8 Use of Advanced Information Technologies for Water Conservation on Salt-Affected Soils

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EXECUTIVE SUMMARY

Water scarcity is an identifying feature of arid and semiarid regions of the world, causing water conservation to be a constant consideration in these areas. Due to the unpredictability and scarcity of natural precipitation in arid and semiarid regions, irrigation is essential for maintaining crop productivity. In general, irrigation and soil salinization go hand in hand, particularly in the arid zones of the world. Water conservation on arid and semiarid soils must be done with constant and careful consideration of the distribution of salinity across the landscape and through the soil profile. Salinity is of concern because it causes a significant decrease in crop productivity due to osmotic and toxic ion effects on plant growth. However, soil salinity can be managed through leaching and the application of various soil amendments. The field-scale management of soil salinity is best handled with knowledge of its spatial and temporal distribution. Ideally, water conservation on irrigated agricultural lands is best achieved by applying irrigation water where, when, and in the amounts needed to adequately leach salts and to meet the crop's water needs. This is not easily done since water content and salinity are highly variable both spatially and temporally across a field and through the root zone. The goal of site-specific irrigation, however, is to account for within-field variation of water content and salinity. Field-scale salinity measurement and mapping protocols have been developed by Corwin and his colleagues at the U.S. Salinity Laboratory in Riverside, California. These protocols utilize advanced information technologies (i.e., geophysical techniques measuring apparent soil electrical conductivity [EC_a], geographic information system [GIS], geostatistics, spatial statistical analysis, and spatial statistical sampling designs) to map the spatiotemporal distribution of soil salinity for management applications. These protocols and technologies also have the potential to map soil water content and texture in most instances. The goal of this chapter is to provide an overview of the approach for delineating site-specific irrigation management units (SSIMUs) from the field-scale characterization of soil salinity, water content, and textural distributions using advanced information technologies. Guidelines, special considerations, protocols, and strengths and limitations are presented. Maps of SSIMUs provide irrigation management information to ameliorate crop yield reduction on salt-affected soils with minimal irrigation water requirements. Land resource managers, water conservation specialists, farmers, extension specialists, and Natural Resource Conservation Service field staff are the beneficiaries of field-scale maps of soil salinity, water content, texture, and SSIMUs, which can be used for crop selection, irrigation and salinity management, and remediation. These tools are important to provide adequate water for crop production while protecting soils from excessive salinization that will degrade soil quality and impair future productivity.

KEYWORDS

Electrical conductivity, sampling, soil salinity, spatial variability

8.1 INTRODUCTION

Due to an ever-growing population with its increasing demand on finite water supplies, the world faces an unprecedented crisis in water resources management, with profound implications for global food security, protection of human health, and maintenance of aquatic ecosystems. Jury and Vaux (2007) provide an insightful look into the emerging global water crisis, identifying a definitive and imminent need for water conservation throughout the world, particularly for water-scarce and water-stressed countries.

The increase in population and urbanization has resulted in severe water shortages throughout the world, which are exacerbated by changes in climate patterns. For instance, the United States has been experiencing an increase in moderate to severe levels of drought particularly in the Southwest, but other areas of the United States are not exempt. This has caused reductions in irrigation water allocations to farmers in the San Joaquin Valley and heightened water conservation measures in urban areas. It is estimated that in the near future four-fifths of the states in the USA are expected to face localized or statewide water shortages. In the mid-1990s, 80 countries that constitute 40% of the world's population were suffering from serious water shortages (CSD 1997). The World Water Council (2000) forecasts that by 2020, the world will be 17% short of the water supply needed to feed the world's population. The United Nations FAO (2011) indicates that by 2025, nearly 2 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be living under stressed water conditions. These statistics just scratch the surface of the compelling data pointing to the need for global water conservation.

In late 2011, the world population passed 7 billion; the United Nations forecasts that the world population will reach 9.3 billion by 2050. There are grave concerns that, at that time, 40% of the global population (i.e., 3.6 billion people) may suffer from food shortage, economic deprivation, and poor health because of water stress. Even though water covers 70% of the earth's surface, less than 3% of the world's water is fresh—the remainder is undrinkable seawater.

8.1.1 Importance of Irrigated Agriculture

Agriculture accounts for more than 70% of the freshwater drawn from lakes, rivers, and underground sources (CSD 1997). In 2000, roughly 57% of the world's freshwater withdrawal and 70% of its consumption took place in Asia, where the world's major irrigated lands are found (Shiklomanov and Roda 2003). From 1970 to 2000, the area of land under irrigation increased from less than 200 million ha to over 270 million ha (United Nations FAO 2001). From a global perspective, irrigated agriculture makes an essential contribution to the food needs of the world, with only 15% of the world's farmland irrigated, and yet it produces 40% of the total food and fiber (World Water Council 2000). Without a doubt, irrigated agriculture is essential to meet the world's ever-increasing demand for food.

Ironically, some of the most agriculturally productive areas of the world occur in water-scarce regions, such as the arid Southwestern United States (e.g., California's

San Joaquin and Imperial–Coachella Valleys) and other arid regions of the world, including the Middle East; the Hai He, Huang He, and Yangtze basins in China; and along the Nile River in Egypt and Sudan. In most cases, these areas owe their successful crop productivity to mild year-round climates and irrigation to supplement inadequate rainfall. Furthermore, global climate change model predictions indicate decreased precipitation for drier regions of the world, with annual average precipitation decreases likely to occur in most of the Mediterranean, Northern Africa, Northern Sahara, Central America, the American Southwest, the Southern Andes, and Southwestern Australia (IPCC 2007).

8.1.2 Need for Water Conservation in Irrigated Agriculture

There is no doubt that the Green Revolution, which dramatically changed the world's crop productivity over the past half century, was successful in large part due to worldwide advances in the use of irrigation. Continued reliance on irrigated agriculture is necessary to meet the growing food demands of an ever-increasing global population, but the high consumptive water use of irrigated agriculture places heavy demands on finite water resources. Agriculture is the largest consumer of freshwater worldwide (UNESCO 2009). Irrigated agriculture cannot possibly meet future food production expectations if it cannot conserve water while concomitantly increasing productivity.

The prospect of feeding a projected additional 2.3 billion people over the next 40 years poses more challenges than encountered in the past 40 years. Global resource experts predict that in the short term, there will be adequate global food supplies, but the distribution of those supplies to malnourished people will be the primary problem. However, in the long term, the obstacles become more formidable though not insurmountable. Although total yields continue to rise on a global basis, there is a disturbing decline in yield growth, with some major crops such as wheat and maize reaching a "yield plateau" (World Resources Institute 1998). Feeding the ever-increasing world population will require a sustainable agriculture that can keep pace with population growth and can balance crop yield with resource utilization, particularly water resources. The concept of sustainable agriculture is predicated on a delicate balance of maximizing crop productivity and maintaining economic stability while minimizing the utilization of finite natural resources and the detrimental environmental impacts of associated agrichemical pollutants. In irrigated agricultural regions throughout the world, which are often located in water-vulnerable arid and semiarid climates, water will be the crucial resource that must be conserved to maintain productivity.

8.1.3 Interrelationship of Salinity and Irrigated Agriculture

The accumulation of soil salinity is a consequence of a variety of processes. 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 the subsequent transport of salts due to capillary rise driven by the evaporative process. However, by far, the most common cause for the accumulation of salts is evapotranspiration (ET) by plants, which results in an increase in salt concentration with depth through the root zone and the accumulation of salts below the root zone. The level of salt accumulation within and below the root zone due to ET depends upon the fraction of irrigation and/or precipitation that flows beyond the root zone, referred to as the leaching fraction (LF). As the LF increases, the total salts within the root zone decrease due to their removal from the root zone by leaching.

The accumulation of salts in the root zone goes hand in hand with irrigated agriculture. Irrigation management of arid and semiarid agricultural soils is more often than not a matter of salinity management through irrigation. Irrigation management in arid and semiarid regions must concomitantly manage salinity to be viable.

Vast areas of irrigated land are known to be threatened by salt accumulation. According to CSD (1997), salinization of approximately 20% of the world's irrigated land results from poor water management practices, with an additional 1.5 million ha affected annually, significantly reducing crop production. Rhoades and Loveday (1990) estimated that 50% of all irrigated systems (totaling approximately 250 million ha) are affected by salinity or shallow water–related problems. Waterlogging and salinization alone represent a significant threat to the world's productivity capacity (Alexandratos 1995).

8.1.4 Need for Site-Specific Irrigation and Salinity Management

Site-specific management (SSM) attempts to manage soil, pests, and crops based upon spatial variation within a field (Larson and Robert 1995). In contrast, conventional farming treats a field uniformly, ignoring the naturally inherent variability of soil and crop conditions between and within fields. There is well-documented evidence that spatial variation within a field is highly significant and amounts to a factor of 3–4 or more for crops (Birrel et al. 1995; Verhagen et al. 1995) and up to an order of magnitude or more for soil variability (Corwin et al. 2003a). SSM is the management of agricultural crops at a spatial scale smaller than the whole field that takes local variation into account to cost-effectively balance crop productivity and quality, detrimental environmental impacts, and the use of resources (e.g., water, fertilizer, pesticides) in an economically optimal way by applying them when, where, and in the amount needed. One of the most promising approaches for attaining sustainability in water-limited agricultural areas is site-specific irrigation management (SSIM). SSIM has the potential to conserve precious freshwater resources by applying irrigation water when, where, and in the amounts needed to optimize yield, which in arid and semiarid climates is often influenced most by salinity and water distributions. To manage within-field variation, georeferenced areas (or units) that are similar with respect to a specified characteristic (e.g., salinity, water content, etc.) must be identified (van Uffelen et al. 1997). Site-specific management units (SSMUs) have been proposed as a means of dealing with the spatial variation of edaphic properties that affect crop productivity (or quality) to achieve the goals of SSM. A SSMU is simply a mapped unit within a field that could be based on soil properties, landscape units, past yield, etc., that is managed to achieve the goals of SSM.

8.1.5 Advanced Information Technologies for Site-Specific Irrigation and Salinity Management

The delineation of site-specific irrigation management units (SSIMUs) is not a trivial task and requires advanced information technologies including proximal sensors, geographic information system (GIS), Global Positioning System (GPS), spatial statistics, and design- or model-based sampling (Corwin and Lesch 2010). Corwin and colleagues (Corwin et al. 2003b; Corwin and Lesch 2010) have developed the methodology for defining SSIMUs based on protocols and guidelines developed by Corwin and Lesch (2003, 2005a) for characterizing the field-scale spatial variability of soil salinity (and other soil properties, including water content and texture) with apparent soil electrical conductivity (EC_a) directed soil sampling.

8.2 FIELD-SCALE SALINITY MEASUREMENT AND MAPPING

The measurement of soil salinity has a long history prior to its assessment with EC_a. Soil salinity refers to the presence of major dissolved inorganic solutes in the soil aqueous phase, which consist of soluble and readily dissolvable salts including charged species (e.g., Na^+, K^+, Mg^{+2}, Ca^{+2}, Cl^-, HCO_3^-, NO_3^-, NO_4^{-2}, and CO_3^{-2}), nonionic solutes, and ions that combine to form ion pairs. The need to measure soil salinity stems from its detrimental impact on plant growth. Effects of soil salinity are manifested in loss of stand, reduced plant growth, reduced yields, and, in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential, making it more difficult for the plant to extract water. Salinity may also cause specific ion toxicity or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth.

8.2.1 Historical Approaches

Historically, six methods have been developed for determining soil salinity at field scales: (1) visual crop observations; (2) electrical conductance of soil solution extracts or extracts at higher than normal water contents; (3) in situ measurement of electrical resistivity (ER); (4) noninvasive measurement of electrical conductance with electromagnetic induction (EMI); (5) in situ measurement of electrical conductance with time domain reflectometry (TDR); and, most recently, (6) multispectral and hyperspectral imagery.

Visual crop observation is the oldest method of determining the presence of soil salinity in a field. It is a quick method, but it has the disadvantage in that salinity development is detected after crop damage has occurred, making it the least desirable method for obtaining soil salinity information. However, remote sensing, including multispectral and hyperspectral imagery, plays an increasing role in agriculture management practices and represents a quantitative approach to visual observation that may offer a potential for early detection of the onset of salinity damage to plants. Even so, multispectral and hyperspectral remote imagery technologies are currently unable to differentiate osmotic from matric or other stresses. This distinction is key to the successful application of remote imagery as a tool to map salinity and/or water content.

The determination of salinity through the measurement of electrical conductance has been well established for decades (U.S. Salinity Laboratory Staff 1954). Electrical conductivity (EC) of water is a function of its chemical composition. McNeal et al. (1970) were among the first to establish the relationship between the EC and molar concentrations of ions in the soil solution. Soil salinity is quantified in terms of the total concentration of the soluble salts, as measured by the EC of the solution in dS m^{-1}. To determine the EC, the soil solution is placed between two electrodes of constant geometry and distance of separation (Bohn et al. 1979). At a constant potential, the current is inversely proportional to the solution's resistance. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. The electrical conductance is a reciprocal of the resistance, as shown in Equation 8.1:

$$EC_T = k/R_T \tag{8.1}$$

where EC_T is the electrical conductivity of the solution in dS m^{-1} at temperature T (°C), k is the cell constant, and R_T is the measured resistance at temperature T. Customarily, EC is expressed at a reference temperature of 25°C for purposes of comparison. The EC measured at a particular temperature T (°C), EC_T, can be adjusted to a reference EC at 25°C, EC_{25}, using the following equations from Handbook 60 (U.S. Salinity Laboratory Staff 1954):

$$EC_{25} = f_T \times EC_T \tag{8.2}$$

where f_T is a temperature conversion factor approximated by Sheets and Hendrickx (1995):

$$f_T = 0.4470 + 1.4034e^{-T/26.815} \tag{8.3}$$

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

Developments in the measurement of soil EC to determine soil salinity shifted away from extractions to the measurement of EC_a because the time and cost of obtaining soil solution extracts prohibited their practical use at field scales. Moreover, the high local-scale soil variability rendered salinity sensors and small-volume soil core samples of limited quantitative value. The use of EC_a to measure salinity has the advantage of increased volume of measurement and quickness of measurement but suffers from the complexity of measuring EC for the bulk soil rather than restricted to the solution phase.

8.2.2 Geospatial EC_a Measurements

To measure soil salinity, the electrical conductance of only the soil solution 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 property that affects bulk soil conductance.

At present, no other measurement provides a greater level of spatial soil information for soil salinity assessment than the geospatial measurements of EC_a. These measurements are particularly useful for directed soil sampling to characterize soil spatial variability of salinity, texture, water content, and other soil properties that are indirectly measured by EC_a (e.g., organic matter [OM], cation exchange capacity [CEC]) (Corwin and Lesch 2005b). The rational for characterizing soil spatial variability with EC_a measurements is based on the hypothesis that this information can be used to develop a directed soil sampling plan that identifies sites that adequately reflect the range and variability of soil salinity and/or other soil properties that are correlated with EC_a. This hypothesis has repeatedly held true for a variety of agricultural applications (Lesch et al. 1992, 2005; Johnson et al. 2001; Corwin and Lesch 2003, 2005b,c; Corwin et al. 2003a,b; Corwin 2005).

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

8.2.2.1 Factors Influencing EC_a

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

$$EC_a = \frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{\theta_{ss} \cdot EC_{ws} + \theta_{ws} \cdot EC_s} + (\theta_{sc} \cdot EC_{sc}) + (\theta_{wc} \cdot EC_{wc}) \tag{8.4}$$

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the soil–water pathway ($cm^3\ cm^{-3}$) and in the continuous liquid pathway ($cm^3\ cm^{-3}$), respectively; θ_{ss} and θ_{sc} are the volumetric contents of the surface conductance ($cm^3\ cm^{-3}$) and indurated solid phases of the soil ($cm^3\ cm^{-3}$), respectively; EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil–water pathway ($dS\ m^{-1}$) and continuous liquid pathway ($dS\ m^{-1}$); and EC_{ss} and EC_{sc} are the electrical conductivities of the surface conductance ($dS\ m^{-1}$) and indurated solid phases ($dS\ m^{-1}$), respectively. Equation 8.4 was reformulated by Rhoades et al. (1989) into Equation 8.5:

$$EC_a = \frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{(\theta_{ss} \cdot EC_{ws}) + (\theta_{ws} \cdot EC_s)} + (\theta_w - \theta_{ws}) \cdot EC_{wc} \tag{8.5}$$

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

$$\theta_w = \frac{(PW \cdot \rho_b)}{100} \tag{8.6}$$

$$\theta_{ws} = 0.639\theta_w + 0.011 \tag{8.7}$$

$$\theta_{ss} = \frac{\rho_b}{2.65} \tag{8.8}$$

$$EC_{ss} = 0.019(SP) - 0.434 \tag{8.9}$$

$$EC_w = \frac{EC_e \cdot \rho_b \cdot SP}{100 \cdot \theta_w} \tag{8.10}$$

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

Because of the pathways of conductance, EC_a is influenced by a complex interaction of edaphic properties including EC_e (soil salinity), texture (quantitatively approximated by SP), θ_w (water content), ρ_b (bulk density), and temperature. The SP and the ρ_b are both directly influenced by clay content and OM. Furthermore, the exchange surfaces on clays and OM provide a solid–liquid phase pathway primarily via exchangeable cations; consequently, clay content and mineralogy, CEC, and OM are recognized as additional factors that influence EC_a measurements. EC_a is a complex property that must be interpreted with these influencing factors in mind.

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 that influence the EC_a measurement at the study site. Corwin and Lesch (2005b) provide a compilation of EC_a studies and the associated dominant soil property or properties that are measured by EC_a for that study.

8.2.2.2 Techniques for Measuring EC_a

There are three primary geophysical techniques for measuring EC_a: ER, EMI, and TDR. ER and EMI are easily mobilized and are well suited for field-scale applications because of the ease and low cost of measurement with a volume of measurement that is sufficiently large (>1 m^3) to reduce the influence of local-scale variability. Developments in agricultural applications of ER and EMI have occurred along parallel paths, with each filling a needed niche based upon inherent strengths and limitations. Even though TDR is a useful and well-studied technique for measuring EC_a, it has lagged behind ER and EMI as an "on-the-go" proximal sensor because it does not provide a continuous stream of georeferenced measurements. Rather, TDR requires the user to go from one location to the next, stopping at each location to take discrete measurements; consequently, it is less rapid and less appealing for mapping EC_a at field scales and larger spatial extents. ER and EMI are the current methods of choice for mapping soil salinity and other soil properties that are related to EC_a, so they, and not TDR, will be subsequently discussed. For greater details regarding ER, EMI, and TDR, refer to Hendrickx et al. (2002).

8.2.2.2.1 Electrical Resistivity

ER was originally used by geophysicists to measure the resistivity of the geological subsurface. ER 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. The electrodes are connected to a resistance meter that measures the potential gradient between the current and the potential electrodes. 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 (Rhoades and Halvorson 1977; Burger 1992). Although two electrodes (one current and one potential electrode) could be used, the stability of the reading is greatly improved with the use of four electrodes.

The resistance is converted to EC using Equation 8.1, where the cell constant, k, in the equation is determined by 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 homogeneous soil, the depth of measurement of the Wenner array is equal to a, and the soil volume measured is roughly equal to πa^3.

There are additional four-electrode configurations that are frequently used, as discussed by Burger (1992), Telford et al. (1990), and Dobrin (1960). The influence of the interelectrode configuration and distance on EC_a is given by (Equation 8.11):

$$EC_{a,25°C} = \frac{1000}{2\pi R_t} \frac{f_t}{\dfrac{1}{\dfrac{1}{r_1} - \dfrac{1}{r_2} - \dfrac{1}{R_1} + \dfrac{1}{R_2}}} \tag{8.11}$$

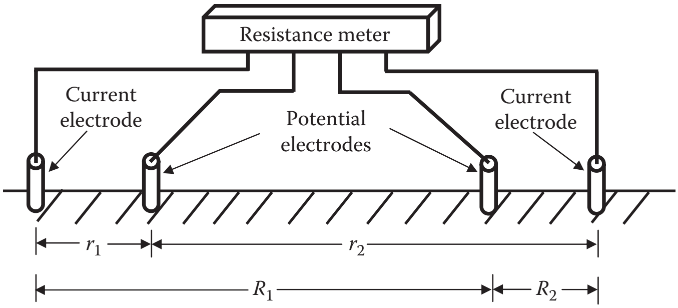

FIGURE 8.1 Schematic of four-electrode probe ER used to measure EC_a. (From Corwin, D.L. and J.M.H. Hendrickx, Solute content and concentration—Indirect measurement of solute concentration: Electrical resistivity—Wenner array. In *Methods of Soil Analysis. Part 4—Physical Methods, Agronomy Monograph No. 9*, eds. J. H. Dane and G.C. Topp, pp. 1282–1287, 2002. Madison, WI: Soil Science Society of America. With permission.)

where $EC_{a,25°C}$ is the EC_a 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 centimeters between the electrodes, as shown in Figure 8.1. For the Wenner array, where $a = r_1 = r_2 = R_1 = R_2$, Equation 8.11 reduces to $EC_a = 159.2 f_t / a R_t$ and $159.2/a$ represents the cell constant (k).

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, the ER has a flexibility that has proven to be advantageous for field application, i.e., 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.

8.2.2.2.2 Electromagnetic Induction

EC_a can be measured noninvasively with EMI. A transmitter coil located at one end of the EMI instrument 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. 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 et al. 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 Limited, 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 root zone (i.e., generally 1–1.5 m). When the instrument is placed in the vertical coil configuration (EM_v, coils perpendicular to the soil surface), the depth of measurement is approximately 1.5 m, and in the horizontal coil configuration (EM_h, coils parallel to the soil surface), the depth of the measurement is 0.75–1.0 m. The perpendicular planar coils in the DUALEM-2 measure to a depth of 1.0 m and are analogous to the horizontal position in the EM-38, while the horizontal coplanar coils in the DUALEM-2 measure to a depth of 3 m and are analogous to the vertical position in the EM-38. The EM-31 has an intercoil spacing of 3.66 m, which corresponds to measurement depths of 3 and 6 m in the horizontal and vertical dipole orientations, respectively, which extends well beyond the root zone of agricultural crops. However, the EM-38 has one major pitfall, which is the need for calibration. The DUALEM-2 does not require calibration. Further details about and operation of the EM-31 and EM-38 equipment are discussed in Hendrickx et al. (2002). Documents concerning the DUALEM-2 can be found online at http://www.dualem.com/documents.html (accessed January 16, 2014).

EC_a measured by EMI at $EC_a < 1.0$ dS m^{-1} is given by Equation 8.12 from McNeill (1980):

$$EC_a - \frac{4}{2\pi \; {}_0 f s^2} \frac{H_s}{H_p} \tag{8.12}$$

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

8.2.2.2.3 Advantages and Disadvantages of ER and EMI

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 relates to the response function. Both EMI and ER have nonlinear response functions, but EC_a measured with EMI is a depth-weighted value that is more nonlinear than ER. More specifically, EMI concentrates its measurement of conductance over the depth of measurement at shallow depths, whereas ER is more nearly uniform with depth. Because of the greater 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 Equation 8.13 from Barnes (1952) for resistors in parallel:

$$EC_x = EC_{a_i - a_{i-1}} - \frac{(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} - a_{i-1})}{(a_i - a_{i-1})} \tag{8.13}$$

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 the 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 dissimilarity of their response functions. An advantage of ER over EMI is the ease of instrument calibration. Calibrating the EM-31 and EM-38 is more involved than for ER equipment. However, there is no need to calibrate the DUALEM-2.

8.2.2.3 Field-Scale Mapping of Soil Salinity and EC_a

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 $EC_a < 1–2$ 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 (i.e., $EC_a > 1–2$ dS m^{-1}), salinity most likely dominates the EC_a reading; consequently, geospatial EC_a measurements most likely map soil salinity.

8.2.2.3.1 Approach and Protocols for EC_a-Directed Soil Sampling

Scientists at the U.S. Salinity Laboratory have developed an integrated system for the measurement of field-scale salinity, which consists of (1) mobile EC_a measurement equipment (Rhoades 1993), (2) protocols for EC_a-directed soil sampling (Corwin and Lesch 2005a), and (3) sample design software (Lesch et al. 2000). The integrated system for mapping soil salinity is schematically illustrated in Figure 8.2.

The protocols of an EC_a survey for measuring soil salinity at field scale include nine 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) calibration of EC_a to EC_e, (7) statistical analysis to determine dominant soil properties influencing the EC_a measurements at the study site, (8) GIS development, and (9) graphic display of spatial data. The basic steps for each element are provided in Table 8.1. A detailed discussion of the protocols can be found in Corwin and Lesch (2005a), and an update of the protocols specific to mapping soil salinity can be found in Corwin and Lesch (2013). Corwin and Lesch (2005c) provide a case study demonstrating the use of the protocols.

8.2.2.3.2 Factors to Consider during an EC_a-Directed Survey

There are a number of considerations that must be followed 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 spatiotemporal changes in salinity patterns of distribution can only be made from EC_a survey

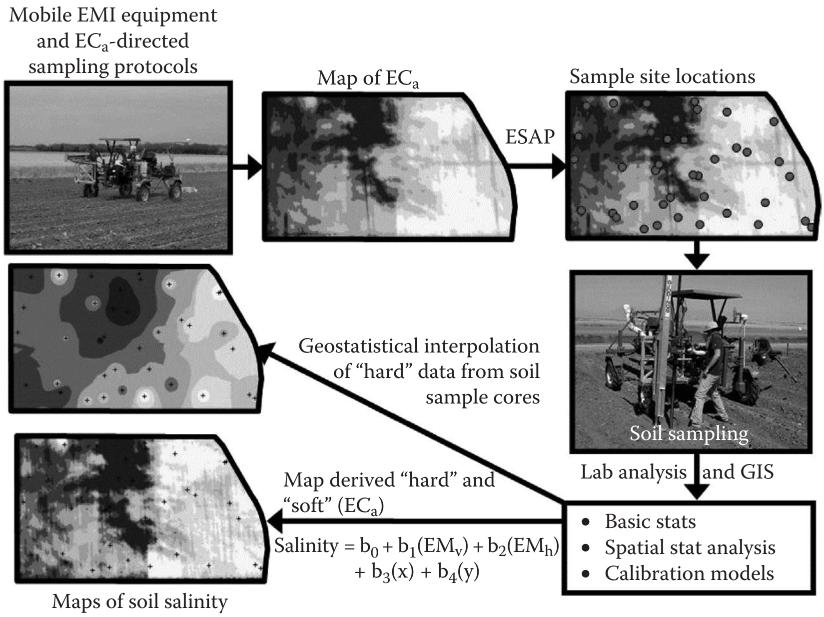

FIGURE 8.2 Schematic of the integrated system for field-scale salinity assessment using EC_a-directed sampling protocols, mobile EMI equipment, ESAP software, and GIS. EM_v refers to EMI measurement in the vertical coil configuration, and EM_h refers to EMI measurement in the horizontal coil configuration. (Modified from Corwin, D.L. et al., Laboratory and field measurements. In *Agricultural Salinity Assessment and Management*, eds. K.K. Tanji and W. Wallender, pp. 295–341, 2012. New York: American Society of Civil Engineers. With permission.)

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 2–4 days after 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 dry-land farming, the survey should occur 2–4 days or longer after a substantial rainfall, 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 that influences 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, whereas 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 the beds and furrows

TABLE 8.1
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 (e.g., inventorying, spatiotemporal monitoring, site-specific management, etc.)
   c. Establish site boundaries
   d. Select GPS coordinate system
   e. Establish EC_a measurement intensity (i.e., number and location of traverses and space between EC_a measurements with careful consideration of edge effects)
   f. Minimize secondary influences on EC_a (e.g., compaction, surface roughness and geometry, metal)
   g. Special EC_a survey design considerations
      i. Presence of beds and furrows: perform separate surveys for the beds and for the furrows
      ii. Vineyards with metal trellising
         A. Maximize distance from metal for surveys with EMI
         B. Place an insulator between metal posts and trellis wires to break the conductance loop from the soil to the posts along the wires and back into the soil (this applies to both ER and EMI surveys)
      iii. Presence of drip lines: perform separate EC_a surveys over and between drip lines
      iv. Variations in surface geometry or roughness: perform separate surveys with separate sampling designs for each area differing in surface roughness or surface geometry
      v. Temporal studies
         A. Reference all EC_a measurement to 25°C or
         B. Conduct EC_a surveys at the same time of the day and the same day of the year
2. EC_a data collection with mobile GPS-based equipment
   a. Conduct drift runs when using EMI to determine the effect of ambient temperature on EMI instrumentation
   b. Geo-reference site boundaries and significant physical geographic features with GPS
   c. Assure that water content at the study site is at or near field capacity (≥70% field capacity) throughout the field (if water content is <70%, then do not conduct EC_a survey)
   d. Measure geo-referenced EC_a data at the predetermined spatial intensity and record associated metadata
   e. Keep the speed of mobile GPS-based equipment < 10 km h^{-1} to reduce GPS positional errors
3. Soil sample design based on geo-referenced EC_a data
   a. Statistically analyze EC_a data using an appropriate statistical sampling design (i.e., model- or design-based 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 (>100 soil samples are desirable but the total number of samples is largely determined by the resources available to analyze the soil properties of concern)
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 salinity (and other soil properties) for 20% or more of the sample locations
   c. Record soil core observations (e.g., temperature, color, $CaCO_3$, gleying, organic matter, mottling, horizonation, textural discontinuities, etc.)

(*Continued*)

TABLE 8.1 (CONTINUED)
Outline of Steps to Conduct an EC_a Field Survey to Map Soil Salinity

5. Laboratory analysis of soil salinity and other EC_a-correlated soil properties relevant to the project objectives
6. Stochastic and/or deterministic calibration of EC_a to EC_e (and to other soil properties, e.g., water content, SP, etc.)
7. Statistical analysis to determine the soil properties influencing EC_a
   a. Perform a basic statistical analysis of soil salinity (and other relevant soil properties) 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
9. Graphic display of spatial distribution of soil salinity (and other properties correlated to EC_a) using various interpolation methods (e.g., inverse distance weighting, cubic spline, geostatistics)

Source: Modified from Corwin, D.L. and S.M. Lesch, *Computers and Electronics in Agriculture* 46(1–3): 103–134, 2005, specifically for mapping soil salinity.

introduce an added level of localized complexity resulting from localized variations in water contents. Higher water contents and greater leaching occur under the furrows, whereas 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 very 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 the spatial EC_a measurements. Geospatial conductance 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.

The above 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

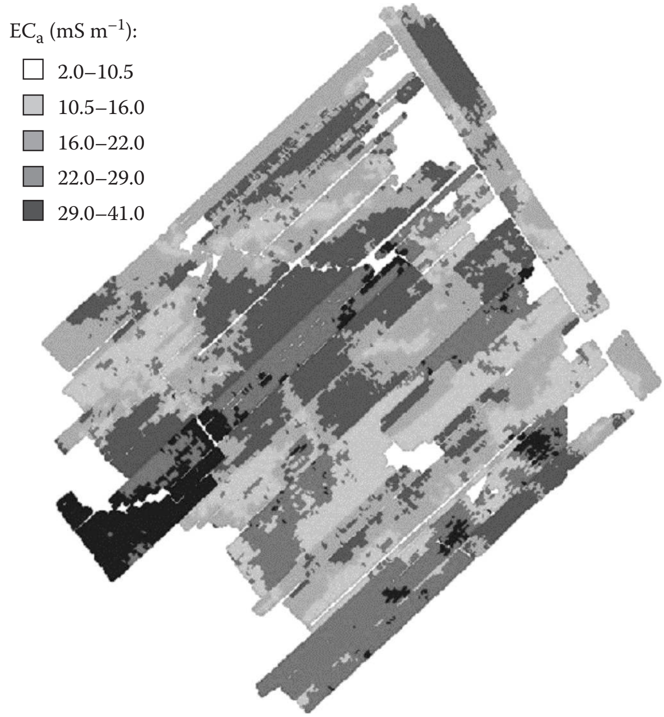

FIGURE 8.3 A poorly designed EC_a survey showing the banding that occurs when surveys are conducted at different times under varying water contents, temperatures, surface roughnesses, and surface geometry conditions. (From Corwin, D.L. and S.M. Lesch, *Journal of Environmental and Engineering Geophysics*, 18:1–25, 2013. With permission.)

on a field that has real differences in water content, soil profile temperature, surface roughness, and surface geometry, then bands of EC_a such as those found in Figure 8.3 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.

8.2.2.3.3 Model- and Design-Based Sampling

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.

Arguably, the most significant element of the protocols is the EC_a-directed soil sampling design. Design-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 recently been 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. (1995), 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), Warrick and Myers (1987), and Russo (1984). 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 2005a).

The prediction-based sampling approach was introduced to EC_a-directed sampling by Lesch et al. (1995). This sampling approach attempts to optimize the estimation of a regression model (i.e., minimize the mean square prediction error produced by the calibration function) while simultaneously 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, etc.), but the exact parameter estimates (associated with the calibration model) may still need to be determined via some type of site-specific sampling design. The response surface approach explicitly optimizes this site-selection process.

A user-friendly software package (ESAP) developed by Lesch et al. (2000), which uses a response surface sampling design, has proven to be particularly effective in delineating spatial distributions of soil properties from EC_a survey data (Corwin and Lesch 2003, 2005c; Corwin et al. 2003a,b, 2006; Corwin 2005). The ESAP software package, which is available online at http://www.ars.usda.gov/services/software/download.htm?softwareid=94, 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, the sample depth increments, and the 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 measurement by the EC_a measurement equipment used. For instance, the Geonics EM-38 measures to a depth of roughly 0.75–1.0 m in the horizontal coil configuration (EM_h) and 1.2–1.5 m in the vertical coil configuration (EM_v). Composite soil cores to the depth of interest can be taken, but generally, cores are taken at depth increments. 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 USDA-ARS Salinity Laboratory because it provides sufficient soil profile information over the root zone (i.e., 0–1.2 to 1.5 m) for statistical analysis without an overly burdensome number of samples to conduct physicochemical analyses. Typically, core samples are taken at 0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5 m depth increments. 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.

8.3 SSIMUs: CASE STUDY

Geospatial measurements of EC_a are a powerful tool in SSM when combined with GIS, spatial statistics, and crop-yield monitoring. It is hypothesized that in instances where EC_a correlates with crop yield, spatial EC_a information can be used to direct a soil sampling plan that identifies sites that adequately reflect the range and variability of various soil properties thought to influence crop yield. The objective is to integrate spatial statistics, GIS, EC_a-directed soil sampling, and a crop-yield response model to (1) identify edaphic properties that influence cotton yield and (2) use this spatial information to delineate SSMUs with associated management recommendations for an irrigated crop (i.e., cotton in the subsequent case study) to increase productivity. The following case study summarizes the work conducted and published by Corwin et al. (2003b). For an in-depth discussion of the delineation of SSM units using proximal sensors, such as ER and EMI, refer to Corwin and Lesch (2010).

8.3.1 EC_a-Directed Sampling Methodology

A 32.4-ha field located in the Broadview Water District on the west side of California's San Joaquin Valley was used as the study site. Broadview Water District is located approximately 100 km west of Fresno, California. The soil at the site is slightly alkaline and has good surface and subsurface drainage (Harradine 1950). The subsoil is thick, friable, calcareous, and easily penetrated by roots and water.

Spatial variation of cotton yield was measured at the study site in August 1999 using a four-row cotton picker equipped with a yield sensor and a GPS. A total of 7706 cotton yield readings were collected (Figure 8.4a). Each yield observation represented a total area of approximately 42 m^2. From August 1999 to April 2000, the field was fallow.

On March 2000, an intensive EC_a survey (Figure 8.4b) was collected using mobile fixed-array ER (Figure 8.5) and mobile EMI (Figure 8.6) equipment, developed by

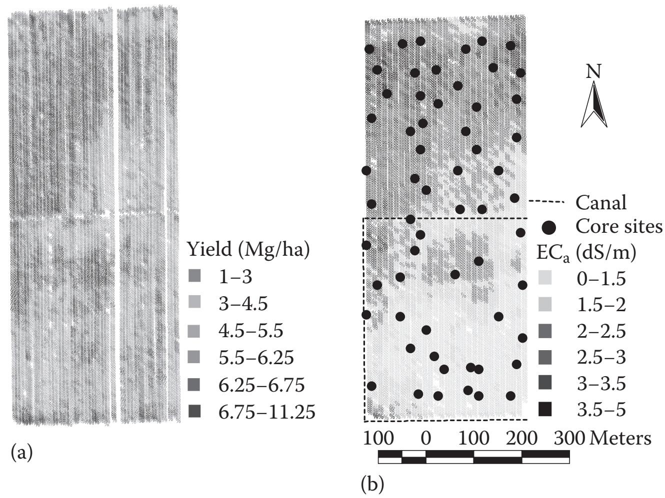

FIGURE 8.4 **(See color insert.)** Maps of (a) cotton yield and (b) EC_a measurements including the locations of the 60 soil core sites. (Modified from Corwin, D.L. et al., *Agronomy Journal* 95(2):352–364, 2003b. With permission.)

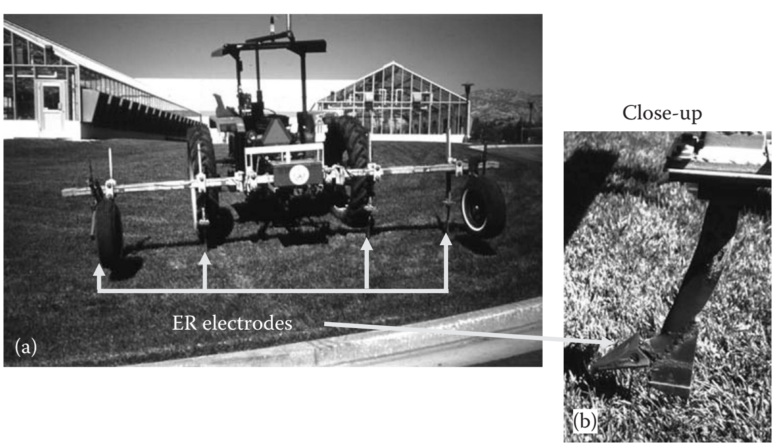

FIGURE 8.5 **(See color insert.)** Mobile GPS-based ER equipment showing (a) fixed-array tool bar holding four ER electrodes and (b) a close-up of one of the ER electrodes.

FIGURE 8.6 Mobile GPS-based EMI equipment showing (a) a side view of the entire rig and (b) a close-up of the sled holding the EMI unit.

Rhoades and colleagues at the U.S. Salinity Laboratory (Rhoades 1992a,b; Carter et al. 1993).

The methods and materials used in the EC_a survey were those subsequently published as a set of guidelines and protocols by Corwin and Lesch (2003, 2005a). The fixed-array ER electrodes were spaced to measure EC_a to a depth of 1.5 m. Over 4000 EC_a measurements were collected (Figure 8.4b).

Following the EC_a survey, soil samples were collected at 60 locations. The data from the EC_a survey were used to direct the selection of soil sample sites. The ESAP-95 version 2.01 software package developed by Lesch et al. (1995, 2000) at the U.S. Salinity Laboratory was used to establish the locations where soil cores were taken based on the EC_a survey data. The software used a model-based response surface sampling strategy to locate the 60 sites. These sites reflected the observed spatial variability in EC_a while simultaneously maximizing the spatial uniformity of the sampling design across the study area. Figure 8.4b visually displays the distribution of EC_a survey data in relation to the locations of the 60 core sites. Soil core samples were taken at each site at 0.3-m increments to a depth of 1.8 m: 0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, 1.2–1.5, and 1.5–1.8 m. The soil samples were analyzed for soil properties thought to influence cotton yield, including pH, boron (B), nitrate–nitrogen (NO_3–N), Cl^-, salinity (EC_e), LF, gravimetric water content (θ_g), bulk density, % clay, and saturation percent. All samples were analyzed following the methods outlined in Agronomy Monograph No. 9 Part 1 (Blake and Hartge 1986) and Part 2 (Page et al. 1982).

Statistical analyses were conducted using SAS software (SAS Institute 1999). The statistical analyses consisted of three stages: (1) determination of the correlation between EC_a and cotton yield using data from the 60 sites, (2) exploratory statistical analysis to identify the significant soil properties that influence cotton yield, and (3) development of a crop-yield response model based on ordinary least squares regression adjusted for spatial autocorrelation with restricted maximum likelihood.

Because the location of EC_a and cotton yield measurements did not exactly overlap, ordinary kriging was used to determine the expected cotton yield at the 60 sites. The spatial correlation structure of yield was modeled with an isotropic variogram. The following fitted exponential variogram was used to describe the spatial structure at the study site:

$$v(\delta) = (0.76)^2 + (1.08)^2[1 - \exp(-D/109.3)] \quad (8.14)$$

where D is the lag distance.

All spatial data were compiled, organized, manipulated, and displayed within a GIS. Kriging was selected as the preferred method of interpolation because in all cases, it outperformed inverse distance weighting based on comparisons using jackknifing.

8.3.2 Development of a Crop Yield Response Model Based on Edaphic Properties

8.3.2.1 Correlation between Cotton Yield and EC_a

The fitted variogram model of Equation 8.14 was used in an ordinary kriging approach to estimate cotton yield at the 60 sites. The correlation of EC_a to yield at the 60 sites was 0.51. The moderate correlation between yield and EC_a suggests that some soil properties that influence EC_a measurements also influence cotton yield, making an EC_a-directed soil sampling strategy a viable approach for this site. The similarity of the spatial distributions of EC_a measurements and cotton yield in Figure 8.4 visually confirms the reasonably close relationship of EC_a to the yield.

8.3.2.2 Exploratory Statistical Analysis

Exploratory statistical analyses were conducted to determine the significant soil properties influencing cotton yield and to establish the general form of the cotton yield response model. The exploratory statistical analysis consisted of three stages: (1) a preliminary multiple linear regression (MLR) analysis, (2) a correlation analysis, and (3) scatter plots of yield versus potentially significant soil properties. The preliminary MLR analysis and the correlation analysis were used to establish the significant soil properties that influence cotton yield, while the scatter plots were used to formulate the general form of the cotton yield response model. Both the preliminary MLR analysis and the correlation analysis showed that the 0–1.5 m depth increment resulted in the best correlations and best fit of the data; consequently, the 0–1.5 m depth increment was considered to correspond to the active root zone.

The preliminary MLR analysis indicated that the following soil properties were most significantly related to cotton yield: EC_e, LF, pH, % clay, θ_g, and ρ_b. The correlation between cotton yield and soil properties indicated that the highest correlation occurred with EC_e.

A scatter plot of EC_e and yield indicates a quadratic relationship where the yield increased up to a salinity of 7.17 dS m^{-1} and then decreased (Figure 8.7a). The scatter plot of LF and the yield shows a negative, curvilinear relationship (Figure 8.7b). The yield shows a minimal response to an LF below 0.4 and falls off rapidly for an LF > 0.4. Clay percentage, pH, θ_g, and ρ_b appear to be linearly related to yield to various degrees (Figure 8.7c–f, respectively). Even though there was clearly no correlation between the yield and the pH ($r = -0.01$; see Figure 8.7d), the pH became significant in the presence of the other variables, which became apparent in both the preliminary MLR analysis and in the final yield response model.

Based on the exploratory statistical analysis, it became evident that the general form of the cotton yield response model was

$$Y = \beta_0 + \beta_1(EC_e) + \beta_2(EC_e)^2 + \beta_3(LF)^2 + \beta_4(pH) + \beta_5(\%\ clay) + \beta_6(\theta_g) + \beta_7(\rho_b) + \varepsilon \quad (8.15)$$

where, based on the scatter plots of Figure 8.7, the relationships between cotton yield (Y) and pH, percentage clay, θ_g, and ρ_b are assumed linear; the relationship between yield and EC_e is assumed to be quadratic; the relationship between the yield and the LF is assumed to be curvilinear; $\beta_0, \beta_1, \beta_2, \ldots, \beta_7$ are the regression model parameters; and ε represents the random error component.

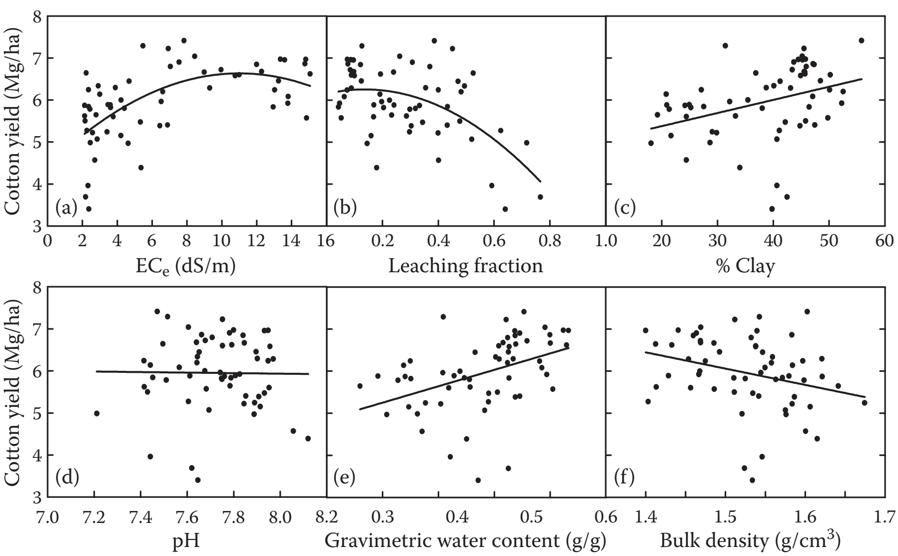

FIGURE 8.7 Scatter plots of soil properties and cotton yield: (a) electrical conductivity of the saturation extract (EC_e, dS m^{-1}), (b) LF, (c) percentage clay, (d) pH, (e) gravimetric water content, and (f) bulk density. (From Corwin, D.L. et al., *Agronomy Journal* 95(2):352–364, 2003b. With permission.)

8.3.2.3 Cotton Yield Response Model

Ordinary least squares regression based on Equation 8.15 resulted in the following response model:

$$Y = 20.90 + 0.38(EC_e) - 0.02(EC_e)^2 - 3.51(LF)^2 - 2.22(pH) + 9.27(\theta_g) + \varepsilon \quad (8.16)$$

where the nonsignificant t-test for % clay and ρ_b indicated that these soil properties did not contribute to the yield predictions in a statistically meaningful manner and dropped out of the regression model, while all other parameters were significant near or below the 0.05 level. The R^2 value for Equation 8.16 was 0.61, indicating that 61% of the estimated spatial yield variation was successfully described by Equation 8.16. However, the residual variogram plot indicated that the errors were spatially correlated, which implied that Equation 8.16 must be adjusted for spatial autocorrelation.

Using a restricted maximum likelihood approach to adjust for spatial autocorrelation, the most robust and parsimonious yield response model for cotton was:

$$Y = 19.28 + 0.22(EC_e) - 0.02(EC_e)^2 - 4.42(LF)^2 - 1.99(pH) + 6.93(\theta_g) + \varepsilon \quad (8.17)$$

A comparison of measured and simulated cotton yields at the locations where EC_a-directed soil samples were taken showed close agreement, with a slope of 1.13, a y-intercept of −0.70, and an R^2 value of 0.57. A visual comparison of the measured and simulated spatial yield distributions of cotton (Figure 8.8) shows a spatial association between interpolated measured (Figure 8.8b) and predicted (Figure 8.8c) maps.

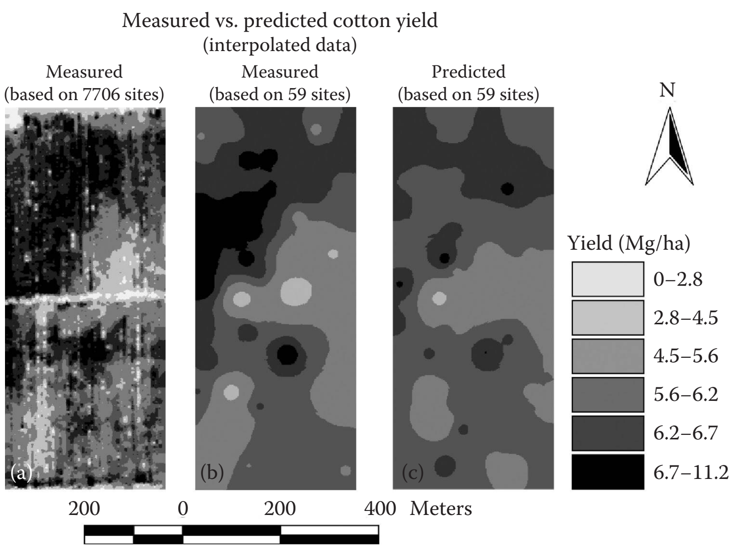

FIGURE 8.8 Comparison of (a) measured cotton yield based on 7706 yield measurements, (b) kriged data at 59 sites for measured cotton yield, and (c) kriged data at 59 sites for predicted cotton yields based on Equation 8.4. (From Corwin, D.L. et al., *Agronomy Journal* 95(2):352–364, 2003b. With permission.)

Sensitivity analysis revealed that LF was the single most significant factor influencing cotton yield with the degree of predicted yield sensitivity to one standard deviation change resulting in a percentage yield reduction for EC_e, LF, pH, and θ_g of 4.6%, 9.6%, 5.8%, and 5.1%, respectively.

8.3.3 Delineating SSIMUs

Based on Equation 8.17, Figure 8.7, and the knowledge of the interaction of the significant factors influencing cotton yield in the Broadview Water District, four recommendations can be made to improve cotton productivity at the study site:

1. Reduce the LF in highly leached areas (i.e., areas where LF > 0.5)
2. Reduce salinity by increased leaching in areas where the average root zone (0–1.5 m) salinity is >7.17 dS m^{-1}
3. Increase the plant-available water (PAW) in coarse-textured areas by more frequent irrigation
4. Reduce the pH where pH > 7.9

Figure 8.9 maps the areas pertaining to the above recommendations. All four recommendations can be accomplished by improving water application scheduling and distribution and by site-specific application of soil amendments. The use of variable-rate irrigation technology at this site would enable the site-specific application of irrigation water at the times and locations needed to optimize yield.

Hypothetically, when crop yield correlates with EC_a, then spatial distributions of EC_a provide a means of determining edaphic properties that influence yield. A yield map could potentially provide the same capability as an EC_a map; but an EC_a map provides information specific to the spatial distribution of edaphic properties, whereas a yield map reflects the influence of numerous additional factors.

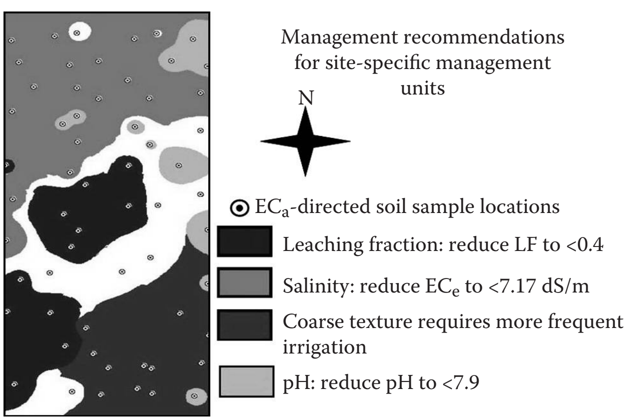

FIGURE 8.9 (See color insert.) Site-specific management units for a 32.4-ha cotton field in the Broadview Water District of central California's San Joaquin Valley. Recommendations are associated with the SSMUs for LF, salinity, texture, and pH. (From Corwin, D.L. and S.M. Lesch, *Computers and Electronics in Agriculture*, 46:11–43, 2005. With permission.)

8.4 OTHER CONSIDERATIONS FOR WATER CONSERVATION IN WATER-SCARCE, SALT-AFFECTED AREAS

Maps of SSIMUs indicate where to apply irrigation water, but knowledge of when to apply and how much to apply is also needed. When to apply is determined primarily by matric and osmotic stress to the plant. Instruments such as a tensiometer to measure the matric potential or a neutron probe or gypsum block to measure water content, which relates to matric potential, are commonly used. Time domain reflectometry and capacitance probes can also be used to measure water content. Irrigation targets are usually set as a percent depletion of the PAW, which is the difference between field capacity (−0.1 bar) and permanent wilting point (−15 bars). The bulk of irrigation research recommends irrigating row crops such as grain or cotton at 50% of the PAW and at 40% for vegetable crops that are more sensitive to water stress. Osmotic stress due to the presence of salts in the soil requires an increase in the frequency of water application because the plant has a combined osmotic and matric stress, which makes it difficult for the plant to imbibe water through the roots. The osmotic potential is generally obtained from a measurement of the dissolved salt concentration in the soil solution, since the osmotic potential in bars is approximately equal to the EC in dS m^{-1} multiplied by a factor of −0.36. The EC of the soil solution is obtained from techniques outlined by Corwin et al. (2012). The positioning of the instrumentation to measure matric and osmotic potentials within a field can be obtained from maps of texture and salinity obtained from EC_a-directed sampling, as explained in Corwin and Lesch (2003, 2005a). From a more practical standpoint, knowing when to irrigate can be determined simply by feel. By squeezing the soil between the thumb and forefinger, or squeezing the soil in the palm of a hand, a fairly accurate estimate of soil moisture can be determined, but this requires considerable experience.

Determining the amount of water to apply is less straightforward than knowing when to apply. To prevent the accumulation of excessive soluble salts in irrigated soils, more water than is required to meet the ET needs of the crops must pass through the root zone to leach soluble salts. This additional irrigation water has typically been expressed as the leaching requirement (LR). LR was originally defined as the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding a level that would significantly reduce crop yield under steady-state conditions, with associated good management and uniformity of leaching (U.S. Salinity Laboratory Staff 1954).

8.4.1 LR: Steady-State vs. Transient Approach

As published in Handbook 60 (U.S. Salinity Laboratory Staff 1954), the original LR model is based on the concept of LF for steady-state conditions with no precipitation or dissolution and good drainage:

$$\mathrm{LF} = \frac{V_{\mathrm{dw}}}{V_{\mathrm{inf}}} = \frac{\mathrm{EC}_{\mathrm{iw}}}{\mathrm{EC}_{\mathrm{dw}}} \tag{8.18}$$

where V_{dw} (mm) and V_{inf} (mm) are the volumes of drainage water and infiltrating irrigation water, respectively, and EC_{iw} (dS m^{-1}) and EC_{dw} (dS m^{-1}) are the electrical conductivities of the irrigation and drainage water, respectively. The LR was originally defined by the U.S. Salinity Laboratory Staff (1954) as the lowest value of LF that could be allowed without EC_{dw} (and thus, inferentially, soil salinity) becoming excessive for optimum plant growth. Thus, the minimum value of LF (i.e., LR) would be given when the maximum permissible salinity level of EC_{dw} (i.e., EC^*_{dw}) was inserted into Equation 8.18 resulting in Equation 8.19, which is considered the original LR model:

$$LR = \frac{EC_{iw}}{EC^*_{dw}} \tag{8.19}$$

The LR is an estimate of what the LF must be to keep soil water salinity within tolerable limits for crop production.

The determination of the LR, as originally formulated in Equation 8.19, required the selection of the appropriate value of EC^*_{dw} for the crop in question. These crop-related values were not known and would be expected to vary with irrigation water salinity and management. However, data obtained from controlled test-plot studies utilizing relatively uniform soil conditions and optimal irrigation and crop management were available (Bernstein 1974; Maas and Hoffman 1977). These controlled studies related the response of many crops to average root zone soil salinity in terms of the EC_e (dS m^{-1}), which is approximately half that of the soil water salinity at field capacity (U.S. Salinity Laboratory Staff 1954). The nearly uniform root zone EC_e values that resulted in 50% yield decreases in forage, field, and vegetable crops, and 10% yield decreases in fruit crops were originally substituted for EC^*_{dw} in Equation 8.19 to estimate the LR. No direct evidence or clear reasoning was given to support the appropriateness of this substitution or the corresponding LR values. Another inherent assumption in the original approach used to determine the LR is that plants respond primarily to average root zone soil salinity. This assumption is not always true. Some evidence for this conclusion is given in Rhoades and Merrill (1976). In addition, the traditional LR model assumes uniform water applications and does not adjust for salt precipitation or dissolution nor does it account for irrigation frequency effects, upward water flow, preferential flow, water chemical composition, and salt removal in surface runoff. Several, but not all, of these inherent weaknesses are accounted for in many of the transient solute transport models that have been developed since 1980, as a consequence of increased computational speeds and memory capabilities of computers.

Work by Letey and Feng (2007) and Corwin et al. (2007) showed that traditional steady-state models calculated higher LRs than more sophisticated and mechanistically rigorous transient models. For instance, Corwin et al. (2007) ran simulations for a typical 6-year crop rotation in California's Imperial Valley and found a reduction in the LR from 0.13 to 0.08. Reducing the estimated LR from 0.13 to 0.8 will reduce irrigation water needs that deplete scarce surface water supplies and will reduce drainage volumes that impact the environment when disposed. To put this into perspective for water conservation, each year, an estimated 2.46×109 m^3

(2 million ac-ft) of water infiltrates into the cropped soil of California's Imperial Valley; consequently, reducing the LR from 0.14 to 0.08 would reduce the drainage volume by approximately 1.23 × 108 m^3 (100,000 ac-ft).

Combining site-specific irrigation management with LRs determined from transient solute transport models will unquestionably conserve significant volumes of water and reduce drainage loads that are costly and difficult to dispose without impacting the environment. In response to the research of Letey and Feng (2007) and Corwin et al. (2007), the University of California Center for Water Resources appointed a workgroup to determine whether the current recommended guidelines for the LR based on traditional steady-state analyses need to be revised. The workgroup concluded that the present guidelines overestimate the LR and the negative consequences of irrigating with saline waters (Letey et al. 2011). This error is most significant at low LFs, which is a fortuitous finding because irrigating to achieve low LFs provides a more efficient use of limited water supplies (Letey et al. 2011).

8.5 CAVEAT

Even though EC_a-directed soil sampling provides a viable means of identifying some soil properties that influence within-field variation of yield and of delineating SSIMUs, it is only one piece of a complicated puzzle of interacting factors that result in observed within-field crop variation. Water conservation is just one aspect of sustainable agriculture. Crop yield is influenced by complex interactions of meteorological (e.g., temperature, humidity, wind, etc.), biological (e.g., pests, earthworms, etc.), anthropogenic (management related), and edaphic (e.g., salinity, soil pH, water content, etc.) factors. Furthermore, sustainability requires more than just a myopic look at crop productivity. Sustainability must balance profitability, crop productivity, optimization of resource inputs (e.g., water, fertilizers, pesticides), and minimization of environmental impacts.

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