Corwin, D.L., Lesch, S.M. and D.B. Lobell. 2012. Laboratory and field measurements.
In: W.W. Wallender and K.K. Tanji (eds.) ASCE Manual and Reports on Engineering Practice No. 71 Agricultural Salinity Assessment and Management (2nd Edition). ASCE, Reston, VA. Chapter 10 pp:295-341.

CHAPTER 10

LABORATORY AND FIELD MEASUREMENTS

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INTRODUCTION

Soil salinity refers to the presence of major dissolved inorganic solutes in the soil solution (i.e., aqueous liquid phase of the soil and its solutes), which consist of soluble and readily dissolvable salts, including charged species (e.g., Na^+, K^+, Mg^{+2}, Ca^{+2}, Cl^-, HCO_3^-, NO_3^-, SO_4^{-2} and CO_3^{-2}), non-ionic solutes, and ions that combine to form ion pairs. The primary source of salts in soil and water is the geochemical weathering of rocks from the earth's upper strata, with atmospheric deposition and anthropogenic activities serving as secondary sources. The predominant mechanism causing the accumulation of salt in the rootzone of agricultural soils is loss of water through evapotranspiration (ET; the combined processes of evaporation from the soil surface and plant transpiration), which selectively removes water, leaving salts behind.

The accumulation of soil salinity can result in reduced plant growth, reduced yields, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential, making it more difficult for the plant to extract water. Salinity may also cause specific-ion toxicity (e.g., Na^+ ion toxicity) or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth.

Irrigated agriculture, which accounts for 35% to 40% of the world's total food and fiber, is adversely affected by soil salinity on roughly half of all irrigated soils (totaling about 250 million ha), with more than 20 million ha severely affected by salinity worldwide (Rhoades and Loveday 1990). Because of the potential detrimental impacts of soil salinity accumulation, it is a crucial soil chemical property that is routinely measured and monitored. This chapter describes common field and laboratory techniques for measuring salinity in the soil and water, with discussion of their practicability and reliability.

FACTORS AFFECTING SOIL SALINITY

The accumulation of soil salinity is a consequence of a variety of processes, some of which are illustrated in Fig. 10-1. In arid and semiarid areas, for example, where precipitation is less than evaporation, salts can accumulate at the soil surface when the depth to the water table is less than 1 to 1.5 m, depending on the soil texture. The accumulation of salts at the soil surface is the consequence of the upward flow of water and subsequent transport of salts due to capillary rise driven by the evaporative process. However, the most common cause for the accumulation of salts is ET by plants, which results in an increase in salt concentration with depth through the rootzone (see graph in Fig. 10-1) and the accumulation of salts below the rootzone. The level of salt accumulation within and below the rootzone due to ET depends on the fraction of irrigation or pre-

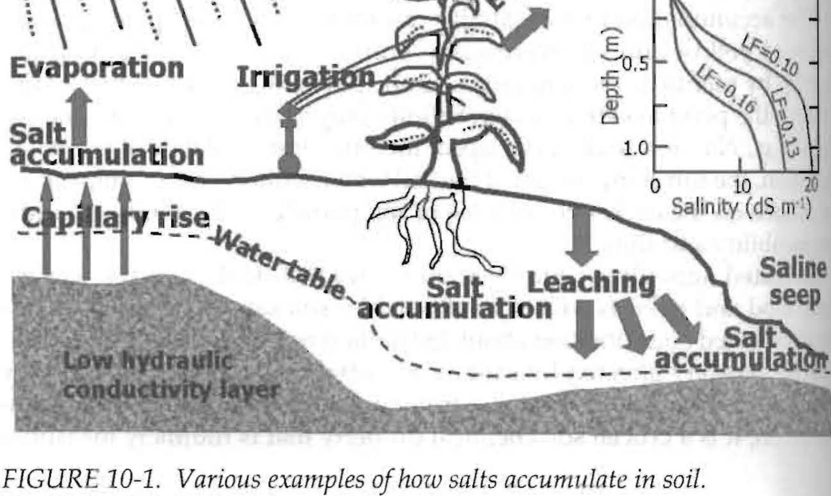

FIGURE 10-1. Various examples of how salts accumulate in soil.

cipitation that flows beyond the rootzone, referred to as the leaching fraction (LF). As the LF increases, the total salts within the rootzone decrease due to their removal from the rootzone by leaching. A third process, which is common in the northern Great Plains of the United States, is the formation of saline seeps. There are several forms of saline seeps differing in their means of development. In general, saline seeps form downslope of recharge areas in locations where discharge is occurring because of the presence of a low conductivity layer and shallow water table (Fig. 10-1). Salts are leached from the upslope recharge area, which tends to be an area of higher conductivity than the downslope discharge area. Once the water and salts from upslope reach the downslope low conductivity layer, they accumulate and are forced to the surface by evaporation.

DIRECT AND INDIRECT ANALYSIS OF SOIL SALINITY

The most common technique for the measurement of soil salinity is laboratory analysis of aqueous extracts of soil samples. Soil salinity is quantified in terms of the concentration of total salts in the soil. The measurement of the total salt concentration of the aqueous extracts of soil samples can be done either directly through the chemical analysis of the chemical constitutes that comprise soil salinity, or indirectly through the measurement of electrical conductivity (EC). The chemical species of primary interest in salt-affected soils include four major cations (Na^+, K^+, Mg^{+2}, Ca^{+2}) and four major anions (Cl^-, HCO_3^-, SO_4^{-2} and CO_3^{-2}) in the soil solution; exchangeable cations (Na^+, K^+, Mg^{+2}, Ca^{+2}); and the precipitated salts calcium carbonate (lime) and calcium sulfate (gypsum). Other soil properties of concern in salt-affected soils include pH, water content of the saturation paste, sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP). Detailed analytical techniques for measuring all of these salinity-related properties can be found in *Methods of Soil Analysis* (Part 3, Sparks 1996; Part 4, Dane and Topp 2002). However, a chemical analysis of the salinity-related properties of primary concern is too labor- and cost-intensive to be practical, particularly when large numbers of samples are involved, such as field-scale assessments of salinity; consequently, the salinity of aqueous extracts of soil samples has been most often measured by EC.

It is well known that the EC of water is a function of its chemical salt composition and total salt concentration (U.S. Salinity Laboratory 1954). In the laboratory, soil salinity is commonly determined from the measurement of the EC of soil-solution extracts, where the current-carrying capacity of the soil solution is proportional to the concentration of ions in the solution. The total concentration of the soluble salts in soil is measured by EC of the soil solution in dS m^{-1}. Over a range of mixed salt concentrations commonly found in soils (1 to 50 meq L^{-1}), total salt concentration (C) in meq L^{-1} is linearly related to electrical conductance of the solution by Eq. 10-1:

$$C \approx 10 \cdot EC_{w\,@\,25\,°C} \qquad (10\text{-}1)$$

where $EC_{w\,@\,25\,°C}$ is the electrical conductivity of the soil solution referenced to 25 °C (dS m^{-1}). If C is measured in mg L^{-1} or ppm, then C is related to $EC_{w\,@\,25\,°C}$ by a factor of 640 (i.e., $C \approx 640 \cdot EC_{w\,@\,25\,°C}$). Over a broader range of salt concentrations (1 to 500 meq L^{-1}) the relationship between C and $EC_{w\,@25\,°C}$ is no longer linear and is best fit with a third-order polynomial or an exponential equation. Another useful relationship is between osmotic potential (ψ_π) and EC, where ψ_π in bars is related to $EC_{w\,@\,25\,°C}$ by a factor of -0.36 (e.g., $\psi_\pi \approx -0.36 \cdot EC_{w\,@\,25\,°C}$; for $3 \leq EC_{w\,@\,25\,°C} \leq 30$ dS m^{-1}).

Theoretical and empirical approaches are available to predict the EC of a solution from its solute composition. Equation 10-2 is an example of a theoretical approach based on Kohlrauch's Law of independent migration of ions, where each ion contributes to the current-carrying ability of an electrolyte solution:

$$EC = \sum_i EC_i = \sum_i \frac{c_i(\lambda_0^i - \beta\sqrt{c_i})}{1000} \qquad (10\text{-}2)$$

where EC is the specific conductance (dS m^{-1}), EC_i is the ionic specific conductance (dS m^{-1}), c_i is the concentration of the ith ion (mmol$_c$ L^{-1}), λ_0^i is the ionic equivalent conductance at infinite dilution (cm^2 S mol$_c^{-1}$), and β is an empirical interactive parameter (Harned and Owen 1958). Equation 10-3 shows an empirical equation developed by Marion and Babcock (1976):

$$\log TSS = 0.990 + 1.055 \log EC \; (r^2 = 0.993) \qquad (10\text{-}3)$$

where TSS is the total soluble salt concentration (mmol$_c$ L^{-1}).

Temperature influences EC; consequently, EC must be referenced to a specific temperature to permit comparison. Electrolytic conductivity increases at a rate of approximately 1.9% per degree centigrade increase in temperature. Customarily, EC is expressed at a reference temperature of 25 °C. The EC measured at a particular temperature t (in °C), EC_t, can be adjusted to a reference EC at 25 °C, $EC_{25\,°C}$, using Eq. 4 from *USDA Handbook 60* (U.S. Salinity Laboratory 1954):

$$EC_{25\,°C} = f_t \cdot EC_t \qquad (10\text{-}4)$$

where, $f_t = 0.4470 + 1.4034 \exp(-t/26.815)$ [from Sheets and Hendrickx (1995)].

METHODS OF LABORATORY, LYSIMETER, AND PLOT-SCALE SOIL SALINITY MEASUREMENT

Historically, four principal methods have been used for measuring soil salinity in the laboratory, in soil lysimeter columns, and at field-plot scales: (1) the EC of soil solution at or near field capacity, of extracts at higher than normal water contents (i.e., including saturation and soil to water ratios of 1:1, 1:2, and 1:5), or of a saturation paste; (2) in-situ measurement of electrical resistivity (ER); (3) noninvasive measurement of EC with electromagnetic induction (EMI); and, most recently, (4) in-situ measurement of EC with time domain reflectometry (TDR).

Electrical Conductivity

To determine the EC of a soil solution extract, the solution is placed in a cell containing two electrodes of constant geometry and distance of separation. An electrical potential is imposed across the electrodes, and the resistance of the solution between the electrodes is measured. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. At constant potential, the current is inversely proportional to the solution's resistance as shown in Eq. 10-5:

$$EC_t = k/R_t \qquad (10\text{-}5)$$

where EC_t is the electrical conductivity of the soil solution in dS m^{-1} at temperature t (°C), k is the cell constant, and R_t is the measured resistance in ohms at temperature t. One dS m^{-1} is equivalent to one mS cm^{-1} and one mmho cm^{-1}, where mmho cm^{-1} are the obsolete units of EC.

Except for the measurement of EC of a saturated soil paste (EC_p), the determination of soluble salts in disturbed soil samples consists of two basic steps: (1) preparation of a soil-water extract, and (2) the measurement of the salt concentration of the extract using EC. Customarily, soil salinity has been defined in terms of laboratory measurements of the EC of the extract of a saturated soil paste (EC_e). This is because it is impractical for routine purposes to extract soil water from samples at typical field water contents; consequently, soil-solution extracts must be made at saturation or higher water contents. The saturation paste extract is the lowest soil-to-water ratio that can be easily extracted with vacuum, pressure, or centrifugation, while providing a sample of sufficient size to analyze. The water content of a saturation paste is roughly twice the field capacity in most soils. Furthermore, EC_e has been the standard measure of salinity used in salt-tolerance plant studies. Most data on the salt tolerance of crops have been expressed in terms of the EC of the saturation paste extract (Bresler et al. 1982; Maas 1986).

Unfortunately, the partitioning of solutes over the three soil phases (gas, liquid, solid) is influenced by the soil-to-water ratio at which the extract is made, so the ratio needs to be standardized to obtain results that can be applied and interpreted universally. Commonly used extract ratios, other than a saturated soil paste, are 1 : 1, 1 : 2, and 1 : 5 soil-to-water mixtures. These extracts are easier to prepare than saturation paste extracts. With the exception of sandy soils, soils containing gypsum, and organic soil, the concentrations of salt and individual ions are approximately diluted by about the same ratio between field conditions and the extract for all samples, which allows conversions between water contents using dilution factors. The conversion of EC from one extract to another is commonly done using a simple dilution factor. For example, if the gravimetric saturation percentage (SP) is 100%, then $EC_e = EC_{1:1} = 5 \cdot EC_{1:5}$, or if SP = 50%, then $EC_e = 2 \cdot EC_{1:1} = 10 \cdot EC_{1:5}$. However, this is not recommended because of potential dissolution-precipitation reactions that may occur. At best, the use of a dilution factor to convert from one extract to another is an approximation.

Any dilution above field water contents introduces errors in the interpretation of data. The greater the dilution is, the greater the deviation between ionic ratios in the sample and the soil solution under field conditions. These errors are associated with mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. In particular, soil samples containing gypsum deviate the most because the calcium (Ca) and sulfate concentration remain nearly constant with sample dilution, while the concentrations of other ions decrease with dilution. The standardized relationship between the extract and the conditions of the soil solution in the field for different soils is not applicable with the use of soil-to-water above saturation. However, the recent development of *Extract Chem* software by Suarez and Taber (2007) allows for the accurate conversion from one extract ratio to another, provided sufficient chemical information is known (for example, knowledge of the major cations and anions and presence/absence of gypsum). The disadvantage of determining soil salinity using a soil sample is the time and labor required, which translates into high cost. However, there is no more accurate way of measuring soil salinity than with extracts from soil samples.

Prior to the 1950s, much of the data on soil salinity were obtained by using a 50-mL cylindrical conductivity cell, referred to as a "Bureau of Soils cup," filled with a saturated soil paste to estimate soluble-salt concentrations by measuring the EC_p. This approach was fast and easy; consequently, it was used to map and diagnose salt-affected soils. When Reitemeier and Wilcox (1946) determined that plant responses to soil salinity correlated more closely with the EC values of the saturation paste extract, the use of the paste was discontinued. A theoretical relationship between EC_p and EC_e has since been developed to overcome the cell's shortcomings. This was done by developing a simple method of determining the volumetric water and volumetric solid contents of the saturation paste, the conductance of the sample surface, and the current pathway of the water in the cell (Rhoades et al. 1999b). Even so, the relationship between EC_p and EC_e is complex; consequently, the measurement of EC_p is not recommended except in instances where obtaining an extract of the saturation paste is not possible or is impractical. Figure 10-2 graphically illustrates the theoretical complexity of the relationship between EC_p and EC_e based on the dual parallel pathway conductance model of Rhoades et al. (1989a,b).

Soil salinity can also be determined from the measurement of the EC of a soil solution (EC_w), where the water content of the soil is less than saturation, usually at field capacity. Ideally, EC_w is the best index of soil salinity because this is the salinity actually experienced by the plant root. Nevertheless, EC_w has not been widely used to express soil salinity for various reasons: (1) it varies over the irrigation cycle as the soil water content changes, so it is not single-valued; and (2) the methods for obtaining soil solution samples at typical field water contents are too labor-, time-, and cost-intensive to be practical (Rhoades et al. 1999b). For disturbed soil samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum- or

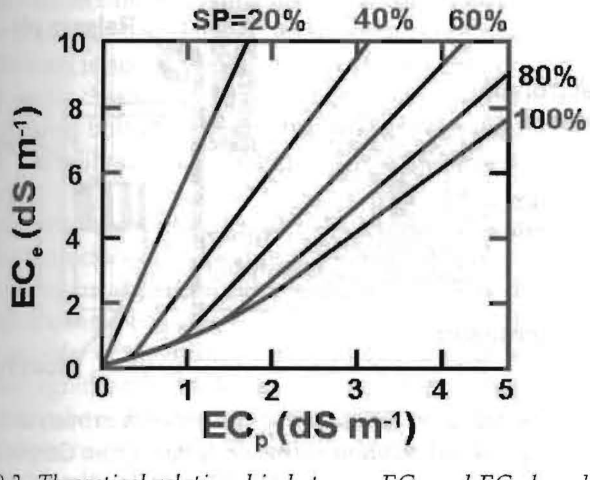

FIGURE 10-2. *Theoretical relationship between EC_e and EC_p based on the dual parallel pathway conductance model of Rhoades et al. (1989a,b).*

pressure-extraction methods. For undisturbed soil samples, EC_w can be determined with a soil-solution extractor (Fig. 10-3a), often referred to as a porous cup extractor, or using an in situ, imbibing-type porous-matrix salinity sensor (Fig. 10-3b).

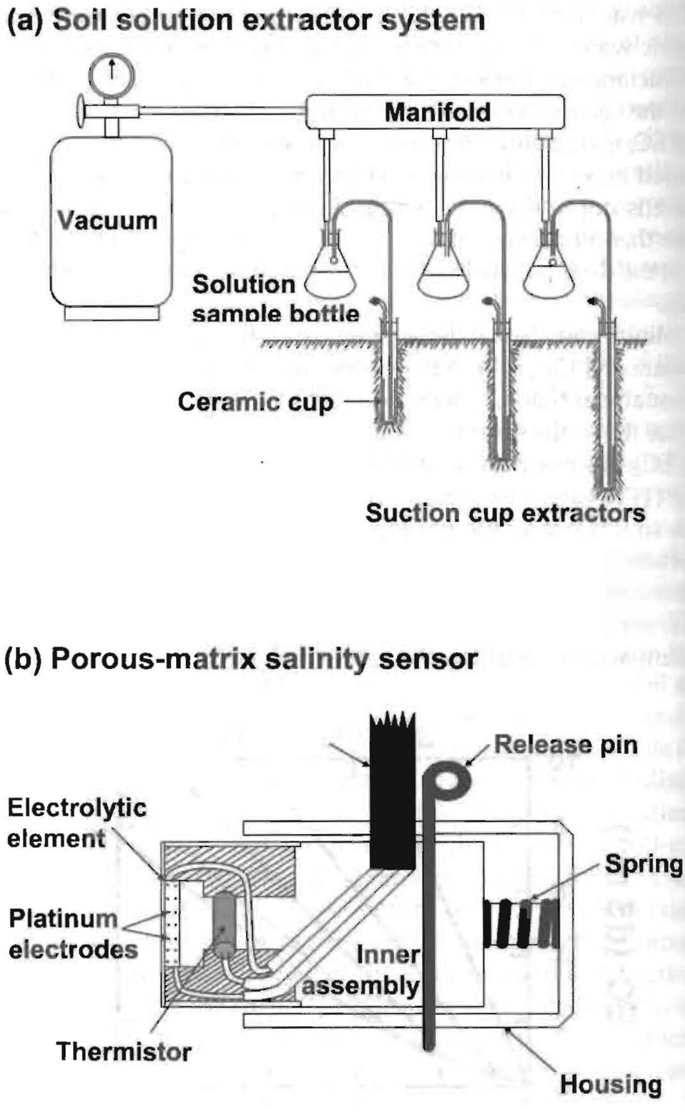

FIGURE 10-3. Instruments for obtaining soil-solution extracts at less than saturation, including (a) soil-solution extractor system (from Corwin 2002a), and (b) porous-matrix salinity sensor (from Corwin 2002b). Reprinted with permission from Soil Science Society of America.

Porous cup soil solution extractors include zero-tension and tension (or suction) cups. Historically, suction cups have been more widely used. No single soil-solution sampling device will perfectly sample under all conditions, so it is important to understand the strengths and limitations of a sampler to determine when to apply certain sampling methods in preference over other methods. In structured soils, suction cups do not sample water in preferential flow paths. Zero-tension cups will almost always sample just saturated flow, which is more closely associated with preferential flow channels, and tension samplers will more efficiently sample unsaturated flow within soil aggregates. Zero-tension cups represent the flux concentration, whereas the tension samples are approximations of resident concentrations.

The basic design of a suction cup apparatus consists of a suction cup, sample collection bottle, manifold (if there is more than one suction cup), an overflow trap, an applied vacuum, and connective tubing (Fig. 10-3a). The general principle behind the operation of suction cup extractors is simply that suction (preferably the suction at field moisture capacity) is placed against the porous cup. This suction opposes the capillary force of the soil at field capacity, causing soil solution to be drawn across the porous wall of the cup as a result of the induced pressure gradient. The imbibed solution is stored in a sample collection chamber. This approach for extracting soil solution is viable when the soil-water matric potential is greater than about −30 kPa (kilopascals, a standard unit of pressure).

The salinity sensor consists of a porous ceramic substrate with an embedded platinum mesh electrode, which is placed in contact with the soil to measure the EC of the soil solution that has been imbibed by the ceramic (Fig. 10-3b). The salinity sensor contains a thermistor designed to temperature-correct the EC readings. Both the electrolytic element and thermistor of a salt sensor (Fig. 10-3b) must be calibrated for proper operation. Calibration is necessary because of (1) the variation in water retention and porosity characteristics of each ceramic, and (2) the variation in electrode spacing, both of which cause the cell constant to vary for each salt sensor. The calibration can change with time, so periodic recalibration is necessary.

There are various advantages and disadvantages to measuring EC using soil solution extractors or soil salinity sensors. The obvious advantage is that EC_w is being measured, but this is outweighed by the disadvantages. Even though the sample volume of a soil-solution extractor (10 to 100 cm^3) is roughly an order of magnitude larger than a salinity sensor (1 to 2 cm^3), both measure significantly limited sample volumes; consequently, there are serious doubts about the ability of soil-solution extractors and porous-matrix salinity sensors to provide representative soil-water samples, particularly at field scales (England 1974; Raulund-Rasmussen 1989; Smith et al. 1990). Soil heterogeneity significantly affects chemical concentrations in the soil solution. Because of their small sphere of measurement, neither solution extractors nor salt sensors adequately integrate spatial variability (Amoozegar-Fard et al. 1982; Haines et al. 1982; Hart and Lowery 1997). Biggar and Nielsen (1976) suggested that soil-solution samples are "point samples" that can provide a good qualitative measurement of soil solutions but are not adequate quantitative measurements unless the field-scale variability is adequately established. Furthermore, salinity sensors demonstrate a response time lag that is dependent on the diffusion of ions between the soil solution and solution in the porous ceramic, which is affected by (1) the thickness of the ceramic conductivity cell, (2) the diffusion coefficients in soil and ceramic, and (3) the fraction of the ceramic surface in contact with soil (Wesseling and Oster 1973). The salinity sensor is generally considered the least desirable method for measuring EC_w because of its low sample volume, unstable calibration over time, and slow response time (Corwin 2002b). Soil-solution extractors have the drawback of requiring considerable maintenance due to cracks in the vacuum lines and clogging of the ceramic cups with algae and fine soil particles. Both solution extractors and salt sensors are considered slow and labor-intensive.

The ability to obtain the EC of a soil solution when the water content is at or less than field capacity, which are the water contents most commonly found in the field, is considerably more difficult than extracts for water contents at or above saturation because of the pressure or suction required to remove the soil solution at field capacity and lower water contents. The EC of the saturated paste is the easiest to obtain, followed by the EC of extracts greater than SP, followed by the EC of extracts less than SP. However, EC_e is most preferred; consequently, either measuring EC_e or being able to relate the EC measurement to EC_e is critical. The techniques of ER, EMI, and TDR measure EC_a, which is discussed in the next section.

Electrical Resistivity

Because of the time and cost of obtaining soil-solution extracts and the lag time associated with porous ceramic cups, developments in the measurement of soil EC shifted in the 1970s to the measurement of the soil EC of the bulk soil, referred to as apparent soil electrical conductivity (EC_a). Apparent soil electrical conductivity provides an immediate, easy-to-take measurement of conductance with no lag time and no need to obtain a soil extract. However, EC_a is a complex measurement that has been misinterpreted and misunderstood by users in the past due to the fact that it is a measure of the EC of the bulk soil, not just a measure of the conductance of the soil solution, which is the desired measurement, since the soil solution is the soil phase that contains the salts affecting plant roots.

The most comprehensive body of research concerning the adaptation and application of geophysical techniques to the measurement of soil salinity within the rootzone (top 1 to 1.5 m of soil) was compiled by scientists at the U.S. Salinity Laboratory. The most recent reviews of this body of research can be found in Corwin (2005), Corwin and Lesch (2005a), and Rhoades et al. (1999b).

Electrical resistivity (ER) was originally used by geophysicists to measure the resistivity of the geological subsurface. Electrical resistivity methods involve the measurement of the resistance to current flow across four electrodes inserted in a straight line on the soil surface at a specified distance between the electrodes (Corwin and Hendrickx 2002). The electrodes are connected to a resistance meter that measures the potential gradient between the current and potential electrodes (Fig. 10-4). These methods were developed in the second decade of the 1900s by Conrad Schlumberger in France and Frank Wenner in the United States for the evaluation of near-surface ER (Burger 1992; Rhoades and Halvorson 1977). Although two electrodes (one current and one potential electrode) can be used, the stability of the reading is greatly improved with the use of four electrodes.

The resistance is converted to EC using Eq. 10-5, where the cell constant, *k*, in that equation is determined by the electrode configuration and distance. The depth of penetration of the electrical current and the volume of measurement increase as the interelectrode spacing increases. The four-electrode configuration is referred to as a Wenner array when the four electrodes are equidistantly spaced (interelectrode spacing = *a*). For a

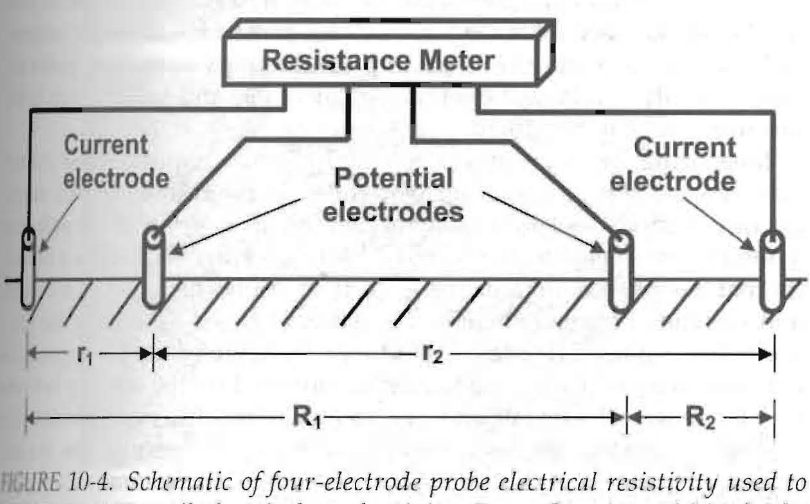

FIGURE 10-4. *Schematic of four-electrode probe electrical resistivity used to measure apparent soil electrical conductivity. From Corwin and Hendrickx (2002) with permission from Soil Science Society of America.*

homogeneous soil, the depth of penetration of the Wenner array is a and the soil volume measured is roughly πa^3.

Other four-electrode configurations are frequently used, as discussed by Burger (1992), Dobrin (1960), and Telford et al. (1990). The influence of the interelectrode configuration and distance on EC_a is reflected in Eq. 10-6:

$$EC_{a,25^\circ C} = \left(\frac{1000}{2\pi R_t}\right)\left\{\frac{f_t}{\dfrac{1}{\dfrac{1}{r_1}-\dfrac{1}{r_2}-\dfrac{1}{R_1}+\dfrac{1}{R_2}}}\right\} \qquad (10\text{-}6)$$

where $EC_{a,25\ ^\circ C}$ is the apparent soil electrical conductivity temperature corrected to a reference of 25 °C (dS m^{-1}), and r_1, r_2, R_1, and R_2 are the distances in cm between the electrodes as shown in Fig. 10-4. For the Wenner array, where $a = r_1 = r_2 = R_1 = R_2$, Eq. 10-6 reduces to $EC_a = 159.2 f_t/aR_t$ and $159.2/a$ represents the cell constant (k).

A variety of four-electrode probes have been commercially developed, reflecting diverse applications. Burial and insertion four-electrode probes are used for continuous monitoring of EC_a and to measure soil profile EC_a, respectively (Fig. 10-5a,b). These probes have volumes of measurement roughly the size of a football (i.e., about 2,500 cm^3). Bedding probes with small volumes of measurement of roughly 25 cm^3 were used to monitor EC_a in seed beds (Fig. 10-5c), but these probes are no longer commercially available. Only the Eijelkamp conductivity meter and probe are commercially available, which is similar in use and basic design to the insertion probe in Fig. 10-5b.

Measuring ER is an invasive technique that requires good contact between the soil and the four electrodes inserted into the soil; consequently, it produces less reliable measurements in dry or stony soils than a noninvasive measurement such as EMI. Nevertheless, ER has a flexibility that has proven advantageous for field application, that is, the depth and volume of measurement can be easily changed by altering the spacing between the electrodes. A distinct advantage of the ER approach is that the volume of measurement is determined by the spacing between the electrodes, which makes a large volume of measurement possible. For example, a 1-m interelectrode spacing for a Wenner array results in a volume of measurement of more than 3 m^3. This large volume of measurement integrates the high level of local-scale variability often associated with EC_a measurements.

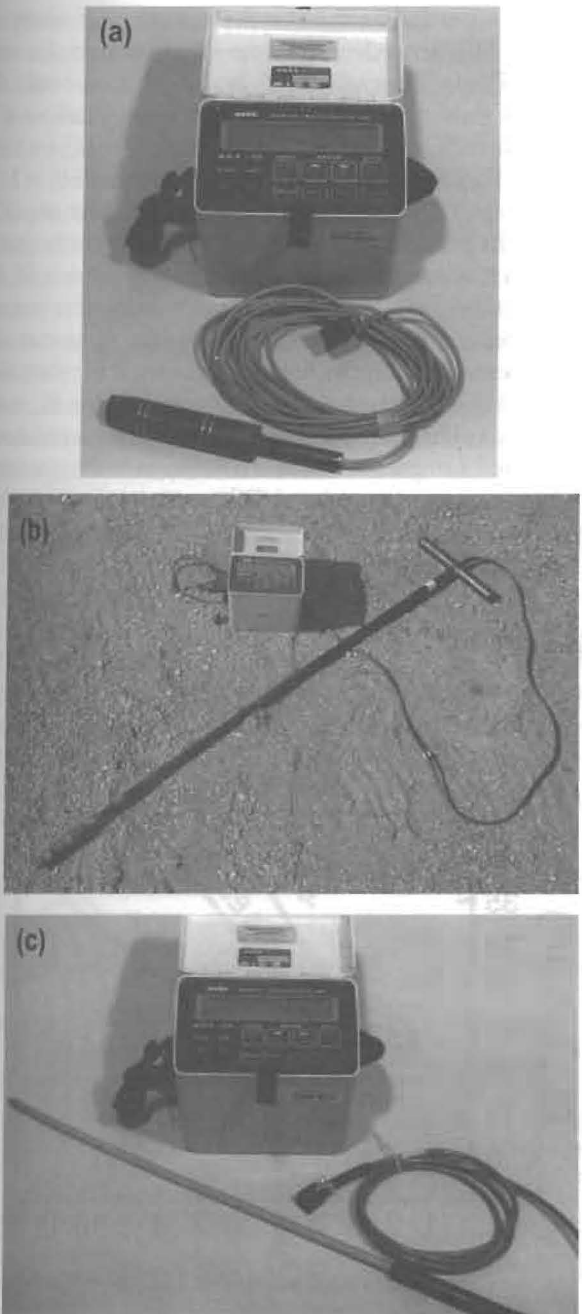

FIGURE 10-5. *Examples of various four-electrode probes: (a) burial probe, (b) insertion probe, and (c) bedding probe.*

Because EC_e is regarded as the standard measure of salinity, a relation between EC_a and EC_e is needed to relate EC_a to salinity. The relationship between EC_a and EC_e is linear when EC_a is above 2 dS m^{-1} and is dependent on soil texture, as shown in Fig. 10-6. Rough approximations of EC_e from EC_a in dS m^{-1} when $EC_a \geq 2$ dS m^{-1} are: $EC_e \approx 3.5 \cdot EC_a$ for fine-textured soils, $EC_e \approx 5.5 \cdot EC_a$ for medium-textured soils, and $EC_e \approx 7.5 \cdot EC_a$ for coarse-textured soils. For $EC_a < 2$ dS m^{-1}, the relation between EC_a and EC_e is more complex. In general, at $EC_a \geq 2$ dS m^{-1} salinity is the dominant conductive constituent; consequently, the relationship between EC_a and EC_e is linear. However, when $EC_a < 2$ dS m^{-1}, other conductive properties (e.g., water and clay content) and properties influencing conductance (e.g., bulk density) have greater influence. For this reason, it is recommended that below an EC_a of 2 dS m^{-1}, the relation between EC_a and EC_e is established by calibration. The calibration between EC_a and EC_e is established by measuring the EC_e of soil samples taken at a minimum of three to four locations within a study area where associated EC_a measurements have been taken. These samples should reflect a range of EC_as and should be collected over the volume of measurement for the EC_a technology used (i.e., ER or EMI).

Electromagnetic Induction

Apparent soil electrical conductivity can be measured noninvasively with EMI. A transmitter coil located at one end of the EMI instrument

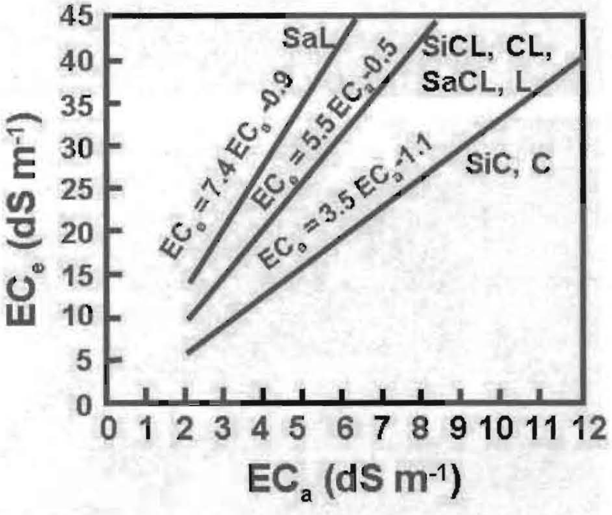

FIGURE 10-6. Relationships between EC_a and EC_e for representative soil types found in the northern Great Plains, United States. Modified from Rhoades and Halvorson (1977).

induces circular eddy-current loops in the soil, with the magnitude of these loops directly proportional to the EC in the vicinity of that loop (Fig. 10-7). Each current loop generates a secondary electromagnetic field that is proportional to the value of the current flowing within the loop. A fraction of the secondary induced electromagnetic field from each loop is intercepted by the receiver coil of the instrument and the sum of these signals is amplified and formed into an output voltage, which is related to a depth-weighted EC_a. The amplitude and phase of the secondary field will differ from those of the primary field as a result of soil properties (e.g., clay content, water content, salinity), spacing of the coils and their orientation, frequency, and distance from the soil surface (Hendrickx and Kachanoski 2002).

The most commonly used EMI conductivity meters in soil science and in vadose zone hydrology are the Geonics EM-31 and EM-38 (Geonics Ltd., Mississauga, Ontario, Canada) and the DUALEM-2 (Dualem Inc., Milton, Ontario, Canada). The EM-38 has had considerably greater application for agricultural purposes because the depth of measurement corresponds roughly to the rootzone (i.e., generally 1 to 1.5 m.). When the instrument is placed in the vertical coil configuration (EM_v, with the coils perpendicular to the soil surface), the depth of measurement is about 1.5 m; in the horizontal coil configuration (EM_h, with the coils parallel to the soil surface), the depth of the measurement is 0.75 to 1.0 m. The EM-31 has an intercoil spacing of 3.66 m, which corresponds to a penetration depth of 3 and 6 m in the horizontal and vertical dipole orientations, respectively, which extends well beyond the rootzone of agricultural

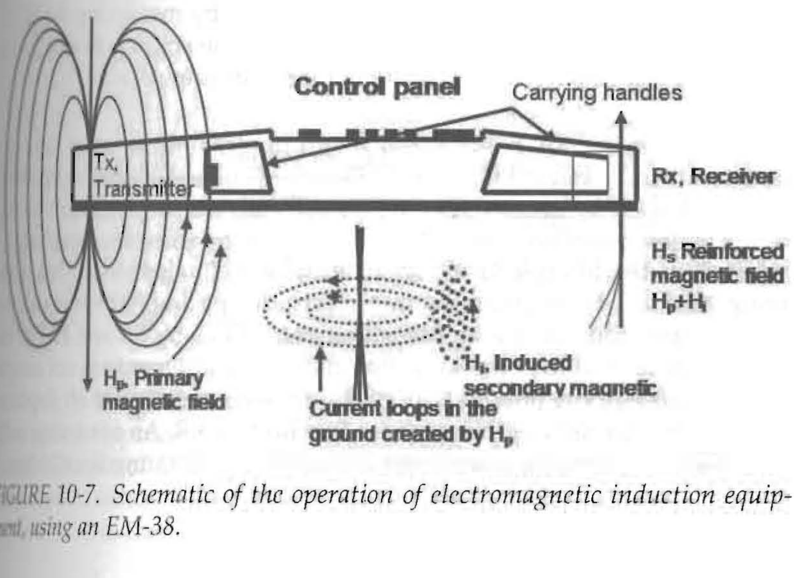

FIGURE 10-7. *Schematic of the operation of electromagnetic induction equipment, using an EM-38.*

crops. However, the EM-38 has one major pitfall—the need for calibration—which the DUALEM-2 does not require. Further details about and operation of the EM-31 and EM-38 equipment are discussed in Hendrickx and Kachanoski (2002). Documents concerning the DUALEM-2 can be found in Dualem (2007).

Apparent soil electrical conductivity measured by EMI at $EC_a < 1.0$ dS m^{-1} is given by Eq. 10-7, from McNeill (1980):

$$EC_a = \frac{4}{2\pi\mu_0 f s^2}\left(\frac{H_s}{H_p}\right) \tag{10-7}$$

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

Both ER and EMI are rapid and reliable technologies for the measurement of EC_a, each with its advantages and disadvantages. The primary advantage of EMI over ER is that EMI is noninvasive, so it can be used on dry and stony soils that would not be amenable to invasive ER equipment. The disadvantage is that EC_a measured with EMI is a depth-weighted value that is nonlinear, whereas ER provides an EC_a measurement that is nearly linear with depth. More specifically, EMI concentrates its measurement of conductance over the depth of penetration at shallow depths, while ER is more uniform with depth. Because of the linearity of the response function of ER, the EC_a for a discrete depth interval of soil, EC_x, can be determined with the Wenner array by measuring the EC_a of successive layers by increasing the interelectrode spacing from a_{i-1} to a_i and using Eq. 10-8 from Barnes (1952) for resistors in parallel:

$$EC_x = EC_{a_i - a_{i-1}} = \frac{(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} - a_{i-1})}{(a_i - a_{i-1})} \tag{10-8}$$

where a_i is the interelectrode spacing, which equals the depth of sampling, and a_{i-1} is the previous interelectrode spacing, which equals the depth of previous sampling. Measurements of EC_a by ER and EMI at the same location and over the same volume of measurement are not comparable because of the nonlinearity of the response function with depth for EMI and the linearity of the response function for ER. An advantage of ER over EMI is the ease of instrument calibration. Calibrating the EM-31 and EM-38 is more involved then for ER equipment. However, there is no need to calibrate the DUALEM-2.

Time Domain Reflectometry

Time domain reflectometry (TDR) was initially adapted for use in measuring water content, θ (Topp and Davis 1981; Topp et al. 1980, 1982). The TDR technique is based on the time for a voltage pulse to travel down a soil probe and back, which is a function of the dielectric constant (ε) of the porous media being measured. Later, Dalton et al. (1984) demonstrated the utility of TDR to also measure EC_a. The measurement of EC_a with TDR is based on the attenuation of the applied signal voltage as it traverses the medium of interest, with the relative magnitude of energy loss related to EC_a (Wraith 2002).

By measuring ε, θ can be determined through calibration (Dalton 1992). The ε is calculated with Eq. 10-9, from Topp et al. (1980):

$$\varepsilon = \left(\frac{ct}{2l}\right)^2 = \left(\frac{l_a}{lv_p}\right)^2 \tag{10-9}$$

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

By measuring the resistive load impedance across the probe (Z_L), EC_a can be calculated with Eq. 10-10, from Giese and Tiemann (1975),

$$EC_a = \frac{\varepsilon_0 c}{l} \cdot \frac{Z_0}{Z_L} \tag{10-10}$$

where ε_0 is the permittivity of free space (8.854×10^{-12} F m^{-1}), Z_0 is the probe impedance (Ω), and $Z_L = Z_u[(2V_0/V_f) - 1]^{-1}$ where Z_u is the characteristic impedance of the cable tester, V_0 is the voltage of the pulse generator or zero-reference voltage, and V_f is the final reflected voltage at an exceedingly long time. To reference EC_a to 25 °C, Eq. 10-11 is used:

$$EC_a = K_c f_t Z_L^{-1} \tag{10-11}$$

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

Advantages of TDR for measuring EC_a include (1) a relatively noninvasive nature since there is only minor interference with soil processes, (2) an ability to measure both soil water content and EC_a, (3) an ability to detect small changes in EC_a under representative soil conditions, (4) the capability of obtaining continuous unattended measurements, and (5) lack of a calibration requirement for soil water content measurements in many cases (Wraith 2002). Even so, TDR has not been the instrument of choice for the measurement of salinity, whether in the laboratory or in the field; consequently, it will not be discussed in detail.

Soil EC_a has become one of the most reliable and frequently used measurements to characterize field variability for application to precision agriculture due to its ease of measurement and reliability (Corwin and Lesch 2003). Although TDR has been demonstrated to compare closely with other accepted methods of EC_a measurement (Heimovaara et al. 1995; Mallants et al. 1996; Reece 1998; Spaans and Baker 1993), it is still not sufficiently simple, robust, or fast enough for the general needs of field-scale soil salinity assessment (Rhoades et al. 1999b). Only ER and EMI have been adapted for the georeferenced measurement of EC_a at field-scale and larger (Rhoades et al. 1999a,b).

SOIL-RELATED (EDAPHIC) FACTORS INFLUENCING THE EC_a MEASUREMENT

The earliest field applications of geophysical measurements of EC_a in soil science involved the determination of salinity through the soil profile of arid zone soils (Cameron et al. 1981; Corwin and Rhoades 1982, 1984; de Jong et al. 1979; Halvorson and Rhoades 1976; Rhoades and Corwin 1981; Rhoades and Halvorson 1977; Williams and Baker 1982). However, it became apparent that the measurement of EC_a in the field to infer soil salinity was more complicated than initially anticipated due to the complexity of current flow pathways arising from the complex interaction of the conductive properties influencing the EC_a measurements and from the spatial heterogeneity of those conductive properties.

The interpretation of EC_a measurements is not trivial because of the complexity of current flow in the bulk soil. Numerous EC_a studies have been conducted that have revealed the site specificity and complexity of geospatial EC_a measurements with respect to the particular property or properties influencing the EC_a measurement at the study site. Table 10-1 (taken from Corwin and Lesch 2005a) is a compilation of EC_a studies and the associated dominant soil property or properties measured by EC_a for each study.

The advantages of the EC_a measurement are that it is rapid, reliable, and easy to take, which have made it an ideal field measurement tool. However, because of the multiple pathways of conductance, it is often difficult to interpret. Corwin and Lesch (2003) provided guidelines for the use of EC_a in agriculture by identifying the complexities of the EC_a measurement

TABLE 10-1. Compilation of Literature Measuring EC_a Categorized According to the Physicochemical and Soil-Related Properties either Directly or Indirectly Measured by EC_a

Soil Property	References
Directly Measured Soil Properties	
Salinity (and nutrients, e.g., NO_3^-)	Halvorson and Rhoades (1976); Rhoades et al. (1976); Rhoades and Halvorson (1977); de Jong et al. (1979); Cameron et al. (1981); Rhoades and Corwin (1981, 1990); Corwin and Rhoades (1982, 1984); Williams and Baker (1982); Greenhouse and Slaine (1983); van der Lelij (1983); Wollenhaupt et al. (1986); Williams and Hoey (1987); Corwin and Rhoades (1990); Rhoades et al. (1989b, 1990, 1999a, 1999b); Slavich and Petterson (1990); Diaz and Herrero (1992); Hendrickx et al. (1992); Lesch et al. (1992, 1995a, 1995b, 1998); Rhoades (1992, 1993); Cannon et al. (1994); Nettleton et al. (1994); Bennett and George (1995); Drommerhausen et al. (1995); Ranjan et al. (1995); Hanson and Kaita (1997); Johnston et al. (1997); Mankin et al. (1997); Eigenberg et al. (1998, 2002); Eigenberg and Nienaber (1998, 1999, 2001); Mankin and Karthikeyan (2002); Herrero et al. (2003); Paine (2003) ; Kaffka et al. (2005); Lesch et al. (2005); Sudduth et al. (2005)
Water content	Fitterman and Stewart (1986); Kean et al. (1987); Kachanoski et al. (1988, 1990); Vaughan et al. (1995); Sheets and Hendrickx (1995); Hanson and Kaita (1997); Khakural et al. (1998); Morgan et al. (2000); Freeland et al. (2001); Brevik and Fenton (2002); Wilson et al. (2002); Farahani et al. (2005); Kaffka et al. (2005); Lesch et al. (2005); Sudduth et al. (2005)
Texture-related (e.g., sand, clay, depth to claypans or sand layers)	Williams and Hoey (1987); Brus et al. (1992); Jaynes et al. (1993); Stroh et al. (1993); Sudduth and Kitchen (1993); Doolittle et al. (1994, 2002); Kitchen et al. (1996); Banton et al. (1997); Boettinger et al. (1997); Rhoades et al. (1999b); Scanlon et al. (1999); Inman et al. (2001); Triantafilis et al. (2001); Anderson-Cook et al. (2002); Brevik and Fenton (2002); Lesch et al. (2005); Sudduth et al. (2005); Triantafilis and Lesch (2005)
Bulk density-related (e.g., compaction)	Rhoades et al. (1999b); Gorucu et al. (2001)

(continued)

TABLE 10-1. Compilation of Literature Measuring EC_a Categorized According to the Physicochemical and Soil-Related Properties either Directly or Indirectly Measured by EC_a (*Continued*)

Soil Property	References
Indirectly Measured Soil Properties	
Organic matter-related (including soil organic carbon, and organic chemical plumes)	Greenhouse and Slaine (1983, 1986); Brune and Doolittle (1990); Nyquist and Blair (1991); Jaynes (1996); Benson et al. (1997); Bowling et al. (1997); Brune et al. (1999); Nobes et al. (2000); Farahani et al. (2005); Sudduth et al. (2005)
Cation exchange capacity	McBride et al. (1990); Triantafilis et al. (2002); Farahani et al. (2005); Sudduth et al. (2005)
Leaching	Slavich and Petterson (1990); Corwin et al. (1999); Rhoades et al. (1999b); Lesch et al. (2005)
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)

From Corwin and Lesch (2005a) with permission from Elsevier.

and how to deal with them. As shown in Fig. 10-8, three parallel pathways of current flow contribute to the EC_a measurement: (1) a liquid phase pathway (Pathway 1) via salts contained in the soil water occupying the large pores, (2) a solid pathway (Pathway 2) via soil particles that are in direct and continuous contact with one another, and (3) a solid-liquid pathway (Pathway 3) primarily via exchangeable cations associated with clay minerals (Rhoades et al. 1999b). To measure soil salinity, the EC of only the soil solution (Pathway 1) is required; consequently, EC_a measures more than just soil salinity. In fact, EC_a is a measure of anything conductive within the volume of measurement and is influenced, whether directly or indirectly, by any edaphic properties that affect bulk soil conductance.

Because of the pathways of conductance, EC_a is influenced by a complex interaction of edaphic properties including salinity, texture (or saturation percentage, SP), water content, bulk density (ρ_b), organic matter (OM), cation exchange capacity (CEC), clay mineralogy, and temperature. The SP and ρ_b are both directly influenced by clay content (or texture) and OM. Furthermore, the exchange surfaces on clays and OM provide a solid-liquid phase pathway primarily via exchangeable cations; conse-

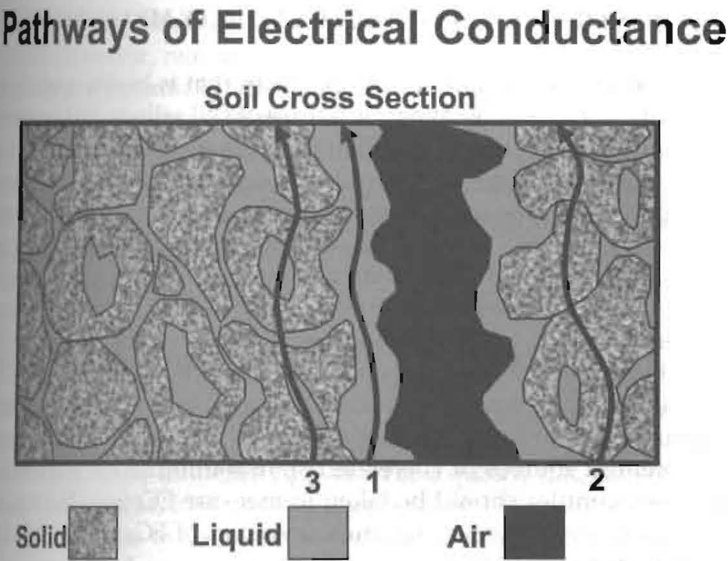

FIGURE 10-8. *Schematic showing the three conductance pathways of apparent soil electrical conductivity (EC_a). Pathway 1 = liquid phase conductance, Pathway 2 = solid phase conductance, and Pathway 3 = solid-liquid phase conductance. From Rhoades et al. (1989b). Reprinted with permission from the Soil Science Society of America.*

quently, clay type and content (or texture), CEC, and OM are recognized as factors influencing EC_a measurements. Measurements of EC_a *must* be interpreted with these influencing factors in mind.

It is of paramount importance that the concept of parallel pathways of conductance is understood in order to interpret EC_a measurements. Interpreting EC_a measurements is accomplished best with ground-truth measurements of the soil physical and chemical properties that potentially influence EC_a at the point of measurement. An understanding and interpretation of geospatial EC_a data can only be obtained from ground-truth measures of soil properties that correlate with EC_a from either a direct influence or indirect association. For this reason, geospatial EC_a measurements are used as a surrogate of soil spatial variability to direct soil sampling when mapping soil salinity at field scales and larger spatial extents. They are not generally used as a direct measure of soil salinity, particularly at $EC_a < 2$ dS m^{-1} where the influence of conductive soil properties other than salinity can have an increased influence on the EC_a reading. At high EC_a values, salinity is most likely dominating the EC_a reading; consequently, geospatial EC_a measurements are most likely mapping soil salinity.

METHODS OF FIELD-SCALE SOIL SALINITY MEASUREMENT

Soil salinity is a dynamic soil property that is highly spatially and temporally variable. The dynamic nature of soil salinity makes mapping and monitoring of salinity a difficult challenge. Mapping and monitoring soil salinity at field scale requires a rapid, reliable, easy method of taking geospatial measurements. The use of soil samples to measure salinity (e.g., EC_e, $EC_{1:1}$, $EC_{1:2}$, $EC_{1:5}$, or EC_p) at field scales is impractical because of the need for hundreds and even thousands of grid samples. The use of soil samples to measure salinity at field scales is only practical when sampling is directed to minimize the number of samples that reflect the range and variability of salinity within the area of study. This can be achieved using easily measured spatial information correlated to soil salinity as a means of directing where to take the fewest samples. Two potential sources of correlated spatial information used to direct where soil samples should be taken to measure EC_e are: (1) visual crop observation, and (2) geospatial measurements of EC_a with mobile ER or EMI equipment.

Associated with visual crop observation but considered a distinct potential approach is the use of multi- and hyperspectral imagery. Even though the use of remote imagery has tremendous potential, at this point it is still restricted to research because the methodology has not been developed for general application to mapping and monitoring salinity. At present, only the use of geospatial measurements of EC_a can provide reliable, accurate maps of salinity at field scales. Even so, remote imagery will unquestionably play a future role in mapping salinity, particularly at landscape scales.

Visual Crop Observation

Visual crop observation is a quick method, but it has the disadvantage that salinity development is detected after crop damage has occurred; consequently, crop yield must be sacrificed to locate areas of salinity development. Furthermore, decreases in crop yield are not necessarily the consequence of only salt accumulation. Crops respond to a variety of anthropogenic (e.g., irrigation uniformity, farm equipment traffic), edaphic (e.g., salinity, water content, texture, OM), biological (e.g., disease, nematodes), meteorological (e.g., precipitation, humidity, temperature), and topographical (e.g., slope, elevation, microrelief) factors, any of which can cause yield reduction. Because of the variety of factors influencing crop yield and quality, the use of visual crop observations to assess soil salinity is not definitive and can be extremely misleading.

The least desirable method to measure salinity distributions in the field is visual observation because crop yields are reduced to obtain soil salininformation, and the crop yield decrements may or may not be related to salinity. However, remote imagery is increasingly becoming a part of agriculture and potentially represents a quantitative approach to visual observation. Remote imagery may offer a potential for early detection of the onset of salinity damage to plants. The expectations for the use of multi- and hyperspectral imagery to map and monitor soil salinity as well as the spatial variability of other soil properties (e.g., water content, mineralogy, and others) is high and will no doubt prove fruitful as research continues in this area.

Geospatial EC_a Measurements

Because of the quickness and ease with which geospatial measurements of EC_a can be obtained and because EC_a measures a variety of properties that potentially influence crop yield and quality (i.e., salinity, water content, texture, OM, bulk density), geospatial EC_a measurements can serve as a surrogate to characterize the spatial variability of a variety of properties, particularly soil salinity (Corwin 2005). It has been hypothesized by Corwin and Lesch (2003, 2005b) that spatial EC_a information can be used to develop a soil sampling plan that identifies sites reflecting the range and variability of soil salinity and/or other soil properties correlated with EC_a. The use of geospatial EC_a measurements to direct a soil sampling plan is referred to as EC_a-directed soil sampling (Corwin 2005). This approach has been demonstrated for not only mapping salinity at field scale (Corwin et al. 2003a; Corwin and Lesch 2005c) but also for applications in (1) precision agriculture to define site-specific management units (Corwin 2005; Corwin et al. 2003b); (2) monitoring management-induced spatio-temporal changes due to degraded water reuse (Corwin et al. 2006); (3) characterizing soil spatial variability (Corwin 2005); and (4) modeling nonpoint source pollutants in the vadose zone (Corwin 2005; Corwin et al. 1999). Each of these applications uses EC_a-directed soil sampling to characterize the spatial variability of a soil property or properties of significance to the particular application.

Electrical resistivity (e.g., Wenner array) and EMI are both well suited for field-scale applications because their volumes of measurement are large, which reduces the influence of local-scale variability. To obtain geospatial measurements, a mobile means of measuring EC_a is essential. Mobile EC_a equipment has been developed by a variety of researchers (Cannon et al. 1994; Carter et al. 1993; Freeland et al. 2002; Jaynes et al. 1993; Kitchen et al. 1996; McNeill 1992; Rhoades 1993). The development of mobile EC_a measurement equipment has made it possible to produce EC_a maps with measurements taken every few meters. Mobile EC_a measurement equipment has been developed for both ER and EMI geophysical approaches.

By mounting the four ER electrodes to "fix" their spacing, considerable time for a measurement is saved. A tractor-mounted version of the "fixed-electrode array" has been developed that georeferences the EC_a measurement with a GPS (Rhoades 1993). The mobile, fixed-electrode-array equipment is well suited for collecting detailed maps of the spatial variability of EC_a at field scales and larger. Veris Technologies (2011) has developed a commercial mobile system for measuring EC_a using the principles of ER, which uses the spacing of 6 coulter electrodes to measure EC_a to depths of 0–30 and 0–91 cm (Fig. 10-9a).

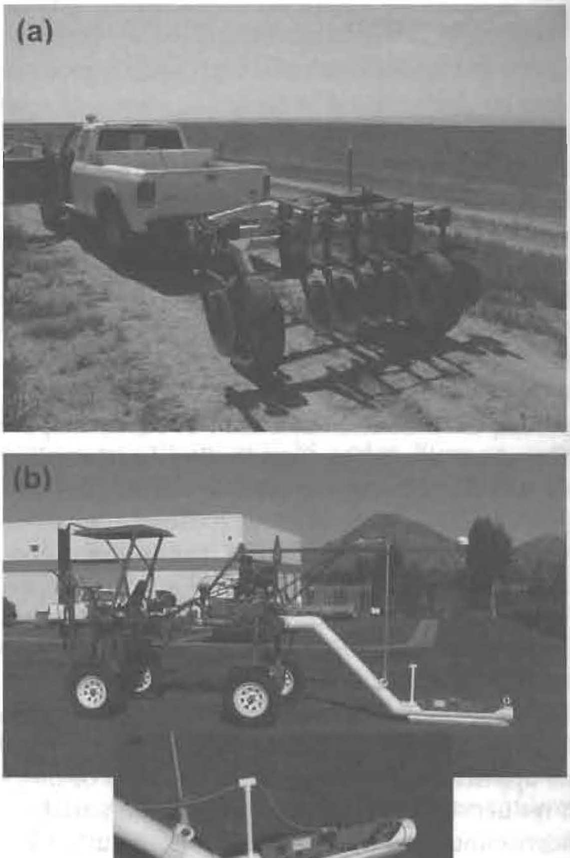

FIGURE 10-9. Mobile apparent soil electrical conductivity (EC_a) equipment: (a) Veris 3100 electrical resistivity rig, and (b) electromagnetic induction rig developed at the U.S. Salinity Laboratory with a close-up of the sled containing a dual-dipole Geonics EM-38.

Mobile EMI equipment developed at the U.S. Salinity Laboratory (Rhoades 1993) is available for appraisal of soil salinity and other soil properties (e.g., water content and clay content) using an EM-38. Recently, the mobile EMI equipment developed at the U.S. Salinity Laboratory was modified by the addition of a dual-dipole EM-38 unit (Fig. 10-8) and DUALEM-2. The dual-dipole EM-38 conductivity meter simultaneously records data in both dipole orientations (horizontal and vertical) at time intervals of just a few seconds between readings. The mobile EMI equipment is suited for the detailed mapping of EC_a and correlated soil properties at specified depth intervals through the root zone. The advantage of the mobile dual-dipole EMI equipment over the mobile fixed-array resistivity equipment is that the EMI technique is noninvasive so it can be used in dry, frozen, or stony soils that would not be amenable to the invasive technique of the fixed-array approach due to the need for good electrode–soil contact. The disadvantage of the EMI approach would be that the EC_a is a depth-weighted value that is nonlinear with depth McNeill (1980).

Scientists at the U.S. Salinity Laboratory have developed an integrated system for the measurement of field-scale salinity consisting of (1) mobile EC_a measurement equipment (Rhoades 1993), (2) protocols for EC_a-directed soil sampling (Corwin and Lesch 2005b), and (3) sample design software (Lesch et al. 2000). The integrated system for mapping soil salinity is schematically illustrated in Figure 10-10.

The protocols of an EC_a survey for measuring soil salinity at field scale include eight basic elements: (1) EC_a survey design, (2) georeferenced EC_a data collection, (3) soil sample design based on georeferenced EC_a data, (4) soil sample collection, (5) physical and chemical analysis of pertinent soil properties, (6) spatial statistical analysis, (7) determination of the dominant soil properties influencing the EC_a measurements at the study site, and (8) GIS development. The basic steps for each element are provided in Table 10-2. A detailed discussion of the protocols can be found in Corwin and Lesch (2005b). Corwin and Lesch (2005c) provide a case study demonstrating the use of the protocols. Arguably, the most significant element of the protocols is the EC_a-directed soil sampling design, which warrants discussion.

Soil Sample Design Based on Geospatial EC_a Data

Once a georeferenced 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 soil sample EC_e and/or (2) delineation of the spatial distribution of soil properties correlated to EC_a within the field surveyed. To establish the locations where soil cores are to be taken, either design-based or prediction-based (i.e., model-based) sampling schemes can be used. Design-

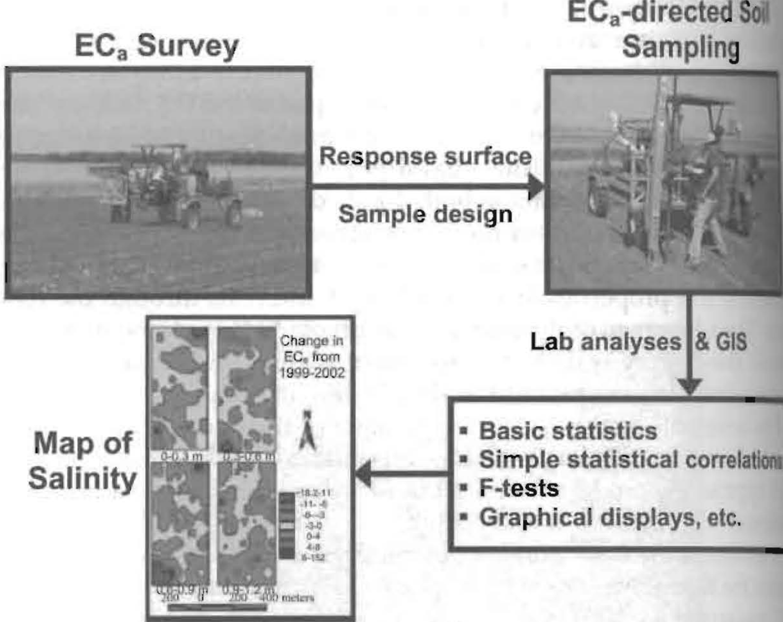

FIGURE 10-10. Schematic of the integrated system for mapping field-scale soil salinity as developed at the U.S. Salinity Laboratory.

based sampling schemes have historically been the most commonly used and hence are more familiar to most research scientists. An excellent review of design-based methods can be found in Thompson (1992). 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. Prediction-based sampling schemes are less common, although significant statistical research has been recently performed in this area (Valliant et al. 2000). Prediction-based sampling approaches have been applied to the optimal collection of spatial data by Müller (2001); the specification of optimal designs for variogram estimation by Müller and Zimmerman (1999); the estimation of spatially referenced linear regression models by Lesch (2005) and Lesch et al. (1995b); and the estimation of geostatistical mixed linear models by Zhu and Stein (2006). Conceptually similar types of nonrandom sampling designs for variogram estimation have been introduced by Bogaert and Russo (1999), Russo (1984), and Warrick and Myers (1987). Both design-based and prediction-based sampling methods can be applied to geospatial EC_a data to direct soil sampling as a means of characterizing soil spatial variability (Corwin and Lesch 2005b).

TABLE 10-2. Outline of Steps to Conduct an EC_a Field Survey to Map Soil Salinity

1. Site description and EC_a survey design
   a. Record site metadata.
   b. Define the project's/survey's objective.
   c. Establish site boundaries.
   d. Select GPS coordinate system.
   e. Establish EC_a measurement intensity.
2. EC_a data collection with mobile GPS-based equipment
   a. Georeference site boundaries and significant physical geographic features with GPS.
   b. Measure georeferenced EC_a data at the predetermined spatial intensity and record associated metadata.
3. Soil sample design based on georeferenced 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).
5. Laboratory analysis of soil salinity and other EC_a-correlated physical and chemical properties defined by project objectives
6. If needed, stochastic and/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
   a. Perform a basic statistical analysis of physical and chemical data, including soil salinity, by depth increment and by composite depth over the depth of measurement of EC_a.
   b. Determine the correlation between EC_a and salinity and between EC_a and other soil properties by composite depth over the depth of measurement of EC_a.
8. GIS database development and graphic display of spatial distribution of soil properties

Modified from Corwin and Lesch (2005b) specifically for mapping soil salinity.

The prediction-based sampling approach was introduced by Lesch et al. (1995b). This sampling approach attempts to optimize the estimation of a regression model, that is, minimize the mean square prediction error produced by the calibration function, while simultaneously ensuring 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. The basis for this sampling approach stems directly from traditional response-surface sampling methodology (Box and Draper 1987).

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 EC_a data. Indeed, many types of ground-, airborne-, and/or satellite-based remotely sensed data are often collected specifically because one expects these data to correlate strongly with some parameter of interest (e.g., crop stress, soil type, soil salinity), but the exact parameter estimates (associated with the calibration model) may still need to be determined via some type of site-specific sampling design. The response-surface approach explicitly optimizes this site selection process.

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 2005; Corwin et al. 2003a,b, 2006; Corwin and Lesch 2003, 2005c). 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, 6 to 20 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.

Once the number and location of the sample sites have been established, the depth of soil core sampling, sample depth increments, and number of sites where duplicate or replicate core samples should be taken are established. The depth of sampling should be the same at each sample site and should extend over the depth of penetration by the EC_a-measurement equipment used. For instance, the Geonics EM-38 measures to a depth of roughly 0.75 to 1.0 m in the horizontal coil configuration (EM_h) and 1.2 1.5 m in the vertical coil configuration (EM_v). Sample depth increments are flexible and depend to a great extent on the study objectives. A depth increment of 0.3 m has been commonly used at the U.S. Salinity Laboratory because it provides sufficient soil profile information over the volume (0–1.2 to 1.5 m) for statistical analysis without an overly burdensome number of samples to conduct physical and chemical analyses. Depth increments should be the same from one sample site to the next. The number of duplicates or replicates taken at each sample site is determined by the desired accuracy for characterizing soil properties and the need for establishing the level of local-scale variability at the site. Duplicates or replicates are not necessarily needed at every sample site to establish local-scale variability.

Considerations when Conducting an EC_a Survey

A number of considerations must be heeded when conducting a geospatial EC_a survey to map soil salinity. Each of these considerations can influence the EC_a measurement, leading to a potential misinterpretation of the salinity distribution. These considerations account for temporal moisture, surface roughness, and surface geometry effects.

Temporal comparisons of geospatial EC_a measurements to determine spatio-temporal changes in salinity patterns of distribution can only be made from EC_a survey data that have been obtained under similar water-content and temperature conditions. Surveys of EC_a should be conducted when the water content is at or near field capacity and the soil profile temperatures are similar. For irrigated fields, EC_a surveys should be conducted roughly two to four days after an irrigation, or longer if the soil is high in clay content and additional time is needed for the soil to drain to field capacity. For dryland farming, the survey should occur two to four days after a substantial rainfall, or longer, depending on soil texture. The effects of temperature can be addressed by taking soil profile temperatures at the time of the EC_a survey and temperature-correcting the EC_a measurements, or by conducting the surveys roughly at the same time during the year so that the temperature profiles are the same for each survey.

The type of irrigation used can influence the within-field spatial distribution of water content and should be kept in mind as a factor influencing EC_a spatial patterns. Sprinkler irrigation has a high level of application uniformity, whereas flood irrigation and drip irrigation are highly nonuniform. In general, flood irrigation results in higher water contents and overleaching at the "head" end of the field, while underleaching and lower water contents can occur at the "tail" end of the field. This general across-the-field trend is observed for both flood irrigation with basins and flood irrigation with beds and furrows, but beds and furrows introduce an added level of localized complexity. Flood irrigation with beds and furrows results in localized variations in water content, with high water contents and greater leaching occurring under the furrows while beds will typically show lower water contents and accumulations of salinity.

The presence or absence of beds and furrows is a significant factor during a geospatial EC_a survey. Measurements taken in furrows will differ from measurements taken in beds due to water flow and salt accumulation patterns. In addition, the physical presence of the bed influences the conductivity pathways, particularly when using EMI. These surface geometry effects are in addition to the effects of moisture and salinity distribution patterns that are present in beds and furrows. To assess salinity in a bed-furrow irrigated field, it is probably best to take the EC_a measurements in the bed. Above all, the EC_a measurements must be consistent, either entirely in the furrow or entirely in the bed.

Surveys of drip-irrigated fields are even more complicated than EC_a surveys of bed-furrow irrigated fields. Drip irrigation produces complex local- and field-scale three-dimensional patterns of water content and salinity that are particularly difficult to spatially characterize with geospatial EC_a measurements (or any salinity measurement technique, for that matter). The easiest approach is to run EC_a transects both over and between drip lines to capture the local-scale variation.

The roughness of the soil surface can also influence spatial EC_a measurements. Geospatial EC_a measurements taken on a smooth field surface will be higher than the same field with a rough surface from disking. This is due to the fact that the disturbed disked soil acts as an insulated layer to the conductance pathways, thereby reducing its conductance. When conducting a geospatial EC_a survey of a field, the entire field must have the same surface roughness.

These factors, if not taken into account when conducting an EC_a survey, will likely produce a "banding" effect. For example, if an EC_a survey is conducted on a field that has areal differences in water content, soil profile temperature, surface roughness, and surface geometry, then bands of EC_a such as those found in Fig. 10-11 will result. These bands reflect the variations in soil moisture, temperature, roughness, and surface geometry, which must be uniform across a field to produce a reliable EC_a survey that can be used to direct soil sampling to spatially characterize the distribution of salinity.

USE OF REMOTE IMAGERY FOR MEASURING SOIL SALINITY AT FIELD AND LANDSCAPE SCALES

While field-based measurements of soil salinity have progressed greatly over the past decades, they remain limited to mapping soil salinity over a small number of fields in a single day. Assessments of soil salinity across entire landscapes and through time are therefore difficult and expensive to conduct with field-based approaches alone. Remote sensing instruments aboard airplanes or satellites routinely acquire measure-

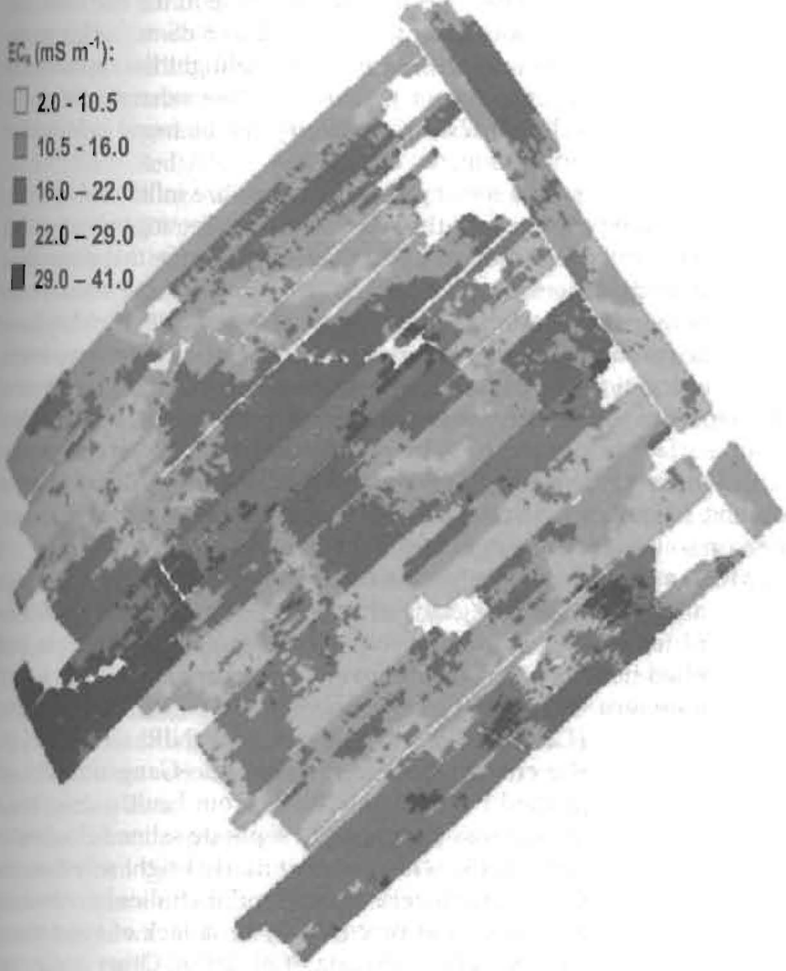

FIGURE 10-11. *A poorly designed apparent soil electrical conductivity (EC_a) survey showing the banding that occurs when surveys are conducted at different times under varying water contents, temperatures, surface roughnesses, and surface geometry conditions.*

ments of energy reflected or emitted from the land surface across wide swaths of land, thus presenting an opportunity for low-cost mapping of salinity at broad scales.

Unfortunately, in our estimation, efforts to relate remote sensing data to soil salinity have achieved limited success. Most methods have been highly empirical in nature, and empirical relationships successful in one case have tended to break down when applied to data from different scales, years, or locations. This is especially true in the case of mapping salinity at slight to moderate levels (EC_e = 2 to 8 dS m^{-1}). Here we provide a selective review of past work and highlight the approaches we believe are most promising for the future. More exhaustive reviews of remote sensing techniques for soil salinity can be found in Metternicht and Zinck (2003) and Mougenot et al. (1993)

As with EC_a, remote sensing measurements are influenced by a range of land surface properties, with soil salinity representing only one of these factors. The overall challenge is to find some measure that is sensitive to soil salinity but insensitive to other factors that vary in the landscape. This measure may be reflectance or emittance at a particular wavelength, or a strategic combination of measurements made at different wavelengths, dates, or locations. Importantly, the appropriate measure may depend on the aspect of soil salinity that is of interest. For example, reflectance from a soil surface is affected by salinity only in the upper few centimeters of soil, which may not be representative of average salinity at greater depths. In contrast, reflectance from plant canopies can provide information on soil salinity throughout the rootzone.

Much of the work on remote sensing of salinity has been done in the two major agricultural regions affected by salinity: the irrigated systems of India and Pakistan and the rain-fed systems of Australia. Early work relied heavily on visual interpretation of aerial photos or Landsat satellite images. Verma et al. (1994) observed that remote indicators of canopy biomass [Landsat red and near-infrared (NIR) reflectance] during the peak of the cropping season in the Indo-Gangetic Plains successfully distinguished barren saline soils from healthy crop land. A Landsat thermal image was then used to separate saline fields from fallow fields with sandy soils, which had similarly bright reflectance values but lower soil moisture levels. Many similar studies have been conducted throughout India that rely mainly on a lack of vegetation on salt-affected soils (IDNP 2002; Sharma et al. 2000). Other studies have used images acquired prior to the growing season, when white salt crusts on the surface of saline soils are significantly brighter than nonsaline soils (IDNP 2002).

Both of these approaches can be quite useful for mapping severely saline soils (EC_e > 25 dS m^{-1}), but are problematic for less severe cases that are not marked by salt crusts and barren land. In general, an important factor in evaluating any study is the range of salinity values sampled. For example, a high model R^2 can be driven by a few points above 20 dS m^{-1}, even though the model's predictive power at lower levels is poor.

The more challenging problem of mapping slight to moderate salinity has been approached in several ways. A common method has been to use the health of crop condition as an indicator of soil salinity. In aerial photos when with color infrared film, dense vegetation appears bright red, saline soils appear bright white, and fields with sparse canopies appear pinkish. Multispectral satellite data can be similarly displayed and interpreted visually. More quantitative measures can also be used, such as the normalized difference vegetation index (NDVI) based on NIR and red reflectance: NDVI = (NIR − Red)/(NIR + Red).

For example, Wiegand et al. (1994, 1996) found strong linear relationships between NDVI and rootzone salinity in salt-affected cotton and sugarcane fields. However, such simple relationships are only likely to exist in cases where salinity is the major factor responsible for variability in crop yield. Landscapes with only slight to moderate salinity are likely to have many other factors, such as field management, that affect yields as much or more than salinity. Extrapolation of relationships within a small number of salt-affected fields to an entire landscape can therefore result in large errors.

To address this problem, some have proposed using average crop yields over a number of years to filter out noise from nonsoil factors, which tend to vary from year to year. Lobell et al. (2007) found very weak relationships between salinity and yields in individual years in the Colorado River delta region of Mexico, but much stronger correspondence between salinity and maximum yield over a six-year period. In Australia, Furby et al. (1995) reported large commission errors for a classification of saline soils when using a single year of image data, because many areas of poor crop condition were incorrectly labeled as saline. These errors of commission were reduced from 20% to 2% by the addition of a second year of Landsat data.

Another common approach is to estimate salinity from soil reflectance measured when the surface is bare. These methods rely on the bright visible reflectance of surface salts, several characteristic absorption features at longer wavelengths, or both (Ben-Dor et al. 2002; Csillag et al. 1993; Dehaan and Taylor 2002). However, because soil reflectance can vary greatly due to spatially and temporally variable moisture or surface roughness conditions, these techniques often result in poor accuracies when applied outside of the calibration dataset. As mentioned, soil salinity at the surface can also correlate poorly with average rootzone salinity.

A less-developed but promising approach is to exploit the spatial dimension of remote sensing data. Because salts tend to be spatially heterogeneous, saline fields may be identified by a high standard deviation of NDVI within fields (Metternicht and Zinck 1997). This approach requires relatively high spatial resolution imagery, accurate information on field boundaries, and a relatively low contribution of other factors to within-field heterogeneity.

Overall, no single remote sensing approach has proven particularly effective for mapping salinity at low to moderate levels. Therefore, the most successful approaches are likely to combine information from a variety of sources, including multiple remote sensing measures as well as several nonremote indicators such as landscape position, soil type, and topography (Furby et al. 1995; Metternicht 2001; Tweed et al. 2007). As with any spatial prediction problem, the use of independent validation data will also be critical to evaluating and improving salinity estimates. For example, simply extrapolating local empirical relationships to estimate regional totals (Madrigal et al. 2003) should be avoided. As Furby et al. (1995) demonstrate, reserving a significant fraction (in their case, half) of sites for independent validation can help to identify shortcomings in the original algorithms and suggest improvements. Another important methodological consideration for regional mapping is that sites should be selected at random and not preferentially in saline areas. Table 10-3 presents a summary of elements that are most likely, in our opinion, to result in successful salinity mapping with remote sensing at landscape scales. Recently, Lobell et al. (2010) published a successful regional-scale salinity assessment of 284,000 ha using these recommended elements.

TABLE 10-3. Some Elements Key to Successful Remote Sensing of Salinity at Landscape Scales

Element	Comment
Well-timed image acquisition	Images should be selected, if possible, from end of dry season for methods based on soil reflectance, or from peak of growing season for methods based on crop canopy reflectance.
Randomly selected training sites	A bias of training sites toward high-salinity fields will likely result in an overestimation of regional salinity levels.
Independent validation data	Prediction errors for test data can be much larger than training errors.
Multiple years of images	Nonsoil factors can heavily influence reflectance in any one year, but will tend to average out over multiple years.
Ancillary data	Combining remote sensing with other GIS data (soil texture, topography, etc.) can greatly improve model accuracy.

SUMMARY

The various methods of measuring/estimating soil salinity have pros and cons:

- While precise and reliable, directly measuring the aqueous extract of soil samples in the laboratory is labor-intensive and costly.
- The use of soil samples to measure salinity at field scales is only effective if sampling is directed using an easy-to-take surrogate measurement, such as apparent soil electrical conductivity (EC_a), to minimize the number of samples.
- The sample volumes of soil solution extractors and soil salinity sensors are small, which affects their ability to provide data representative of field conditions.
- Measurements of apparent soil conductivity (EC_a) can be made based on electrical resistivity (ER), electromagnetic induction (EMI), and time-domain reflectometry (TDR). In general, when measuring EC_a, it is important to take into consideration the multiple pathways of electrical conductivity in the bulk soil; consequently, EC_a may be affected by salinity, texture, water content, bulk density, organic matter in the soil, cation exchange capacity, clay mineralogy, and soil temperature.
- For field-scale salinity measurement, a systematic EC_a-directed sampling approach is required that minimizes the primary influences of soil property effects (such as water content, texture, bulk density, and soil temperature) and avoids the confounding secondary influences of soil condition effects (such as surface roughness, presence or absences of beds and furrows, ambient air temperature effects on the instrumentation, and compaction) to reliably measure the target property of soil salinity.
- Remote sensing techniques are an experimental approach to mapping soil salinity over regional scales with tremendous potential, but better correlations between energy strength and spectrum and field conditions are needed before the technique is reliable.

The technique for measuring and mapping soil salinity at field scale with EC_a-directed soil sampling is well understood, and an eight-step protocol is outlined in Table 10-2.

REFERENCES

Amoozegar-Fard, A., Nielsen, D. R., and Warrick, A. W. (1982). "Soil solute concentration distributions for spatially varying pore water velocities and apparent diffusion coefficients." *Soil Sci. Soc. Am. J.*, 46, 3–9.

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

Banton, O., Seguin, M. K., and Cimon, M. A. (1997). "Mapping field-scale physical properties of soil with electrical resistivity." *Soil Sci. Soc. Am. J.*, 61(4), 1010–1017.

Barnes, H. E. (1952). "Soil investigation employing a new method of layer-value determination for earth resistivity interpretation." *Highway Res. Board Bull.*, 65, 26–36.

Ben-Dor, E., Patkin, K., Banin, A., and Karnieli, A. (2002). "Mapping of several soil properties using DAIS-7915 hyperspectral scanner data: A case study over clayey soils in Israel." *Int. J. Remote Sens.*, 23, 1043–1062.

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

Benson, A. K., Payne, K. L., and Stubben, M. A. (1997). "Mapping groundwater contamination using DC resistivity and VLF geophysical methods: A case study." *Geophysics*, 62(1), 80–86.

Biggar, J. W., and Nielsen, D. R. (1976). "Spatial variability of the leaching characteristics of a field soil." *Water Resour. Res.*, 12, 78–84.

Boettinger, J. L., Doolittle, J. A., West, N. E., Bork, E. W., and Schupp, E. W. (1997). "Nondestructive assessment of rangeland soil depth to petrocalcic horizons using electromagnetic induction." *Arid Soil Res. Rehabil.*, 11(4), 372–390.

Bogaert, P., and Russo, D. (1999). "Optimal spatial sampling design for the estimation of the variogram based on a least squares approach." *Water Resour. Res.*, 35, 1275–1289.

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

Box, G. E. P., and Draper, N. R. (1987). *Empirical model-building and response surfaces*, John Wiley and Sons, New York.

Bresler, E., McNeal, B. L., and Carter, D. L. (1982). *Saline and sodic soils*, Springer-Verlag, New York, 174–181.

Brevik, E. C., and Fenton, T. E. (2002). "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 Surv. Horiz.*, 43, 9–13.

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

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

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

Burger, H. R. (1992). *Exploration geophysics of the shallow subsurface*, Prentice Hall, Upper Saddle River, N.J.

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

Cameron, M. E., McKenzie, R. C., and Lachapelle, G. (1994). "Soil-salinity mapping with electromagnetic induction and satellite-based navigation methods." *Can. J. Soil Sci.*, 74(3), 335–343.

Carter, L. M., Rhoades, J. D., and Chesson, J. H. (1993). *Mechanization of soil salinity assessment for mapping*, ASAE Paper No. 931557, 1993 ASAE Winter Meetings, December 12-17, 1993, Chicago, ASAE, St. Joseph, Mich.

Cook, P. G., and Kilty, S. (1992). "A helicopter-borne electromagnetic survey to delineate groundwater recharge rates." *Water Resour. Res.*, 2 (11), 2953–2961.

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

Corwin, D. L. (2002a). "Solute content and concentration—Measurement of solute concentration using soil water extraction: Suction cups," in *Methods of soil analysis. Part 4: Physical methods*, J. H. Dane and G. C. Topp, eds., SSSA Book Series No. 5. SSSA, Madison, Wisc., 1261–1268.

——. (2002b). "Solute content and concentration—Measurement of solute concentration using soil water extraction: Porous matrix sensors," in *Methods of soil analysis. Part 4: Physical methods*, J. H. Dane and G. C. Topp, eds., SSSA Book Series No. 5. SSSA, Madison, Wisc., 1269–1273.

——. (2005). "Geospatial measurements of apparent soil electrical conductivity for characterizing spatial variability," in *Soil-water-solute process characterization: An integrated approach*, J. Alvarez-Benedi and R. Munoz-Carpena, eds., CRC Press, Boca Raton, Fla., 639–672.

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

Corwin, D. L., and Hendrickx, J. M. H. (2002). "Solute content and concentration—Indirect measurement of solute concentration: Electrical resistivity—Wenner array," in *Methods of soil analysis. Part 4: Physical methods*, J. H. Dane and G. C. Topp, eds., Agronomy Monograph No. 9, SSSA, Madison, Wisc., 1282–1287.

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

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

——. (2005a). "Apparent soil electrical conductivity measurements in agriculture." *Comput. Electron. Agric.*, 46, 11–43.

——. (2005b). "Characterizing soil spatial variability with apparent soil electrical conductivity I. Survey protocols." *Comput. Electron. Agric.*, 46, 103–133.

——. (2005c). "Characterizing soil spatial variability with apparent soil electrical conductivity II. Case study." *Comput. Electron. Agric.*, 46, 135–152.

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

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

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

———. (1984). "Measurement of inverted electrical conductivity profiles using electromagnetic induction." *Soil Sci. Soc. Am. J.*, 48, 288–291.

———. (1990). "Establishing soil electrical conductivity: Depth relations from electromagnetic induction measurements." *Commun. Soil Sci. Plant Anal.*, 21(11–12), 861–901.

Csillag, F., Pasztor, L., and Biehl, L. L. (1993). "Spectral band selection for the characterization of salinity status of soils." *Remote Sens. Environ.*, 43, 231–242.

Dalton, F. N. (1992). "Development of time domain reflectometry for measuring soil water content and bulk soil electrical conductivity," in *Advances in measurement of soil physical properties: Bringing theory into practice*, G. C. Topp, W. D. Reynolds, and R. E. Green, eds., SSSA Special Publication 30, SSSA, Madison, Wisc., 143–167.

Dalton, F. N., Herkelrath, W. N., Rawlins, D. S., and Rhoades, J. D. (1984). "Time domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe." *Science*, 224, 989–990.

Dane, J. H., and Topp, G. C. (eds.). (2002). *Methods of soil analysis: Part 4: Physical methods*. SSSA Book Series 5. SSSA, Madison, Wisc.

Dehaan, R. L., and Taylor, G. R. (2002). "Field-derived spectra of salinized soils and vegetation as indicators of irrigation-induced soil salinization." *Remote Sens. Environ.*, 80, 406–417.

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

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

Dobrin, M. B. (1960). *Introduction to geophysical prospecting*, McGraw-Hill, New York.

Doolittle, J. A., Indorante, S. J., Potter, D. K., Hefner, S. G., and McCauley, W. M. (2002). "Comparing three geophysical tools for locating sand blows in alluvial soils of southeast Missouri." *J. Soil Water Conserv.*, 57(3), 175–182.

Doolittle, J. A., Sudduth, K. A., Kitchen, N. R., and Indorante, S. J. (1994). "Estimating depths to claypans using electromagnetic induction methods." *J. Soil Water Conserv.*, 49(6), 572–575.

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

Dualem. (2007). "DUALEM-2," Dualem Inc., Milton, Ontario, Canada, www.dualem.com/documents.html, accessed June 2007.

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

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

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

—— (1999). *Soil conductivity map differences for monitoring temporal changes in an agronomic field*, ASAE Paper No. 992176, ASAE, St. Joseph, Mich.

—— (2001). *Identification of nutrient distribution at abandoned livestock manure handling site using electromagnetic induction*, ASAE Paper No. 012193 ASAE Annual International Meeting, July 30–August 1, 2001, Sacramento, California, ASAE, St. Joseph, Mich.

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

England, C. B. (1974). "Comments on 'A technique using porous cups for water sampling at any depth in the unsaturated zone,' by W. W. Wood." *Water Resour. Res.*, 10, 1049.

Farahani, H. J., Buchleiter, G. W., and Brodahl, M. K. (2005). "Characterization of soil electrical conductivity variability in irrigated sandy and non-saline fields in Colorado." *Trans. ASAE*, 48(1), 155–168.

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

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

Fraisse, C. W., Sudduth, K. A., and Kitchen, N. R. (2001). "Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity." *Trans. ASAE*, 44 (1), 155–166.

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

Freeland, R. S., Yoder, R. E., Ammons, J. T., and Leonard, L. L. (2002). "Mobilizing surveying of soil conductivity using electromagnetic induction." *Appl. Eng. Agric.*, 18(1), 121–126.

Furby, S. L., Wallace, J. F., Caccetta, P., and Wheaton, G. A. (1995). "Detecting and monitoring salt-affected land." CSIRO Mathematical and Information Sciences, www.cmis.csiro.au/rsm/research/salmapmon/salmapmon.html, accessed July 4, 2007.

Giese, K., and Tiemann, R. (1975). "Determination of the complex permittivity from thin-sample time domain reflectometry: Improved analysis of the step response waveform." *Adv. Mol. Relax. Processes*, 7, 45–59.

Gorucu, S., Khalilian, A., Han, Y. J., Dodd, R. B., Wolak, F. J., and Keskin, M. (2001). *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, July 30–August 1, 2001, Sacramento, California, ASAE, St. Joseph, Mich.

Greenhouse, J. P., and Slaine, D. D. (1983). The use of reconnaissance electromagnetic methods to map contaminant migration." *Ground Water Monit. Rev.*, 3(2), 47–59.

———. (1986). "Geophysical modelling and mapping of contaminated groundwater around three waste disposal sites in southern Ontario." *Can. Geotech. J.*, 23, 372–384.

Haines, B. L., Waide, J. B., and Todd, R. L. (1982). "Soil solution nutrient concentrations sampled with tension and zero-tension lysimeters: Report of discrepancies." *Soil Sci. Soc. Am. J.*, 46, 658–661.

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

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

Harned, H. S., and Owen, B. B. (1958). *The physical chemistry of electrolyte solutions*. Reinhold Publishing Corp., New York.

Hart, G. L., and Lowery, B. (1997). "Axial-radial influence of porous cup soil solution samplers in a sandy soil." *Soil Sci. Soc. Am. J.*, 61, 1765–1773.

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

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

Hendrickx, J. M. H., and Kachanoski, R. G. (2002). "Solute content and concentration: Indirect measurement of solute concentration: Nonintrusive electromagnetic induction," in *Methods of soil analysis. Part 4: Physical methods*, J. H. Dane and G. C. Topp, eds., Agronomy Monograph No. 9, SSSA, Madison, Wisc., 1297–1306.

Herrero, J., Ba, A. A., and Aragues, R. (2003). "Soil salinity and its distribution determined by soil sampling and electromagnetic techniques." *Soil Use Mgmt.*, 19(2), 119–126.

Indo-Dutch Network Project (IDNP). (2002). *Indo-Dutch network project. A methodology for identification of waterlogging and soil salinity conditions using remote sensing*, CCSRI, Karnal, India and Alterra-ILRI, Wageningen, The Netherlands.

Inman, D. J., Freeland, R .S., Yoder, R. E., Ammons, J. T., and Leonard, L. L. (2001). "Evaluating GPR and EMI for morphological studies of loessial soils." *Soil Sci.*, 166(9), 622–630.

Jacobsen, O. H., and Schjønning, P. (1993). "A laboratory calibration of time domain reflectometry for soil water measurements including effects of bulk density and texture." *J. Hydrol.* 151, 147–157.

Jaynes, D. B. (1996). "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*, SSSA Special Publication No. 48, D. L. Corwin and K. Loague, eds., SSSA, Madison, Wisc., 205–216.

Jaynes, D. B., Colvin, T. S., and Ambuel, J. (1993). *Soil type and crop yield determinations from ground conductivity surveys*, ASAE Paper No. 933552, 1993 ASAE Winter Meetings, December 14–17, 1993, Chicago, ASAE, St. Joseph, Mich.

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

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

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

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

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

Kaffka, S. R., Lesch, S. M., Bali, K. M., and Corwin, D. L. (2005). "Site-specific management in salt-affected sugar beet fields using electromagnetic inductive methods." *Comput. Electron. Agric.*, 46, 329–350.

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

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

Kitchen, N. R., Sudduth, K. A., and Drummond, S. T. (1996). "Mapping of sand deposition from 1993 Midwest floods with electromagnetic induction measurements." *J. Soil Water Conserv.*, 51(4), 336–340.

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

Lesch, S. M. (2005). "Sensor-directed response surface sampling designs for characterizing spatial variation in soil properties." *Comput. Electron. Agric.*, 46 (1–3), 153-179.

Lesch, S. M., Corwin, D. L., and Robinson, D. A. (2005). "Apparent soil electrical conductivity mapping as an agricultural management tool in arid zone soils." *Comput. Electron. Agric.*, 46 (1–3), 351–378.

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

Lesch, S. M., Rhoades, J. D., and Corwin, D. L. (2000). *ESAP-95 version 2.10R: User and tutorial guide*, Research Report 146, USDA-ARS, U.S. Salinity Laboratory, Riverside, Calif.

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

Lesch, S. M., Strauss, D. J., and Rhoades, J. D. (1995a). "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.

———. (1995b). "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.

Lobell, D. B., Lesch, S. M., Corwin, D. L., Ulmer, M. G., Anderson, K. A., Potts, D. J., Doolittle, J. A., Matos, M. R., and Baltes, M. J. (2010). "Regional-scale assessment of soil salinity in the Red River Valley using multi-year MODIS EVI and NDVI," *J. Environ. Qual.*, 39, 35–41.

Lobell, D. B., Ortiz-Monasterio, J. I., Gurrola, F. C., and Valenzuela, L. (2007). "Identification of saline soils with multiyear remote sensing of crop yields." *Soil Sci. Soc. Am. J.*, 71, 777–783.

Madrigal, L. P., Wiegand, C. L., Meraz, J. G., Rubio, B. D. R., Estrada, X. C., and Ramirez, O. L. (2003). "Soil salinity and its effect on crop yield: A study using satellite imagery in three irrigation districts." *Ingenieria Hidraulica En Mexico*, 18, 83–97.

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

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

Mankin, K. R., and Karthikeyan, R. (2002). "Field assessment of saline seep remediation using electromagnetic induction." *Trans. ASAE*, 45(1), 99–107.

Maas, E. V. 1986. "Salt tolerance of plants." *Appl. Agric. Res.*, 1, 12–25.

Marion, G. M., and Babcock, K. L. (1976). "Predicting specific conductance and salt concentration of dilute aqueous solution." *Soil Sci.*, 122, 181–187.

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

McNeill, J. D. (1980). *Electromagnetic terrain conductivity measurement at low induction numbers*, Technical Note TN-6, Geonics Ltd., Mississauga, Ontario, Canada.

———. (1992). "Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters," in *Advances in measurements of soil physical properties: Bringing theory into practice*, SSSA Special Publication No. 30, G. C. Topp, W. D. Reynolds, and R. E. Green, eds., ASA-CSSA-SSSA, Madison, Wisc., 201–229.

Metternicht, G. (2001). "Assessing temporal and spatial changes of salinity using fuzzy logic, remote sensing and GIS. Foundations of an expert system." *Ecol. Model.*, 144, 163–179.

Metternicht, G., and Zinck, J. A. (1997). "Spatial discrimination of salt- and sodium-affected soil surfaces." *Int. J. Remote Sens.*, 18, 2571–2586.

——. (2003). "Remote sensing of soil salinity: Potentials and constraints." *Remote Sens. Environ.*, 85, 1–20.

Mougenot, B., Pouget, M., and Epema, G. F. (1993). "Remote sensing of salt affected soils." *Remote Sens. Rev.*, 7, 241–259.

Morgan, C. L. S., Norman, J. M., Wolkowski, R. P., Lowery, B., Morgan, G. D., and Schuler, R. (2000). "Two approaches to mapping plant available water: EM-38 measurements and inverse yield modeling," in *Proc., 5th Int. Conf. on Precision Agriculture, Minneapolis, Minnesota, July 16–19, 2000*, P. C. Roberts, R. H. Rust, and W. E. Larson, eds., ASA-CSSA-SSSA, Madison, Wisc., 14 [CD-ROM].

Müller, W. G. (2001). *Collecting spatial data: Optimum design of experiments for random fields*, 2nd ed., Physica-Verlag, Heidelberg.

Müller, W. G., and Zimmerman, D. L. (1999). "Optimal designs for variogram estimation." *Environmetrics*, 10, 23–37.

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

Nobes, D. C., Armstrong, M. J., and Close, M. E. (2000). "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(3), 328–336.

Nyquist, J. E., and Blair, M. S. (1991). "Geophysical tracking and data logging system: Description and case history." *Geophysics*, 56(7), 1114–1121.

Paine, J. G. (2003). "Determining salinization extent, identifying salinity sources, and estimating chloride mass using surface, borehole, and airborne electromagnetic induction methods." *Water Resour. Res.*, 39(3), 1059.

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

Raulund-Rasmussen, K. (1989). "Aluminum contamination and other changes of acid soil solution isolated by means of porcelain suction cups." *J. Soil Sci.*, 40, 95–102.

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

Reitemeier, R. F., and Wilcox, L. V. (1946). "A critique of estimating soil solution concentrations from the electrical conductivity of saturated soils." *Soil Sci.*, 61, 281–293.

Rhoades, J. D. (1992). "Instrumental field methods of salinity appraisal," in *Advances in measurement of soil physical properties: Bringing theory into practice*, SSSA Special Publication No. 30, G. C. Topp, W. D. Reynolds, and R. E. Green, eds., SSSA, Madison, Wisc., 231–248.

——. (1993). "Electrical conductivity methods for measuring and mapping soil salinity," in *Advances in agronomy*, D. L. Sparks, ed., Vol. 49, Academic Press, San Diego, Calif., 201–251.

Rhoades, J. D., Chanduvi, F., and Lesch, S. (1999b). *Soil salinity assessment: Methods and interpretation of electrical conductivity measurements*, FAO Irrigation and Drainage Paper No. 57, Food and Agriculture Organisation of the United Nations, Rome.

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

———. (1990). "Soil electrical conductivity: Effects of soil properties and application to soil salinity appraisal,." *Commun. Soil Sci. Plant Anal.*, 21, 837–860.

Rhoades, J. D., Corwin, D. L., and Lesch, S. M. (1999a). "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*, D. L. Corwin, K. Loague, and T. R. Ellsworth, eds., Geophysical Monograph 108, American Geophysical Union, Washington, D.C., 197–215.

Rhoades, J. D., and Halvorson, A. D. (1977). *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, Calif., 1–45.

Rhoades, J. D., and Loveday, J. (1990). "Salinity in irrigated agriculture," in *Irrigation of agricultural crops*, Agronomy Monograph No. 30, B. A. Stewart and D. R. Nielsen, eds., SSSA, Madison, Wisc., 1089–1142.

Rhoades, J. D., Manteghi, N. A., Shouse, P. J., and Alves, W. J. (1989a). "Estimating soil salinity from saturated soil-paste electrical conductivity." *Soil Sci. Soc. Am. J.*, 53, 428–433.

———. (1989b). "Soil electrical conductivity and soil salinity: New formulations and calibrations. *Soil Sci. Soc. Am. J.*, 53, 433–439.

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

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

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

Salama, R. B., Bartle, G., Farrington, P., and Wilson, V. (1994). "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.

Scanlon, B. R., Paine, J. G., and Goldsmith, R. S. (1999). "Evaluation of electromagnetic induction as a reconnaissance technique to characterize unsaturated flow in an arid setting." *Ground Water*, 37(2), 296–304.

Sharma, R. C., Saxena, R. K., and Verma, K. S. (2000). "Reconnaissance mapping and management of salt-affected soils using satellite images." *Int. J. Remote Sens.*, 21, 3209–3218.

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

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

Smith, C. N., Parrish, R. S., and Brown, D. S. (1990). "Conducting field studies for testing pesticide leaching models." *Int. J. Environ. Anal. Chem.*, 39, 3–21.

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.

Sparks, D. L., ed. (1996). *Methods of soil analysis: Part 3—Chemical methods*, SSSA Book Series 5, SSSA, Madison, Wisc.

Stroh, J. C., Archer, S. R., Doolittle, J. A., and Wilding, L. P. (2001). Detection of edaphic discontinuities with ground-penetrating radar and electromagnetic induction." *Landscape Ecol.*, 16(5), 377–390.

Stroh, J. C., Archer, S. R., Wilding, L. P., and Doolittle, J. A. (1993). "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.

Suarez, D. L., and Taber, P. (2007). *ExtractChem software: Version 1.0.18*, U.S. Salinity Laboratory, Riverside, Calif.

Sudduth, K. A., and Kitchen, N. R. (1993). *Electromagnetic induction sensing of claypan depth*, ASAE Paper No. 931531, 1993 ASAE Winter Meetings, December 12–17, 1993, Chicago, ASAE, St. Joseph, Mich.

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. (2005). "Relating apparent electrical conductivity to soil properties across the north-central USA." *Comput. Electron. Agric.*, 46 (1–3), 263–283.

Telford, W. M., Gledart, L. P., and Sheriff, R. E. (1990). *Applied geophysics*, 2nd ed., Cambridge University Press, Cambridge, UK.

Thompson, S. K. (1992). *Sampling*, John Wiley and Sons, Inc., New York.

Topp, G. C., and Davis, J. L. 1981. "Detecting infiltration of water through the soil cracks by time-domain reflectometry." *Geoderma* 26, 13–23.

Topp, G. C., Davis, J. L., and Annan, A. P. (1980). "Electromagnetic determination of soil water content: Measurement in coaxial transmission lines." *Water Resour. Res.*, 16, 574–582.

——. (1982). "Electromagnetic determination of soil water content using TDR: 1. Applications to wetting fronts and steep gradients." *Soil Sci. Soc. Am. J.*, 46, 672–678.

Triantafilis, J., Ahmed, M. F., and Odeh, I. O. A. (2002). "Application of a Mobile Electromagnetic Sensing System (MESS) to assess cause and management of soil salinization in an irrigated cotton-growing field." *Soil Use Mgmt.*, 18(4), 330–339.

Triantafilis, J., Huckel, A. I., and Odeh, I. O. A. (2001). "Comparison of statistical prediction methods for estimating field-scale clay content using different combinations of ancillary variables." *Soil Sci.*, 166(6), 415–427.

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

Tweed, S . O., Leblanc, M., Webb, J. A., and Lubczynski, M. W. (2007). "Remote sensing and GIS for mapping groundwater recharge and discharge areas in salinity-prone catchments, southeastern Australia." *Hydrogeol. J.*, 15, 75–96.

U.S. Salinity Laboratory. (1954). *Diagnosis and improvement of saline and alkali soils*, U.S. Department of Agriculture Handbook No. 60, U.S. Government Printing Office, Washington, D.C.

Valliant, R., Dorfman, A. H., and Royall, R. M. (2000). *Finite population sampling and inference: A prediction approach*, John Wiley and Sons, Inc., New York.

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

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

Veris Technologies. (2011) "Products," Veris Technologies, Salina, Kansas, www.veristech.com, accessed January 21, 2011.

Verma, K. S., Saxena, R. K., Barthwal, A. K., and Deshmukh, S. N. (1994). "Remote-sensing technique for mapping salt-affected soils." *Int. J. Remote Sens.*, 15, 1901–1914.

Warrick, A. W., and Myers, D. E. (1987). "Optimization of sampling locations for variogram calculations." *Water Resour. Res.*, 23, 496–500.

Wesseling, J., and Oster, J. D. (1973). "Response of salinity sensors to rapidly changing salinity." *Soil Sci. Soc. Am. Proc.*, 37, 553–557.

Wiegand, C. L., Anderson, G., Lingle, S., and Escobar, D. (1996). "Soil salinity effects on crop growth and yield: Illustration of an analysis and mapping methodology for sugarcane." *J. Plant Physiol.*, 148, 418–424.

Wiegand, C. L., Rhoades, J. D., Escobar, D. E., and Everitt, J. H. (1994). "Photographic and videographic observations for determining and mapping the response of cotton to soil-salinity." *Remote Sens. Environ.*, 49, 212–223.

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

Williams, B. G., and Hoey, D. (1987). "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.

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

Wollenhaupt, N. C., Richardson, J. L., Foss, J. E., and Doll, E. C. (1986). "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.

Wraith, J. M. (2002). "Solute content and concentration: Indirect measurement of solute concentration: Time domain reflectometry," in *Methods of soil analysis. Part 4: Physical methods*, J. H. Dane and G. C. Topp, eds., Agronomy Monograph No. 9. SSSA, Madison, Wisc., 1289–1297.

Zhu, Z., and Stein, M. L. (2006). "Spatial sampling design for prediction with estimated parameters." *J. Agric. Bio. Environ. Statistics*, 11, 24–44.

NOTATION

CEC = cation exchange capacity

EC = electrical conductivity

EC_a = electrical conductivity of the bulk soil, referred to as apparent soil electrical conductivity

EC_e = electrical conductivity of an extract of a saturated soil paste

EC_e = electrical conductivity of saturated soil paste
EC_w = electrical conductivity of a soil solution
EM_h = electromagnetic induction when the instrument coils are parallel to the soil surface
EM_v = electromagnetic induction when the instrument coils are perpendicular to the soil surface
EMI = electromagnetic induction
ER = electrical resistivity
ET = evapotranspiration
NDVI = normalized difference vegetation index
SP = saturation percentage
TDR = time domain reflectometry