θ_g, ρ_b, and temperature. 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. Soil EC_a is expected to increase with increasing clay and OM contents, because EC_{ss} and θ_w (or more correctly θ_{ws}) increase with clay and OM. With EC_{ss} regarded as a function of clay, CEC, and OM (Rhoades et al., 1976; Shainberg et al., 1980), it is not surprising that most field observations of EC_a versus soil properties have identified clay, CEC, and OM as main factors dominating EC_a variability in nonsaline soils. It is noted from Equation (4.6) that conductance through alternating layers of soil particles and soil solution pathway (the first term) is complicated, and its contribution to EC_a is not obvious as the dynamic soil properties of EC_w and θ_w change. As soil water content changes, EC_w is expected to change. As soil water evaporates, EC_w is expected to increase due to increased concentration of free ions in solution. These are counteracting mechanisms contributing to the complexity of EC_a and soil property relationships. In other words, empirical EC_a versus soil property functions are expected to be temporally variable unless EC_w and θ_w remain relatively unchanged. As discussed previously (Equation (4.3), the other important soil variable causing change in EC_a is temperature, with EC_a increasing by approximately 1.9 percent per degree centigrade. This could be significant for shallow depths that may exhibit the greatest temperature variation. Apparent soil electrical conductivity is a complex physicochemical 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, water content, bulk density, and temperature. Although the effect of soil static and dynamic factors on spatial variability of EC_a is of significant importance, understanding their influence on the temporal variability of EC_a is equally important. That is particularly true if delineated EC_a zones are to be used to manage agricultural inputs across the field for multiple years. 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 (i.e., water content) affect only the magnitude of measured EC_a (Johnson et al., 2003). This was clearly demonstrated by Farahani and Buchleiter (2004), who used multiyear measurements of EC_a from three irrigated and nonsaline sandy fields in eastern Colorado and quantified their degree of temporal change. For each field, soil EC_a values were highly correlated between measurement days (for periods of a few days to 4 years between measurements), but significant deviations from the 1:1 line (indicative of temporal variability) were exhibited. In spite of the temporal variability of the absolute magnitudes of EC_a, delineating spatial patterns of EC_a into low, medium, and high zones across each field was highly stable over time, mainly because they reflect the static soil properties. 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. For this reason, it is imperative that the soil properties dominating EC_a measurements within a field are established to be able to correctly interpret spatial EC_a survey data.

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 or properties influencing the EC_a measurement at that study site. Table 4.1 is a compilation of various laboratory and field studies and the associated dominant soil property or properties measured.

Many of the misinterpretations and misunderstandings regarding past field EC_a surveys have been due to a disregard for the complex and dynamic interrelationship and influence of various physical and chemical properties on EC_a, which are quantified in Equation (4.6) through Equation (4.11). Because EC_a does not measure an individual soil property such as salinity or water content, but rather is a product of the influence of several properties, geospatial EC_a surveys are best used to direct soil sampling in order to characterize the spatial variability of those properties that correlate with EC_a at a given study site (Corwin, 2005). Characterizing spatial variability with EC_a-directed soil sampling is based on the hypothesis that when EC_a correlates with a soil property or properties, then spatial EC_a information can be used to identify sites that reflect the range and variability of the property or properties. In instances where EC_a correlates with a particular soil property, an EC_a-directed soil sampling approach will establish the spatial distribution of that property with an optimum number of site locations to characterize the variability and keep labor costs minimal (Corwin et al., 2003a; Lesch, 2005). Also, if EC_a is correlated with crop yield, then an EC_a-directed soil sampling approach can be used to identify those soil properties that are causing the variability in crop yield (Corwin et al., 2003b).

4.3 GUIDELINES FOR CONDUCTING A FIELD-SCALE EC_a-DIRECTED SOIL SAMPLING SURVEY FOR AGRICULTURE

The basic steps of a field-scale EC_a survey for characterizing spatial variability include (1) EC_a survey design, (2) geo-referenced EC_a data collection, (3) soil sample design based on geo-referenced EC_a data, (4) soil sample collection, (5) physicochemical analysis of pertinent soil properties, (6) stochastic or deterministic calibration of EC_a to soil properties, (7) determination of the soil properties influencing the EC_a measurements at the study site, and (8) GIS development. Details on EC_a-directed soil sampling protocols are presented by Corwin and Lesch (2005b, 2005c). Outlined protocols are provided in Table 4.2. Of the eight basic steps, EC_a-directed soil sample design, stochastic or deterministic calibration of EC_a, and determination of the soil properties influencing the geospatial EC_a measurements are the least understood and yet are crucial for correctly understanding and interpreting spatial EC_a data. Ideally, efforts must be directed toward mapping EC_a when the soil property of interest is expected to have its greatest influence on EC_a values. This maximizes the likelihood of inferring the spatial patterns of the soil property of interest from the EC_a map. For instance, the effect of texture (or clay content) on EC_a is more pronounced at higher water contents (Dalgaard et al., 2001), suggesting EC_a field mapping when the soil is wet rather than dry.

4.3.1 EC_a-DIRECTED SOIL SAMPLE DESIGN

An EC_a survey of a field is most often conducted with either mobile ER or EMI equipment that has been coupled to a GPS. Depending on the level of detail desired, from 100 to several thousand spatial measurements of EC_a are taken generally in regularly spaced traverses across the field of interest. The use of mobile EMI equipment has one slight advantage over the use of mobile ER equipment due to the fact that EMI is noninvasive, which is the ability to take measurements on dry and stony soils.

Once a geo-referenced EC_a survey is conducted, the data are used to establish the locations of the soil core sample sites for (1) calibration of EC_a to a correlated soil sample property (e.g., salinity, water content, and clay content) and (2) delineation of the spatial distribution of soil properties correlated to EC_a within the field surveyed. Currently, two different sampling schemes are used to establish the locations where soil cores are to be taken: design-based and model-based sampling schemes. Design-based sampling schemes have historically been the most commonly used and, hence, are more familiar to most research scientists. Design-based methods include simple random sampling, stratified random sampling, multistage sampling, cluster sampling, and network sampling schemes. The use of unsupervised classification by Fraisse et al. (2001) and Johnson et al. (2001) is an example of design-based sampling. Model-based sampling schemes are less common. Specific model-based sampling approaches that have direct application to agricultural and environmental survey work are described by McBratney and Webster (1983), Russo (1984), and Lesch et al. (1995a, 1995b, 2005).

The sampling approach introduced by Lesch et al. (1995a, 1995b, 2005) is specifically designed for use with ground-based soil EC_a data. This sampling approach attempts to optimize the estimation of a regression model (i.e., minimize the mean square prediction error produced by the calibration function), while simultaneously insuring that the independent regression model residual error assumption remains approximately valid. This, in turn, allows an ordinary regression model to be used to predict soil property levels at all remaining (i.e., nonsampled) conductivity survey sites.

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

TABLE 4.2

Outline of Steps for an EC_a-Directed Soil Sampling Survey

1. Site description and EC_a survey design
    (a) Record site metadata
    (b) Establish site boundaries
    (c) Select Global Positioning System (GPS) coordinate system
    (d) Establish EC_a measurement intensity
2. EC_a data collection with mobile GPS-based equipment
    (a) Geo-reference site boundaries and significant physical geographic features with GPS
    (b) Measure geo-referenced EC_a data at the predetermined spatial intensity and record associated metadata
3. Soil sample design based on geo-referenced EC_a data
    (a) Statistically analyze EC_a data using an appropriate statistical sampling design to establish the soil sample site locations
    (b) Establish site locations, depth of sampling, sample depth increments, and number of cores per site
4. Soil core sampling at specified sites designated by the sample design
    (a) Obtain measurements of soil temperature through the profile at selected sites
    (b) At randomly selected locations obtain duplicate soil cores within a 1 m distance of one another to establish local-scale variation of soil properties
    (c) Record soil core observations (e.g., mottling, horizonation, textural discontinuities, etc.)
5. Laboratory analysis of appropriate soil physical and chemical properties defined by project objectives
6. If needed, stochastic or deterministic calibration of EC_a to EC_e or to other soil properties (e.g., water content and texture)
7. Spatial statistical analysis to determine the soil properties influencing EC_a and crop yield
    (a) Soil quality assessment:
        (1) Perform a basic statistical analysis of physical and chemical data by depth increment and by composite depth over the depth of measurement of EC_a
        (2) Determine the correlation between EC_a and physical and chemical soil properties by composite depth over the depth of measurement of EC_a
    (b) Site-specific crop management (if EC_a correlates with crop yield, then)
        (1) Perform a basic statistical analysis of physical and chemical data by depth increment and by composite depths
        (2) Determine the correlation between EC_a and physical and chemical soil properties by depth increment and by composite depths
        (3) Determine the correlation between crop yield and physical and chemical soil properties by depth and by composite depths to determine depth of concern (i.e., depth with consistently highest correlation, whether positive or negative, of soil properties to yield) and the significant soil properties influencing crop yield (or crop quality)
        (4) Conduct an exploratory graphical analysis to determine the relationship between the significant physical and chemical properties and crop yield (or crop quality)
        (5) Formulate a spatial linear regression (SLR) model that relates soil properties (independent variables) to crop yield or crop quality (dependent variable)
        (6) Adjust this model for spatial autocorrelation, if necessary, using Restricted Maximum Likelihood or some other technique
        (7) Conduct a sensitivity analysis to establish dominant soil property influencing yield or quality
8. Geographic information system (GIS) database development and graphic display of spatial distribution of soil properties

Source: Corwin, D.L., and Lesch, S.M., *Comp. Electron. Agric.*, 46, 103–133, 2005. With permission.

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. This approach explicitly optimizes this site selection process.

A user-friendly software package (ESAP) developed by Lesch et al. (2000), which uses a response-surface sampling design, has proven to be particularly effective in delineating spatial distributions of soil properties from EC_a survey data (Corwin and Lesch, 2003; Corwin et al., 2003a, 2003b, 2006). 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, six to twenty 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.

In a detailed study of the utility of EC_a mapping, Farahani and Buchleiter (2004) used two different soil sampling designs for comparison. Measured EC_a data from three center-pivot fields, two near the town of Wiggins and one near Yuma in eastern Colorado, were used to identify sample locations using ESAP and a combination of cluster analysis and random soil sampling within clusters. For the latter sampling design, three to five sample locations were randomly selected from each of five delineated EC_a zones (according to cluster analysis). For the sandy and nonsaline fields in eastern Colorado, both sampling methods effectively captured the spatial variability. The random sampling from within EC_a clusters was found to be simple and subsequently used in a number of dryland and irrigated fields to characterize EC_a delineated zones for the purposes of site-specific management.

4.3.2 CALIBRATION OF EC_a TO SOIL PROPERTIES

Apparent soil electrical conductivity can be calibrated to any soil property that significantly influences the EC_a measurement, such as salinity, θ_g, clay content, SP, ρ_b, and OM. As indicated in Table 4.1, there are numerous studies that document the relationships between soil electrical conductivity and various soil physical and chemical properties. All of the data analysis and interpretation presented in these papers can be classified into two data modeling categories: deterministic and stochastic.

In general, stochastic models are based on some form of objective sampling methodology used in conjunction with various statistical calibration techniques. The most common types of calibration equations are geostatistical models (generalized universal kriging models and cokriging models) and spatially referenced regression models.

Traditionally, universal kriging models have been viewed as an extension of the ordinary kriging technique and used primarily to account for large-scale (nonstationary) trends in spatial data. However, this modeling technique can be easily generalized to model ancillary survey data (such EMI or ER data) when this data correlates well with some spatially varying soil property of interest (e.g., soil salinity). This generalization is commonly referred to as a "spatial linear model" or "spatial random field model" in the statistical literature. This modeling approach requires the estimation of a regression equation with a spatially correlated error structure. This type of model probably represents the most versatile and accurate statistical calibration approach, provided enough calibration sample sites are collected ($n > 50$) to ensure a good estimate of the correlated error structure.

Regardless of their versatility, spatial linear models are typically used in regional situations. Such an approach is rarely used for field-scale survey work, due to the large number of required calibration soil samples, which makes this approach economically impractical. Instead, most calibration equations of soil properties are spatially referenced regression models. A spatially referenced regression model is just an ordinary regression equation that includes the soil property being calibrated with EC_a and trend surface parameters. The model assumes an independent error structure that can usually be achieved through carefully designed sampling plans, such as the response-surface sampling design. In practice, these are the only models that can be reasonably estimated with a limited number of soil samples ($n < 15$).

Deterministic conductivity data modeling and interpretation have been carried out either from a geophysical or a soil science approach. In the geophysical approach, mathematically sophisticated inversion algorithms are generally employed. These approaches, which rely heavily on geophysical theory, have met with limited success for the interpretation of near-surface EC_a data. Part of the reason for the lack of success is that most geophysical inversion approaches assume that (1) there are multiple conductivity signal readings available for each survey point and (2) that distinct, physical strata differences exist within the near-surface soil horizon. Neither of these conditions is typically satisfied in most EC_a surveys.

A more common technique, which is used in soil science, is to employ some form of deterministic conversion model (i.e., an equation that converts EC_a to a soil property based on knowledge of other soil properties). One model of this type that has been shown to be useful is the model developed by Rhoades et al. (1989, 1990; see Equation (4.6) through Equation (4.11)) and extended by Lesch and Corwin (2003). The model demonstrates that soil EC can be reduced to a nonlinear function of five soil properties: EC_e, SP, θ_g, ρ_b, and soil temperature. In Rhoades et al. (1990), the model was used to estimate field soil salinity levels based on EC_a survey data and measured or inferred information about the remaining soil physical properties. Corwin and Lesch (2003) and Lesch et al. (2000) showed that this model can also be used to assess the degree of influence that each of these soil properties has on the acquired EC_a-survey data.

4.3.3 DETERMINATION OF THE SOIL PROPERTIES INFLUENCING EC_a

In the past, the fact that EC_a is a function of several soil properties (i.e., soil salinity, texture, water content, etc.) has sometimes been overlooked in the application of EC_a measurements to agriculture. For instance, precision agriculture studies relating EC_a to crop yield have met with inconsistent results due to the fact that a combination of factors influence EC_a measurements to varying degrees across units of management, thereby confounding interpretation. In areas of saline soils, salinity dominates the EC_a measurements, and interpretations are often straightforward. However, in areas other than arid zone soils, texture and water content or even OM may be the dominant properties measured by EC_a. To use spatial measurements of EC_a in a soil quality or site-specific crop management context, it is necessary to understand what factors are most significantly influencing the EC_a measurements within the field of study. There are two commonly used approaches for determining the predominant factors influencing EC_a measurement: (1) wavelet analysis and (2) simple statistical correlation.

An explanation of the use of wavelet analysis for determining the soil properties influencing EC_a measurements is provided by Lark et al. (2003). Even though wavelet analysis is a powerful tool for determining the dominant complex interrelated factors influencing EC_a measurement, it requires soil sample data collected on a regular grid or equal-spaced transect. Grid or equal-spaced transect sampling schemes are not as practical for determining spatial distributions of soil salinity or other correlated soil properties from EC_a measurements as the statistical and graphical approach developed by Lesch et al. (1995a, 1995b, 2000).

The most practical means of interpreting and understanding the tremendous volume of spatial data from an EC_a survey is through statistical analysis and graphic display. For a soil quality assessment, a basic statistical analysis of all physical and chemical data by depth increment provides an understanding of the vertical profile distribution. A basic statistical analysis consists of the determination of the mean, minimum, maximum, range, standard deviation, standard error, coefficient of variation, and skewness for each depth increment (e.g., 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m) and by composite depth (e.g., 0 to 1.2 m) over the depth of measurement of EC_a. In the case of EC_a measured with ER, the composite depth over the depth of measurement of EC_a is based on the spacing between the electrodes, while in the case of EMI measurements of EC_a, the composite depth over the depth of measurement of EC_a is based on the spacing between the coils and the orientation of the coils (i.e., vertical or horizontal). The calculation of the correlation coefficient between EC_a and mean value of each soil property by depth increment and composite depth over multiple sample sites determines those soil properties that correlate best with EC_a and those soil properties that are spatially represented by the EC_a-directed sampling design. Those properties not correlated with EC_a are not spatially characterized with the EC_a-directed sampling design, indicating

TABLE 4.3

Correlation Coefficients (r) between Shallow (0 to 0.3 m) and Deep (0 to 0.9 m) EC$_a$ (mS m^{-1}) and Their Corresponding (Same Depth) Soil Properties at Three Colorado Fields

	Wiggins 1		Wiggins 2		Yuma	
Soil Property	**Shallow EC$_a$**	**Deep EC$_a$**	**Shallow EC$_a$**	**Deep EC$_a$**	**Shallow EC$_a$**	**Deep EC$_a$**
Sand (%)	–0.96	–0.95	–0.84	–0.90	–0.76	–0.90
Silt (%)	0.82	0.91	0.67	0.80	0.68	0.84
Clay (%)	0.96	0.94	0.89	0.94	0.82	0.93
Bulk density ((b, Mg m^{-3})	–0.13	–0.53	–0.34	–0.52	—	—
Organic matter (g g^{-1}%)	0.92	0.92	0.75	0.79	0.80	0.89
Ca^{+2} (meq L^{-1})	0.85	0.92	0.94	0.88	0.82	0.82
Mg^{+2} (meq L^{-1})	0.91	0.94	0.93	0.87	0.58	0.75
K^{+1} (meq L^{-1})	0.80	0.76	0.73	0.75	0.67	0.86
Na^{+1} (meq L^{-1})	0.65	0.87	0.62	0.79	0.58	0.26
CEC (meq 100 g^{-1})	0.86	0.93	0.94	0.88	0.87	0.87
pH	–0.81	–0.76	–0.48	–0.48	0.50	0.23
Soluble salts (EC$_{1:1}$, mS m^{-1})	0.86	0.95	0.24	0.66	0.86	0.78

a design-based sampling scheme such as stratified random sampling is probably needed to better spatially characterize these soil properties.

An example of a simple statistical approach to infer EC$_a$ versus soil properties relations is given by the correlation coefficients between EC$_a$ and soil properties by depth (the terms "shallow" and "deep" refer to soil depths of 0 to 0.3 m and 0 to 0.9 m, respectively) given in Table 4.3 (Farahani et al., 2005). As given, the EC$_a$ measurements from these sandy soils are very useful in inferring texture variability with correlation coefficient values between EC$_a$ and clay (or sand) well over 0.8.

Crop yield monitoring data in conjunction with EC$_a$ survey data can be used from a site-specific crop management perspective (1) to identify those soil properties influencing yield and (2) to delineate site-specific management units (SSMU). For site-specific crop management, an understanding of the influence of spatial variation in soil properties on within-field crop-yield (or crop quality) variation is crucial. To accomplish this using EC$_a$, crop yield (or crop quality) must correlate with EC$_a$ within a field. If crop yield (or crop quality) and EC$_a$ are correlated, then basic statistical analyses by depth increment (e.g., 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m) and by composite depths (e.g., 0 to 0.3, 0 to 0.6, 0 to 0.9, and 0 to 1.2 m) are performed. As before, the correlation between EC$_a$ and mean values of each physical and chemical soil property for each depth increment and each composite depth establishes those soil properties that are spatially characterized with the EC$_a$-directed sampling design. The correlations between crop yield (or crop quality) and soil properties will also establish the depth of concern (i.e., the root zone of the crop), which will be the composite depth that consistently has the highest correlation of each soil property (i.e., each soil property determined to be significant to influencing yield) with crop yield (or crop quality). Exploratory graphical analyses (i.e., scatter plots of crop yield or crop quality and each soil property) are then conducted for the depth of concern to determine the linear or curvilinear relationship between the significant physical and chemical properties and crop yield (or crop quality). A spatial linear regression is formulated that relates the significant soil properties as the independent variables to crop yield (or crop quality) as the dependent variable. The functional form of the model is developed from the exploratory graphic analysis. If necessary, the model is adjusted for spatial autocorrelation using restricted maximum likelihood or some other technique. This entire spatial statistical analysis process is clearly demonstrated by Corwin et al. (2003b) and Corwin and Lesch (2005c).

To use spatial measurements of EC_a in a site-specific crop management context, it is not only necessary to understand those soil-related factors that influence within-field variation in crop yield (or crop quality), but also to pinpoint the dominant soil-related factors influencing within-field crop variation. Corwin et al. (2003b) used sensitivity analysis simulations to arrive at the dominant edaphic and anthropogenic factors influencing within-field cotton yield variations. Sensitivity analysis involves increasing a single independent variable (i.e., edaphic factors) and observing the resultant effect on the dependent variable (i.e., crop yield or crop quality). This is done for each independent variable. The relative effect of each independent variable on the dependent variable determines the independent variable that most significantly influences the dependent variable.

4.3.4 CASE STUDIES

Table 4.4 is a compilation of correlation data for six field study sites where EC_a surveys using EMI were performed for the purpose of salinity appraisal. Table 4.4 shows the variation in the influence of various soil properties upon EC_a for different field locations. In all cases, the surveys were performed as outlined in Table 4.2. An intensive EC_a survey was performed, followed by soil core sample site selection where from six to twenty sites were selected for sampling. An analysis was performed on the soil cores for various physical and chemical properties (e.g., saturation percentage, salinity, and water content). The correlations in Table 4.2 were determined using the EC_a survey and soil sample data. The correlations in Table 4.2 indicate the soil properties influencing the EC_a reading most. Following is a discussion about the six EC_a surveys presented in Table 4.2.

4.3.4.1 Coachella Valley Wheat (*Triticum aestvum* L.) Field

This is an example of a survey where the salinity represented by ln (EC_e), the soil texture reflected by the saturation percentage (SP), and the volumetric water content (θ_w) correlate with the EMI data, which are represented as ln(EMI_{ave}), where EMI_{ave} is the geometric mean of the vertical and horizontal EMI readings (i.e., sqrt[$EMI_h \cdot EMI_v$]).

4.3.4.2 Coachella Valley Sorghum Field

This field is an example of where only salinity correlates well with the EMI data. Note from Table 4.5 that neither the soil texture nor volumetric water content correlate with salinity with $r = -0.10$ and $r = 0.28$, respectively. Because of this lack of correlation with salinity and because the texture and water content exhibit minimal sample variation (i.e., sample range for SP is 51.0 to 61.1 percent; sample range for θ_w is 0.33 to 0.41 $cm^3\ cm^{-3}$), they correlate poorly with the EMI data with $r = -0.20$ and $r = 0.25$, respectively (Table 4.2).

4.3.4.3 Broadview Water District (Quarter Sections 16-2 and 16-3)

These combined quarter sections display large variability in soil texture, as indicated by SPs ranging from 33.2 to 85 percent, and in water content (θ_w ranges from 0.21 to 0.39 $cm^3\ cm^{-3}$) with relatively minimal salinity variation (80 percent of the samples fell below the mean value of 3.65 dS m^{-1}). Salinity, SP, and water content correlate with the EMI data. Saturation percentage and water content are highly correlated with $r = 0.84$ and $r = 0.86$, respectively (Table 4.2).

4.3.4.4 Fresno Cotton (*Gossypium hirsutum* L.) Field

The Fresno cotton field is of particular interest because of the high positive correlation of EMI data with salinity ($r = 0.87$) and moderate positive correlation with SP ($r = 0.71$) but a negative correlation with water content ($r = -0.65$). The negative correlation between SP and water content (see Table 4.5; $r = -0.78$) suggests an unexpected inverse relationship between texture and water content.

TABLE 4.4

Means and Ranges of Soil Factors (EC$_e$, SP, and θ_w) and the Correlations of ln(EMI$_{ave}$) with ln(EC$_e$), SP, and θ_w for Six Field-Scale Surveys

	Soil Factors (EC$_e$, SP, and θ_w)		
Field	**Mean**	**Range**	**Correlation**[a]
Coachella Valley Wheat Field			
ln(EMI$_{ave}$) and ln(EC$_e$)	2.33	0.85–6.64	0.87
ln(EMI$_{ave}$) and SP	40.4	36.5–45.8	0.78
ln(EMI$_{ave}$) and θ_w	0.24	0.18–0.32	0.77
Coachella Valley Sorghum Field			
ln(EMI$_{ave}$) and ln(EC$_e$)	10.1	5.37–16.8	0.88
ln(EMI$_{ave}$) and SP	57.0	51.0–61.1	–0.20
ln(EMI$_{ave}$) and θ_w	0.38	0.33–0.41	0.25
Broadview Water District (Quarter Sections 16-2 and 16-3)			
ln(EMI$_{ave}$) and ln(EC$_e$)	3.65	1.61–8.19	0.62
ln(EMI$_{ave}$) and SP	50.3	33.2–85.0	0.84
ln(EMI$_{ave}$) and θ_w	0.31	0.21–0.39	0.86
Fresno Cotton Field			
ln(EMI$_{ave}$) and ln(EC$_e$)	5.42	1.28–9.57	0.87
ln(EMI$_{ave}$) and SP	79.4	59.3–103.0	0.71
ln(EMI$_{ave}$) and θ_w	0.28	0.22–0.33	–0.65
Coachella Valley—Kohl Ranch Field			
ln(EMI$_{ave}$) and ln(EC$_e$)	11.8	3.73–22.9	0.94
ln(EMI$_{ave}$) and SP	63.3	59.7–66.7	–0.33
ln(EMI$_{ave}$) and θ_w	0.33	0.30–0.36	0.76
ln(EMI$_{ave}$) and ln(SAR)	23.2	5.55–40.2	0.89
ln(EMI$_{ave}$) and ln(B)	1.44	0.52–2.57	0.91
Broadview Water District (Quarter Section 10-2)			
ln(EMI$_{ave}$) and ln(EC$_e$)	2.66	0.90–5.69	0.80
ln(EMI$_{ave}$) and SP	55.4	40.6–67.4	0.49
ln(EMI$_{ave}$) and θ_w	0.38	0.29–0.42	0.59
ln(EMI$_{ave}$) and ρ_b	1.35	1.26–1.44	–0.35
ln(EMI$_{ave}$) and sand	25.5	8.35–49.9	–0.38
ln(EMI$_{ave}$) and silt	39.3	26.3–51.6	0.42
ln(EMI$_{ave}$) and clay	35.3	23.8–44.5	0.29

Note: EM$_{ave}$ is the geometric mean (i.e., sqrt[EMI$_h$ · EMI$_v$]) of the EC$_a$ taken in the horizontal (EMI$_h$) and vertical (EMI$_v$) coil configurations using EMI, EC$_e$ is the electrical conductivity of the saturation paste (dS m^{-1}), SP is the saturation percentage, θ_w is the volumetric water content (cm^3 cm^{-3}), SAR is the sodium adsorption ratio, B is boron (mg kg^{-1}), ρ_b is the bulk density (g cm^{-3}), sand is the percent sand, silt is the percent silt, and clay is the percent clay.

[a] The correlation column corresponds to the correlation between the measured EC$_a$ and the specified soil property.

Source: Modified from Corwin, D.L., and Lesch, S.M., *Agron. J.*, 95, 455–471, 2003. With permission.

TABLE 4.5
Correlation Matrix of Soil Properties for the Six Field-Scale EC_a Surveys

Field	$\ln(EC_e)$	SP	θ_w
Coachella Valley Wheat Field			
$\ln(EC_e)$	1.00	0.69	0.66
SP		1.00	0.91
0_w			1.00
Coachella Valley Sorghum Field			
$\ln(EC_e)$	1.00	–0.10	0.28
SP		1.00	–0.47
0_w			1.00
Broadview Water District (Quarter Sections 16-2 and 16-3)			
$\ln(EC_e)$	1.00	0.23	0.33
SP		1.00	0.82
0_w			1.00
Fresno Cotton Field			
$\ln(EC_e)$	1.00	0.38	–0.37
SP		1.00	–0.78
0_w			1.00
Coachella Valley—Kohl Ranch Field			
$\ln(EC_e)$	1.00	–0.39	0.72
SP		1.00	–0.04
0_w			1.00
Broadview Water District (Quarter Section 10-2)			
$\ln(EC_e)$	1.00	0.08	0.14
SP		1.00	0.91
0_w		1.00	

Source: Modified from Corwin, D.L., and Lesch, S.M., Agron. J., 95, 455–471, 2003. With permission.

Note: ECe is the electrical conductivity of the saturation extract (dS m^{-1}), SP is the saturation percentage. θ_w is the volumetric water content ($cm^3\ cm^{-3}$).

4.3.4.5 Coachella Valley—Kohl Ranch Field

This field displays a range of correlations between EMI and soil properties (Table 4.2). Salinity correlates very well, water content fairly well, and soil texture exhibits weak negative correlation indicating that the dominant soil properties influencing the EMI reading are salinity and water content. In addition, two secondary properties, SAR and boron, were measured. The fact that these correlated quite well with the EMI data suggests the close association of these properties with salinity in this particular field because the EMI reading does not directly measure SAR or boron but is rather an artifact of solute flow.

4.3.4.6 Broadview Water District (Quarter Section 10-2)

The dominant soil property influencing the EMI reading is salinity, with a correlation between $\ln(EMI_{ave})$ and $\ln(EC_e)$ of 0.80. No strong correlation was found between EMI data and a variety of soil properties, including SP, water content, bulk density, and separates of sand, silt, and clay.

From Table 4.4 and Table 4.5, what is known about the interrelationship of soil properties influencing the EC_a measurement for agricultural soils in the arid southwest? First, it is clear that the inner-correlation structure of the various primary soil properties (EC_e, SP, θ_w) determines how well each property ultimately correlates with the EC_a signal data. However, the variability of each soil property also influences the final correlation estimates, because increased variability in any given soil property directly translates into increased variation in the EC_a data. Obviously, one may encounter many diverse types of inner-correlation structures and different degrees of specific soil property variation as shown in Table 4.4 and Table 4.5. Thus, the ultimate correlation between the EC_a signal data and any specific soil property may be quite different from field to field. For example, this effect is clearly evident in the $\ln(EMI_{ave})$ and SP correlation estimates shown in Table 4.4, where the observed estimates range from −0.33 to 0.84. Second, with respect to EC_e data, the best scenario for the prediction of salinity from EC_a signal data occurs when the EC_e, SP, and θ_w cross-correlation estimates are all positive and high (i.e., near 1), and the SP and θ_w variation is minimal.

4.4 CLOSING REMARKS

The need for a means of measuring within-field variation in soil salinity within the root zone in a quick, reliable, and cost-effective manner resulted in the development of GPS-based mobile ER and EMI techniques to measure and map EC_a. However, the measurement of EC_a is complicated by the influence of several soil properties aside from soil salinity, including soil texture, temperature, and water content. This has enabled geospatial measurements of EC_a to become a tool for directing soil sampling to characterize spatial variability of soil properties correlated with EC_a within a given field. When maps of EC_a are properly understood, they can be used to (1) provide a graphic inventory of the scope of the soil salinity problem, (2) provide useful spatial information concerning soil texture and water content, (3) identify potential areas in need of improved irrigation and drainage management, (4) identify areas in need of reclamation, (5) provide a means of monitoring management-induced spatiotemporal changes in soil properties that potentially influence crop production, or (6) provide a means to identify edaphic factors influencing within-field crop variation.

REFERENCES

Anderson-Cook, C.M., Alley, M.M., Roygard, J.K.F., Khosla, R., Noble, R.B., and Doolittle, J.A., Differentiating soil types using electromagnetic conductivity and crop yield maps, *Soil Sci. Soc. Am. J.*, 66, 1562–1570, 2002.

Banton, O., Seguin, M.K., and Cimon, M.A., Mapping field-scale physical properties of soil with electrical resistivity, *Soil Sci. Soc. Am. J.*, 61, 1010–1017, 1997.

Bennett, D.L., and George, R.J., Using the EM38 to measure the effect of soil salinity on *Eucalyptus globulus* in south-western Australia, *Agric. Water Manage.*, 27, 69–86, 1995.

Benson, A.K., Payne, K.L., and Stubben, M.A., Mapping groundwater contamination using DC resistivity and VLF geophysical methods—A case study, *Geophysics*, 62, 80–86, 1997.

Boettinger, J.L., Doolittle, J.A., West, N.E., Bork, E.W., and Schupp, E.W., Nondestructive assessment of rangeland soil depth to petrocalcic horizon using electromagnetic induction, *Arid Soil Res. Rehabil.*, 11, 372–390, 1997.

Bohn, H.L., McNeal, B.L., and O'Connor, G.A., *Soil Chemistry*, John Wiley & Sons, New York, 1979.

Bowling, S.D., Schulte, D.D., and Woldt, W.E., A geophysical and geostatistical methodology for evaluating potential subsurface contamination from feedlot runoff retention ponds, ASAE Paper No. 972087, 1997 ASAE Winter Meetings, December 1997, Chicago, IL, ASAE, St. Joseph, MI, 1997.

Brevik, E.C., and Fenton, T.E., The relative influence of soil water, clay, temperature, and carbonate minerals on soil electrical conductivity readings taken with an EM-38 along a Mollisol catena in central Iowa, *Soil Survey Horizons*, 43, 9–13, 2002.

Briggs, L.J., Electrical instruments for determining the moisture, temperature, and solute salt content of soils, *U.S. Dept. Agric. Bulletin 15*, 1899.

Brune, D.E., and Doolittle, J., Locating lagoon seepage with radar and electromagnetic survey, *Environ. Geol. Water Sci.*, 16, 195 and 207, 1990.

Brune, D.E., Drapcho, C.M., Radcliff, D.E., Harter, T., and Zhang, R., Electromagnetic survey to rapidly assess water quality in agricultural watersheds, ASAE Paper No. 992176, ASAE, St. Joseph, MI, 1999.

Brus, D.J., Knotters, M., van Dooremolen, W.A., van Kernebeek, P., and van Seeters, R.J.M., The use of electromagnetic measurements of apparent soil electrical conductivity to predict the boulder clay depth, *Geoderma*, 55, 79–93, 1992.

Cameron, D.R., de Jong, E., Read, D.W.L., and Oosterveld, M., Mapping salinity using resistivity and electromagnetic inductive techniques, *Can. J. Soil Sci.*, 61, 67–78, 1981.

Cannon, M.E., McKenzie, R.C., and Lachapelle, G., Soil-salinity mapping with electromagnetic induction and satellite-based navigation methods, *Can. J. Soil Sci.*, 74, 335–343, 1994.

Cook, P.G., and Kilty, S., A helicopter-borne electromagnetic survey to delineate groundwater recharge rates, *Water Resour. Res.*, 28, 2953–2961, 1992.

Cook, P.G., Walker, G.R., Buselli, G., Potts, I., and Dodds, A.R., The application of electromagnetic techniques to groundwater recharge investigations, *J. Hydrol.*, 130, 201–229, 1992.

Corwin, D.L., Geospatial measurements of apparent soil electrical conductivity for characterizing soil spatial variability, in *Soil-Water-Solute Characterization: An Integrated Approach*, Álvarez-Benedí, J., and Muñoz-Carpena, R., Eds., CRC Press, Boca Raton, FL, pp. 639–672, 2005.

Corwin, D.L., and Lesch, S.M., Application of soil electrical conductivity to precision agriculture: Theory, principles, and guidelines, *Agron. J.*, 95, 455–471, 2003.

Corwin, D.L., and Lesch, S.M., Apparent soil electrical conductivity measurements in agriculture, *Comput. Electron. Agric.*, 46, 11–43, 2005a.

Corwin, D.L., and Lesch, S.M., Characterizing soil spatial variability with apparent soil electrical conductivity: I. Survey protocols, *Comp. Electron. Agric.*, 46, 103–133, 2005b.

Corwin, D.L., and Lesch, S.M., Characterizing soil spatial variability with apparent soil electrical conductivity: II. Case study. *Comp. Electron. Agric.*, 46, 135–152, 2005c.

Corwin, D.L., and Rhoades, J.D., An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements, *Soil Sci. Soc. Am. J.*, 46, 517–520, 1982.

Corwin, D.L., and Rhoades, J.D., Measurement of inverted electrical conductivity profiles using electromagnetic induction, *Soil Sci. Soc. Am. J.*, 48, 288–291, 1984.

Corwin, D.L., and Rhoades, J.D., Establishing soil electrical conductivity-depth relations from electromagnetic induction measurements, *Commun. Soil Sci. Plant Anal.*, 21, 861–901, 1990.

Corwin, D.L., Carrillo, M.L.K., Vaughan, P.J., Rhoades, J.D., and Cone, D.G., Evaluation of GIS-linked model of salt loading to groundwater. *J. Environ. Qual.*, 28, 471–480, 1999.

Corwin, D.L., Kaffka, S.R., Hopmans, J.W., Mori, Y., Lesch, S.M., and Oster, J.D., Assessment and field-scale mapping of soil quality properties of a saline-sodic soil, *Geoderma*, 114, 231–259, 2003a.

Corwin, D.L., Lesch, S.M., Oster, J.D., and Kaffka, S.R., Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity, *Geoderma*, 131, 369–387, 2006.

Corwin, D.L., Lesch, S.M., Shouse, P.J., Soppe, R., and Ayars, J.E., Delineating site-specific management units using geospatial EC$_a$ measurements, in *Handbook of Agricultural Geophysics*, Allred, B., Daniels, J., and Ehsani, R., Eds., CRC Press, Boca Raton, FL, 2008.

Corwin, D.L., Lesch, S.M., Shouse, P.J., Soppe, R., and Ayars, J.E., Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity, *Agron. J.*, 95, 352–364, 2003b.

Corwin, D.L., Rhoades, J.D., and Vaughan, P.J., GIS applications to the basin-scale assessment of soil salinity and salt loading to groundwater, in *Applications of GIS to the Modeling of Non-Point Source Pollutants in the Vadose Zone*, Corwin, D.L., and Loague, K., Eds., SSSA Spec. Publ. 48, SSSA, Madison, WI, pp. 295–313, 1996.

Dalgaard, M., Have, H., and Nehmdahl, H., Soil clay mapping by measurement of electromagnetic conductivity, in *Third European Conference on Precision Agriculture,* Vol. 1, Agro Montpellier, Montpellier, France, pp. 349–354, 2001.

de Jong, E., Ballantyne, A.K., Caneron, D.R., and Read, D.W., Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys, *Soil Sci. Soc. Am. J.*, 43, 810–812, 1979.

Diaz, L., and Herrero, J., Salinity estimates in irrigated soils using electromagnetic induction, *Soil Sci.*, 154, 151–157, 1992.

Doolittle, J.A., Indorante, S.J., Potter, D.K., Hefner, S.G., and McCauley, W.M., Comparing three geophysical tools for locating sand blows in alluvial soils of southeast Missouri, *J. Soil Water Conserv.*, 57, 175–182, 2002.

Doolittle, J.A., Sudduth, K.A., Kitchen, N.R., and Indorante, S.J., Estimating depths to claypans using electromagnetic induction methods, *J. Soil Water Conserv.*, 49, 572–575, 1994.

Drommerhausen, D.J., Radcliffe, D.E., Brune, D.E., and Gunter, H.D., Electromagnetic conductivity surveys of dairies for groundwater nitrate, *J. Environ. Qual.*, 24, 1083–1091, 1995.

Eigenberg, R.A., Doran, J.W., Nienaber, J.A., Ferguson, R.B., and Woodbury, B.L., Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop, *Agric. Ecosyst. Environ.*, 88, 183–193, 2002.

Eigenberg, R.A., Korthals, R.L., and Neinaber, J.A., Geophysical electromagnetic survey methods applied to agricultural waste sites, *J. Environ. Qual.*, 27, 215–219, 1998.

Eigenberg, R.A., and Nienaber, J.A., Electromagnetic survey of cornfield with repeated manure applications, *J. Environ. Qual.*, 27, 1511–1515, 1998.

Eigenberg, R.A., and Nienaber, J.A., Soil conductivity map differences for monitoring temporal changes in an agronomic field, ASAE Paper No. 992176, ASAE, St. Joseph, MI, 1999.

Eigenberg, R.A., and Nienaber, J.A., Identification of nutrient distribution at abandoned livestock manure handling site using electromagnetic induction, ASAE Paper No. 012193, 2001 ASAE Annual International Meeting, 30 July–1 August 2001, Sacramento, CA, ASAE St. Joseph, MI, 2001.

Ellsbury, M.M., Woodson, W.D., Malo, D.D., Clay, D.E., Carlson, C.G., and Clay, S.A., Spatial variability in corn rootworm distribution in relation to spatially variable soil factors and crop condition, in *Proc. 4th International Conference on Precision Agriculture*, Robert, P.C., Rust, R.H., and Larson, W.E., Eds., St. Paul, MN, 19–22 July 1998, ASA-CSSA-SSSA, Madison, WI, pp. 523–533, 1999.

Farahani, H.J., and Buchleiter, G.W., Temporal stability of soil electrical conductivity in irrigated sandy fields in Colorado, *Trans. ASAE,* 47, 79–90, 2004.

Farahani, H.J., Buchleiter, G.W., and Brodahl, M.K., Characterization of soil electrical conductivity variability in irrigated sandy and non-saline fields in Colorado, *Trans. ASAE*, 48, 155–168, 2005.

Fenton, T.E., and Lauterbach, M.A., Soil map unit composition and scale of mapping related to interpretations for precision soil and crop management in Iowa, in *Proc. 4th International Conference on Precision Agriculture*, Robert, P.C., Rust, R.H., and Larson, W.E., Eds., St. Paul, MN, 19–22 July 1998, ASA-CSSA-SSSA, Madison, WI, pp. 239–251, 1999.

Fitterman, D.V., and Stewart, M.T., Transient electromagnetic sounding for groundwater, *Geophysics,* 51, 995–1005, 1986.

Fraisse, C.W., Sudduth, K.A., and Kitchen, N.R., Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity, *Trans. ASAE*, 44, 155–166, 2001.

Freeland, R.S., Branson, J.L., Ammons, J.T., and Leonard, L.L., Surveying perched water on anthropogenic soils using non-intrusive imagery, *Trans. ASAE*, 44, 1955–1963, 2001.

Gardner, F.D., The electrical method of moisture determination in soils: Results and modifications in 1897, U.S. Dept. Agric. Bulletin 12, 1898.

Gorucu, S., Khalilian, A., Han, Y.J., Dodd, R.B., Wolak, F.J., and Keskin, M., Variable depth tillage based on geo-referenced soil compaction data in coastal plain region of South Carolina, ASAE Paper No. 011016, 2001 ASAE Annual International Meeting, 30 July–1 Aug. 2001, Sacramento, CA, ASAE St. Joseph, MI, 2001.

Greenhouse, J.P., and Slaine, D.D., The use of reconnaissance electromagnetic methods to map contaminant migration, *Ground Water Monit. Rev.*, 3, 47–59, 1983.

Greenhouse, J.P., and Slaine, D.D., Geophysical modelling and mapping of contaminated groundwater around three waste disposal sites in southern Ontario, *Can. Geotech. J.*, 23, 372–384, 1986.

Halvorson, A.D., and Rhoades, J.D., Field mapping soil conductivity to delineate dryland seeps with four-electrode techniques, *Soil Sci. Soc. Am. J.*, 44, 571–575, 1976.

Hanson, B.R., and Kaita, K., Response of electromagnetic conductivity meter to soil salinity and soil-water content, *J. Irrig. Drain. Eng.*, 123, 141–143, 1997.

Heimovaara, T.J., Focke, A.G., Bouten, W., and Verstraten, J.M., Assessing temporal variations in soil water composition with time domain reflectometry, *Soil Sci. Soc. Am. J.*, 59, 689–698, 1995.

Hendrickx, J.M.H., Baerends, B., Raza, Z.I., Sadig, M., and Chaudhry, M.A., Soil salinity assessment by electromagnetic induction of irrigated land, *Soil Sci. Soc. Am. J.*, 56, 1933–1941, 1992.

Herrero, J., Ba, A.A., and Aragues, R., Soil salinity and its distribution determined by soil sampling and electromagnetic techniques, *Soil Use Manage.*, 19, 119–126, 2003.

Inman, D.J., Freeland, R.S., Yoder, R.E., Ammons, J.T., and Leonard, L.L., Evaluating GPR and EMI for morphological studies of loessial soils, *Soil Sci.*, 166, 622–630, 2001.

Jaynes, D.B., Mapping the areal distribution of soil parameters with geophysical techniques, in *Applications of GIS to the Modeling of Non-Point Source Pollutants in the Vadose Zone*, Corwin, D.L., and Loague, K., Eds., SSSA Special Publication No. 48, SSSA, Madison, WI, pp.205–216, 1996.

Jaynes, D.B., Colvin, T.S., and Ambuel, J., Soil type and crop yield: Determinations from ground conductivity surveys, ASAE Paper No. 933552, 1993 ASAE Winter Meetings, 14–17 December 1993, Chicago, IL, ASAE, St. Joseph, MI, 1993.

Jaynes, D.B., Colvin, T.S., and Kaspar, T.C., Identifying potential soybean management zones from multi-year yield data, *Comput. Electron. Agric.*, 46, 309–327, 2005.

Jaynes, D.B., Kaspar, T.C., Colvin, T.S., and James, D.E., Cluster analysis of spatiotemporal corn yield patterns in an Iowa field, *Agron. J.*, 95, 574–586, 2003.

Jaynes, D.B., Novak, J.M., Moorman, T.B., and Cambardella, C.A., Estimating herbicide partition coefficients from electromagnetic induction measurements, *J. Environ. Qual.*, 24, 36–41, 1995.

Johnson, C.K., Doran, J.W., Duke, H.R., Weinhold, B.J., Eskridge, K.M., and Shanahan, J.F., Field-scale electrical conductivity mapping for delineating soil condition, *Soil Sci. Soc. Am. J.*, 65, 1829–1837, 2001.

Johnson, C.K., Doran, J.W., Eghball, B., Eigenberg, R.A., Wienhold, B.J., and Woodbury, B.L, Status of soil electrical conductivity studies by central state researchers, ASAE Paper No. 032339, 2003 ASAE Annual International Meeting, 27–30 July 2003, Las Vegas, NV, ASAE, St. Joseph, MI, 2003.

Johnston, M.A., Savage, M.J., Moolman, J.H., and du Pleiss, H.M., Evaluation of calibration methods for interpreting soil salinity from electromagnetic induction measurements, *Soil Sci. Soc. Am. J.*, 61, 1627–1633, 1997.

Kachanoski, R.G., de Jong, E., and Van-Wesenbeeck, I.J., Field scale patterns of soil water storage from noncontacting measurements of bulk electrical conductivity, *Can. J. Soil Sci.*, 70, 537–541, 1990.

Kachanoski, R.G., Gregorich, E.G., and Van-Wesenbeeck, I.J., Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods, *Can. J. Soil Sci.*, 68, 715–722, 1988.

Kaffka, S.R., Lesch, S.M., Bali, K.M., and Corwin, D.L., Relationship of electromagnetic induction measurements, soil properties, and sugar beet yield in salt-affected fields for site-specific management, *Comput. Electron. Agric.*, 46, 329–350, 2005.

Kean, W.F., Jennings Walker, M., and Layson, H.R., Monitoring moisture migration in the vadose zone with resistivity, *Ground Water*, 25, 562–571, 1987.

Khakural, B.R., Robert, P.C., and Hugins, D.R., Use of non-contacting electromagnetic inductive method for estimating soil moisture across a landscape, *Commun. Soil Sci. Plant Anal.*, 29, 2055–2065, 1998.

Kitchen, N.R., Sudduth, K.A., and Drummond, S.T., Mapping of sand deposition from 1993 Midwest floods with electromagnetic induction measurements, *J. Soil Water Conserv.*, 51, 336–340, 1996.

Kitchen, N.R., Sudduth, K.A., Myers, D.B., Drummond, S.T., and Hong, S.Y., Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity, *Comput. Electron. Agric.*, 46, 285–308, 2005.

Kravchenko, A.N., Bollero, G.A., Omonode, R.A., and Bullock, D.G., Quantitative mapping of soil drainage classes using topographical data and soil electrical conductivity, *Soil Sci. Soc. Am. J.*, 66, 235–243, 2002.

Lark, R.M., Kaffka, S.R., and Corwin, D.L., Multiresolution analysis of data of electrical conductivity of soil using wavelets, *J. Hydrol.*, 272, 276–290, 2003.

Lesch, S.M., Sensor-directed spatial response surface sampling designs for characterizing spatial variation in soil properties, *Comp. Electron. Agric.*, 46, 153–179, 2005.

Lesch, S.M., and Corwin, D.L., Using the dual-pathway parallel conductance model to determine how different soil properties influence conductivity survey data, *Agron. J.*, 95, 365–379, 2003.

Lesch, S.M., Corwin, D.L., and Robinson, D.A., Apparent soil electrical conductivity mapping as an agricultural management tool in arid zone soils, *Comput. Electron. Agric.*, 46, 351–378, 2005.

Lesch, S.M., Herrero, J., and Rhoades, J.D., Monitoring for temporal changes in soil salinity using electromagnetic induction techniques, *Soil Sci. Soc. Am. J.*, 62, 232–242, 1998.

Lesch, S.M., Rhoades, J.D., Lund, L.J., and Corwin, D.L., Mapping soil salinity using calibrated electromagnetic measurements, *Soil Sci. Soc. Am. J.*, 56, 540–548, 1992.

Lesch, S.M., Rhoades, J.D., and Corwin, D.L., ESAP-95 Version 2.10R: User manual and tutorial guide, *Research Rpt. 146*, USDA-ARS George E. Brown, Jr. Salinity Laboratory, Riverside, CA, 2000.

Lesch, S.M., Strauss, D.J., and Rhoades, J.D., Spatial prediction of soil salinity using electromagnetic induction techniques: 1. Statistical prediction models: A comparison of multiple linear regression and cokriging, *Water Resour. Res.*, 31, 373–386, 1995a.

Lesch, S.M., Strauss, D.J., and Rhoades, J.D., Spatial prediction of soil salinity using electromagnetic induction techniques: 2. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation, *Water Resour. Res.*, 31, 387–398, 1995b.

Lund, E.D., Christy, C.D., and Drummond, P.E., Using yield and soil electrical conductivity (ECa) maps to derive crop production performance information, in *Proceedings of the 5th International Conference on Precision Agriculture* (CD-ROM), Roberts, P.C., Rust, R.H., and Larson, W.E., Eds., Minneapolis, MN 16–19 July 2000, ASA-CSSA-SSSA, Madison, WI, 2000.

Mallants, D., Vanclooster, M., Toride, N., Vanderborght, J., van Genuchten, M.Th., and Feyen, J., Comparison of three methods to calibrate TDR for monitoring solute movement in undisturbed soil, *Soil Sci. Soc. Am. J.*, 60, 747–754, 1996.

Mankin, K.R., Ewing, K.L., Schrock, M.D., and Kluitenberg, G.J., Field measurement and mapping of soil salinity in saline seeps, ASAE Paper No. 973145, 1997 ASAE Winter Meetings, December 1997, Chicago, IL, ASAE, St. Joseph, MI, 1997.

Mankin, K.R., and Karthikeyan, R., Field assessment of saline seep remediation using electromagnetic induction, *Trans. ASAE*, 45, 99–107, 2002.

Marion, G.M., and Babcock, K.L., Predicting specific conductance and salt concentration in dilute aqueous solutions, *Soil Sci.*, 122, 181–187, 1976.

McBratney, A.B., and Webster, R., Optimal interpolation and isarithmic mapping of soil properties V. Coregionalization and multiple sampling strategy, *J. Soil Sci.*, 34, 137–162, 1983.

McBride, R.A., Gordon, A.M., and Shrive, S.C., Estimating forest soil quality from terrain measurements of apparent electrical conductivity, *Soil Sci. Soc. Am. J.*, 54, 290–293, 1990.

McNeill, J.D., Electrical conductivity of soils and rocks, Technical Note TN-5, Geonics Ltd., Mississauga, Ontario, Canada, 1980.

Morgan, C.L.S., Norman, J.M., Wolkowski, R.P., Lowery, B., Morgan, G.D., and Schuler, R., Two approaches to mapping plant available water: EM-38 measurements and inverse yield modeling, in *Proceedings of the 5th International Conference on Precision Agriculture* (CD-ROM), Roberts, P.C., Rust, R.H., and Larson, W.E., Eds., Minneapolis, MN 16–19 July 2000, ASA-CSSA-SSSA, Madison, WI, p. 14, 2000.

Nettleton, W.D., Bushue, L., Doolittle, J.A., Wndres, T.J., Indorante, S.J., Sodium affected soil identification in south-central Illinois by electromagnetic induction, *Soil Sci. Soc. Am. J.*, 58, 1190–1193, 1994.

Nobes, D.C., Armstrong, M.J., and Close, M.E., Delineation of a landfill leachate plume and flow channels in coastal sands near Christchurch, New Zealand, using a shallow electromagnetic survey method, *Hydrogeol. J.*, 8, 328–336, 2000.

Nyquist, J.E., and Blair, M.S., Geophysical tracking and data logging system: Description and case history, *Geophysics* 56, 1114–1121, 1991.

Paine, J.G., Determining salinization extent, identifying salinity sources, and estimating chloride mass using surface, borehole, an airborne electromagnetic induction methods, *Water Resour. Res.*, 39, 1059, 2003.

Ranjan, R.S., Karthigesu, T., and Bulley, N.R., Evaluation of an electromagnetic method for detecting lateral seepage around manure storage lagoons, ASAE Paper No. 952440, ASAE, St. Joseph, MI, 1995.

Reece, C.F., Simple method for determining cable length resistance in time domain reflectometry systems, *Soil Sci. Soc. Am. J.*, 62, 314–317, 1998.

Rhoades, J.D., Instrumental field methods of salinity appraisal, in *Advances in Measurement of Soil Physical Properties: Bring Theory into Practice*, Topp, G.C., Reynolds, W.D., and Green, R.E., Eds., SSSA Special Publication No. 30. Soil Science Society of America, Madison, WI, pp. 231–248, 1992.

Rhoades, J.D., Electrical conductivity methods for measuring and mapping soil salinity, in *Advances in Agronomy*, Sparks, D.L., Ed., vol. 49, Academic Press, San Diego, CA, pp. 201–251, 1993.

Rhoades, J.D., and Corwin, D.L., Determining soil electrical conductivity–depth relations using an inductive electromagnetic soil conductivity meter, *Soil Sci. Soc. Am. J.*, 45, 255–260, 1981.

Rhoades, J.D., and Corwin, D.L., Soil electrical conductivity: Effects of soil properties and application to soil salinity appraisal, *Commun. Soil Sci. Plant Anal.*, 21, 837–860, 1990.

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.

Rhoades, J.D., and Ingvalson, R.D., Determining salinity in field soils with soil resistance measurements, *Soil Sci. Soc. Amer. Proc.*, 35, 54–60, 1971.

Rhoades, J.D., Chanduvi, F., and Lesch, S., Soil salinity assessment: Methods and interpretation of electrical conductivity measurements, *FAO Irrigation and Drainage Paper #57*, Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 1–150, 1999a.

Rhoades, J.D., Corwin, D.L., and Lesch, S.M., Geospatial measurements of soil electrical conductivity to assess soil salinity and diffuse salt loading from irrigation, in *Assessment of Non-Point Source Pollution in the Vadose Zone*, Corwin, D.L., Loague, K., and Ellsworth, T.R., Eds., Geophysical Monograph 108, American Geophysical Union, Washington, D.C., pp. 197–215, 1999b.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., and Alves, W.J., Soil electrical conductivity and soil salinity: New formulations and calibrations, *Soil Sci. Soc. Am. J.*, 53, 433–439, 1989.

Rhoades, J.D., Raats, P.A.C., and Prather, R.J., Effects of liquid-phase electrical conductivity, water content and surface conductivity on bulk soil electrical conductivity, *Soil Sci. Soc. Am. J.*, 40, 651–655, 1976.

Rhoades, J.D., Shouse, P.J., Alves, W.J., Manteghi, N.M., and Lesch, S.M., Determining soil salinity from soil electrical conductivity using different models and estimates, *Soil Sci. Soc. Am. J.*, 54, 46–54, 1990.

Russo, D., Design of an optimal sampling network for estimating the variogram, *Soil Sci. Soc. Am. J.*, 48, 708–716, 1984.

Salama, R.B., Bartle, G., Farrington, P., and Wilson, V., Basin geomorphological controls on the mechanism of recharge and discharge and its effect on salt storage and mobilization: Comparative study using geophysical surveys, *J. Hydrol.*, 155 (1 / 2), 1–26, 1994.

Sauer, Jr., M.C., Southwick, P.F., Spiegler, K.S., and Wyllie, M.R.J., Electrical conductance of porous plugs: Ion exchange resin-solution systems, *Ind. Eng. Chem*, 47, 2187–2193, 1955.

Scanlon, B.R., Paine, J.G., and Goldsmith, R.S., Evaluation of electromagnetic induction as a reconnaissance technique to characterize unsaturated flow in an arid setting, *Ground Water*, 37, 296–304, 1999.

Shainberg, J., Rhoades, J.D., and Prather, R.J., Effect of exchangeable sodium percentage, cation exchange capacity, and soil solution concentration on soil electrical conductivity, *Soil Sci. Soc. Am. J.*, 44, 469–473, 1980.

Sheets, K.R., and Hendrickx, J.M.H., Non-invasive soil water content measurement using electromagnetic induction, *Water Resour. Res.*, 31, 2401–2409, 1995.

Slavich, P.G., and Petterson, G.H., Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements, *Aust. J. Soil Res.*, 28, 453–463, 1990.

Slavich, P.G., and Yang, J., Estimation of field-scale leaching rates from chloride mass balance and electromagnetic induction measurements, *Irrig. Sci.*, 11, 7–14, 1990.

Spaans, E.J.A., and Baker, J.M., 1993. Simple baluns in parallel probes for time domain reflectometry, *Soil Sci. Soc. Am. J.*, 57, 668–673, 1993.

Stogryn, A., Equations for calculating the dielectric constant of saline water, *IEEE Trans. Microwave Theory Technol. MIT* 19, 733–736, 1971.

Stroh, J.C., Archer, S.R., Doolittle, J.A., and Wilding, L.P., Detection of edaphic discontinuities with ground-penetrating radar and electromagnetic induction, *Landscape Ecology*, 16, 377–390, 2001.

Stroh, J.C., Archer, S.R., Wilding, L.P., and Doolittle, J.A., Assessing the influence of subsoil heterogeneity on vegetation in the Rio Grande Plains of south Texas using electromagnetic induction and geographical information system, College Station, Texas, *The Station*, March 1993, 39–42, 1993.

Sudduth, K.A., and Kitchen, N.R., Electromagnetic induction sensing of claypan depth, ASAE Paper No. 931531, 1993 ASAE Winter Meetings, 12–17 Dec. 1993, Chicago, IL. ASAE, St, Joseph, MI, 1993.

Sudduth, K.A., Kitchen, N.R., Bollero, G.A., Bullock, D.G., and Wiebold, W.J., Comparison of electromagnetic induction and direct sensing of soil electrical conductivity, *Agron. J.*, 95, 472–482, 2003.

Sudduth, K.A., Kitchen, N.R., Hughes, D.F., and Drummond, S.T., Electromagnetic induction sensing as an indicator of productivity on claypan soils, in *Proc. Second International Conference on Site-Specific Management of Agricultural Systems*, Robert, P.C., Rust, R.H., and Larson, W.E., Eds., Minneapolis, MN, 27–30 Mar. 1994, ASA-CSSA-SSSA, Madison, WI, pp. 671–681, 1995.

Sudduth, K.A., Kitchen, N.R., Wiebold, W.J., Batchelor, W.D., Bollero, G.A., Bullock, D.G., Clay, D.E., Palm, H.L., Pierce, F.J., Schuler, R.T., and Thelen, K.D., Relating apparent electrical conductivity to soil properties across the north-central USA, *Comput. Electron. Agric.*, 46, 263–283, 2005.

Triantafilis, J., and Lesch, S.M., Mapping clay content variation using electromagnetic induction techniques, *Comput. Electron. Agric.*, 46, 203–237, 2005.

Triantafilis, J., Ahmed, M.F., and Odeh, I.O.A., Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinization in an irrigated cotton-growing field, *Soil Use Manage.*, 18, 330–339, 2002.

Triantafilis, J., Huckel, A.I., and Odeh, I.O.A., Comparison of statistical prediction methods for estimating field-scale clay content using different combinations of ancillary variables, *Soil Sci.*, 166, 415–427, 2001.

U.S. Salinity Laboratory Staff, Diagnosis and improvement of saline and alkali soils, *USDA Handbook 60*, U.S. Government Printing Office, Washington, DC, pp. 1–160, 1954.

van der Lelij, A., Use of an electromagnetic induction instrument (type EM38) for mapping of soil salinity, Internal Report Research Branch, Water Resources Commission, NSW, Australia, 1983.

Vaughan, P.J., Lesch, S.M., Corwin, D.L., and Cone, D.G., Water content on soil salinity prediction: A geostatistical study using cokriging, *Soil Sci. Soc. Am. J.*, 59, 1146–1156, 1995.

Wenner, F., A method of measuring earth resistivity, in scientific papers of the U.S. Bureau of Standards, No. 258, pp. 469–78, 1915.

Whitney, M., Gardner, F.D., and Briggs, L.J., An electrical method of determining the moisture content of arable soils, *U.S. Dept. Agric., Division of Soils, Bulletin 6*, 5–26, 1897.

Williams, B.G., and Baker, G.C., An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards, *Aust. J. Soil Res.*, 20, 107–118, 1982.

Williams, B.G., and Hoey, D., The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils, *Aust. J. Soil Res.*, 25, 21–27, 1987.

Wilson, R.C., Freeland, R.S., Wilkerson, J.B., and Yoder, R.E., Imaging the lateral migration of subsurface moisture using electromagnetic induction, ASAE Paper No. 023070, 2002 ASAE Annual International Meeting, 28–31 July 2002, Chicago, IL, ASAE, St. Joseph, MI, 2002.

Wollenhaupt, N.C., Richardson, J.L., Foss, J.E., and Doll, E.C., A rapid method for estimating weighted soil salinity from apparent soil electrical conductivity measured with an aboveground electromagnetic induction meter, *Can. J. Soil Sci.* 66, 315–321, 1986.

Wraith, J.M., and Or, D., Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development, *Water Resour. Res.*, 35, 361–369, 1999.

Zalasiewicz, J.A., Mathers, S.J., and Cornwell, J.D., The application of ground conductivity measurements to geological mapping, *Quaternary J.f Eng. Geol. London*, 18, 139–148, 1985.