

Agronomy Journal

Volume 95

May–June 2003

Number 3

SYMPOSIUM PAPERS

Application of Soil Electrical Conductivity to Precision Agriculture: Theory, Principles, and Guidelines

D. L. Corwin* and S. M. Lesch

ABSTRACT

Due in large measure to the prodigious research efforts of Rhoades and his colleagues at the George E. Brown, Jr., Salinity Laboratory over the past two decades, soil electrical conductivity (EC), measured using electrical resistivity and electromagnetic induction (EM), is among the most useful and easily obtained spatial properties of soil that influences crop productivity. As a result, soil EC has become one of the most frequently used measurements to characterize field variability for application to precision agriculture. The value of spatial measurements of soil EC to precision agriculture is widely acknowledged, but soil EC is still often misunderstood and misinterpreted. To help clarify misconceptions, a general overview of the application of soil EC to precision agriculture is presented. The following areas are discussed with particular emphasis on spatial EC measurements: a brief history of the measurement of soil salinity with EC, the basic theories and principles of the soil EC measurement and what it actually measures, an overview of the measurement of soil salinity with various EC measurement techniques and equipment (specifically, electrical resistivity with the Wenner array and EM), examples of spatial EC surveys and their interpretation, applications and value of spatial measurements of soil EC to precision agriculture, and current and future developments. Precision agriculture is an outgrowth of technological developments, such as the soil EC measurement, which facilitate a spatial understanding of soil–water–plant relationships. The future of precision agriculture rests on the reliability, reproducibility, and understanding of these technologies.

THE PREDOMINANT MECHANISM causing the salt accumulation in irrigated agricultural soils is evapotranspiration. The salt contained in the irrigation water is left behind in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration. The effects of salinity are manifested in loss of stand, reduced rates of plant growth, reduced yields, and in severe cases, total crop failure (Rhoades and Loveday, 1990). Salinity limits water uptake by plants by reducing the osmotic potential and thus the total soil water potential. Salinity may also cause specific ion toxicity or upset the nutritional bal-

ance. 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, depending on salinity level and exchangeable cation composition. Aside from decreasing crop yield and impacting soil hydraulics, salinity can detrimentally impact ground water, and in areas where tile drainage occurs, drainage water can become a disposal problem as demonstrated in the southern San Joaquin Valley of central California.

From a global perspective, irrigated agriculture makes an essential contribution to the food needs of the world. While only 15% of the world's farmland is irrigated, roughly 35 to 40% of the total supply of food and fiber comes from irrigated agriculture (Rhoades and Loveday, 1990). However, vast areas of irrigated land are threatened by salinization. Although accurate worldwide data are not available, it is estimated that roughly half of all existing irrigation systems (totaling about 250 million ha) are affected by salinity and waterlogging (Rhoades and Loveday, 1990).

Salinity within irrigated soils clearly limits productivity in vast areas of the USA and other parts of the world. It is generally accepted that the extent of salt-affected soil is increasing. In spite of the fact that salinity buildup on irrigated lands is responsible for the declining resource base for agriculture, we do not know the exact extent to which soils in our country are salinized, the degree to which productivity is being reduced by salinity, the increasing or decreasing trend in soil salinity development, and the location of contributory sources of salt loading to ground and drainage waters. Suitable soil inventories do not exist and until recently, neither did practical techniques to monitor salinity or assess the

Abbreviations: EC, electrical conductivity; EC_a, apparent soil electrical conductivity; EC_e, electrical conductivity of the saturated soil paste extract; EC_w, electrical conductivity of soil water; EM, electromagnetic induction; EM_{avg}, the geometric mean of the vertical and horizontal electromagnetic induction readings; EM_v, electromagnetic induction measurement in the horizontal coil-mode configuration; EM_v, electromagnetic induction measurement in the vertical coil-mode configuration; GIS, geographical information system; GPS, global positioning systems; NPS, nonpoint source; SP, saturation percentage; TDR, time domain reflectometry; θ_w, total volumetric water content.

USDA-ARS, George E. Brown, Jr., Salinity Lab., 450 West Big Springs Rd., Riverside, CA 92507-4617. Received 23 Apr. 2001. *Corresponding author (dcorwin@ussl.ars.usda.gov).

Published in Agron. J. 95:455–471 (2003).

impacts of changes in management on soil salinity and salt loading. A means of assessing soil salinity across the landscape is essential to the management of soil salinity. Because of the influence of soil salinity on crop productivity and the dynamic spatio-temporal nature of salinity, real-time measurement and monitoring of the spatial and temporal distribution of soil salinity is a crucial piece of information for precision agriculture applications on irrigated agricultural soils of the arid southwestern USA.

Precision agriculture (or site-specific agriculture) utilizes rapidly evolving electronic information technologies to modify land management in a site-specific manner as conditions change spatially and temporally (van Schilfhaarde, 1999). The intent of precision agriculture is to optimize crop production while minimizing detrimental environmental effects. First conceived in the mid-1980s, the technological pieces needed to bring precision agriculture into its own fell into place in the mid-1990s with the maturation of global positioning systems (GPS) and geographical information systems (GIS). As such, precision agriculture is a technologically driven system (van Schilfhaarde, 1999). The measurement of soil EC is among the technologies that have helped to bring precision agriculture from a concept to a potential tool for addressing the issue of agricultural sustainability.

The determination of total solute concentration (i.e., salinity) through the measurement of electrical conductance has been well established for decades (U.S. Salinity Lab. Staff, 1954). Soil EC measurement is a means of easily quantifying and monitoring soil salinity in irrigated agricultural areas of arid-zone soils. Soil salinity refers to the presence of the major dissolved inorganic solutes in the aqueous phase consisting of soluble and readily dissolvable salts in soil, including charged species (e.g., Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , HCO_3^- , NO_3^- , SO_4^{2-} and CO_3^{2-}), nonionic solutes, and ions that combine to form ion pairs. 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} (U.S. Salinity Lab. Staff, 1954). For pure solutions, it is known that the EC of the pure solution σ_w is a function of the chemical composition as characterized by Eq. [1]:

$$\sigma_w = k \sum_{i=1}^n \lambda_i M_i |v_i| \quad [1]$$

where k is the cell constant accounting for electrode geometry, λ is the molar limiting ion conductivity ($\text{S m}^2 \text{mol}^{-1}$), M is the molar concentration (mol m^{-3}), v is the absolute value of the ion charge, and i denotes the ion species in solution. Marion and Babcock (1976) were among the first to confirm the existence of a relationship between EC and molar concentrations of ions in the soil solution. The relationship of EC of soil water (EC_w) to aggregate or individual ions in soil has also been confirmed by recent work of Kachanoski et al. (1992), Vanclouster et al. (1993), Wraith et al. (1993), Mallants et al. (1994), Ward et al. (1994), Heimovaara et al. (1995), Nissen et al. (1998), and Das et al. (1999).

Operationally, soil EC is determined for an aqueous extract of a soil sample. Ideally, it would be desirable to determine the concentrations of individual solutes in

soil water over the entire range of field water contents with a quick, easy measurement, but practical methods are not currently available to do so. Because of the time, labor, and cost of obtaining soil solution extracts, developments in soil salinity measurement over the past two decades have shifted to EC measurement of the bulk soil, referred to as the apparent soil electrical conductivity (EC_a). The EC_a measures conductance through not only the soil solution, but also through the solid soil particles and via exchangeable cations that exist at the solid-liquid interface of clay minerals.

Apparent soil electrical conductivity 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 (Rhoades et al., 1999b). The value of spatial measurements of EC_a to precision agriculture is widely acknowledged, but EC_a is still often misunderstood and misinterpreted. To help clarify misconceptions, a general overview of the application of EC_a to precision agriculture is presented. It is the objective of this paper to describe the practical technology and methodology for real-time measurement of EC_a , with particular emphasis on spatial EC_a measurements applied to precision agriculture. The following areas are discussed: a brief history of the measurement of soil salinity with EC, the basic theories and principles of the soil EC measurement and what it actually measures, an overview of the measurement of soil salinity with various EC measurement techniques and equipment (specifically, electrical resistivity with the Wenner array and EM), examples of spatial EC surveys and their interpretation, applications, and value of spatial measurements of soil EC to precision agriculture, and current and future developments.

BRIEF HISTORY OF THE MEASUREMENT OF SOIL SALINITY

Historically, five methods have been used for determining soil salinity: (i) visual crop observations, (ii) the electrical conductance of soil solution extracts or extracts at higher-than-normal water contents, (iii) in situ measurement of electrical conductance with electrical resistivity using the Wenner array, (iv) noninvasive measurement of electrical conductance with EM, and most recently (v) in situ measurement of electrical conductance with time domain reflectometry.

The first method, visual crop observation, is quick and economical, but it has the disadvantage that salinity development is detected after crop damage has occurred. For this reason, visual observation is the least desirable method for assessing soil salinity. However, on fields where long-term, field-scale patterns of soil salinity exist, visual observations from one year provide useful information for succeeding years.

The second method, electrical conductance of the soil solution extract, gives a quantitative measure of soil salinity but requires considerable resources for field sampling and laboratory analysis, plus the volume of soil measurement is very small and ill-suited to characterize and map the extreme variability of salinity at field scales and larger (Corwin, 2002a). Customarily,

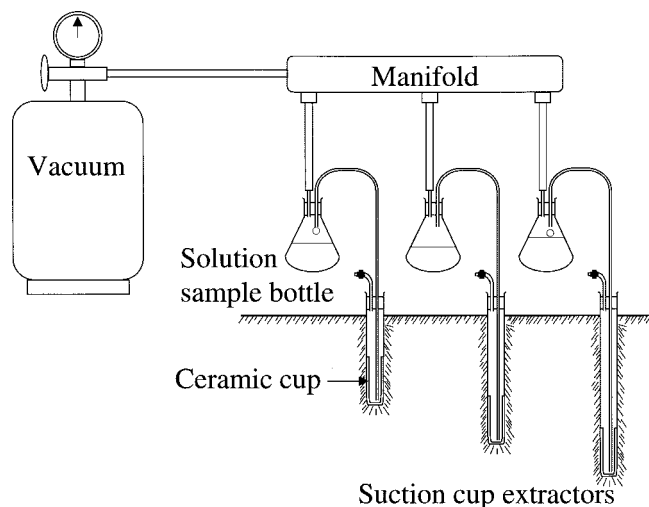


Fig. 1. Diagram of the basic suction cup extractor setup for sampling the soil solution. Taken from Corwin (2002a).

soil salinity has been defined in terms of EC of the saturated soil paste extract (EC_e). This is because it is impractical for routine purposes to extract soil water from samples at typical water contents; consequently, soil solution extracts must be made at higher-than-normal water contents. Unfortunately, the partitioning of solutes over the three soil phases (i.e., gas, liquid, and solid) is influenced by the soil/water ratio at which the extract is made so that the ratio needs to be standardized to obtain results that can be applied and interpreted universally. Commonly used extract ratios aside from a saturated soil paste are 1:1 ($EC_{1:1}$), 1:2 ($EC_{1:2}$), and 1:5 ($EC_{1:5}$) soil/water mixtures. However, soil salinity can also be determined from the measurement of EC_w . Theoretically, EC_w is the best index of soil salinity because this is the soil solution salinity actually experienced by the plant root. Nevertheless, EC_w has not been widely used to express soil salinity for various reasons: (i) It varies over the irrigation cycle as the soil water content changes, so it is not single valued (Rhoades, 1978), and (ii) the methods for obtaining soil solution samples for routine EC_w analysis are too labor, time, and cost intensive at typical field water contents to be practical for field-scale applications (Rhoades et al., 1999a). For disturbed soil samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum or pressure extraction methods (Rhoades and Oster, 1986). For undisturbed soil samples, EC_w can be determined either in the laboratory on a soil solution sample collected with a soil solution extractor (Fig. 1) or directly in the field using in situ, imbibing-type porous-matrix salinity sensors (Fig. 2).

There are serious doubts about the ability of soil solution extractors and porous-matrix salinity sensors (also known as soil salinity sensors) to provide representative soil water samples (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, both solution extractors and salt sensors do not adequately integrate spatial variability (Amoozegar-Fard

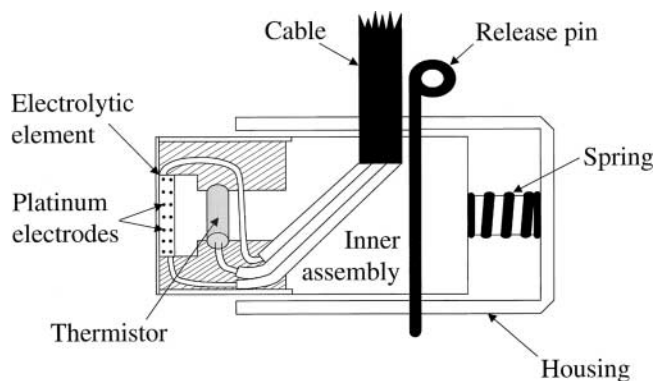


Fig. 2. Schematic of the porous-matrix salinity sensor. Taken from Corwin (2002b).

et al., 1982; Haines et al., 1982; Hart and Lowery, 1997); consequently, Biggar and Nielsen (1976) suggested that soil solution samples are “point samples” that can provide good qualitative, but not quantitative, estimates unless field-scale variability is adequately established. Furthermore, salinity sensors demonstrate a response-time lag that depends on diffusion of ions between the soil solution and solution in the porous ceramic cell, which is affected by (i) thickness of the ceramic conductivity cell, (ii) diffusion coefficients in soil and ceramic, and (iii) fraction of the ceramic surface in contact with soil (Wesseling and Oster, 1973). The salinity sensor is generally considered the least desirable method of measuring EC_w because of its low sample volume, unstable calibration over time, and slow response (Corwin, 2002b).

Electrical resistivity (e.g., Wenner array) and EM are both well suited for precision agriculture applications because their volumes of measurement are large, which reduces the influence of local-scale variability. However, electrical resistivity is an invasive technique that requires good contact between the soil and four electrodes inserted into the soil; consequently, it produces less reliable measurements in dry or stony soils than the noninvasive EM measurement. The EM has become the first choice for measuring soil salinity in a geospatial context because (i) measurements can be taken as quickly as one can move from one location to the next, (ii) the large volume of soil measured reduces local-scale variability, and (iii) measurements in relatively dry or stony soils are possible because no contact is necessary between the soil and the EM sensor (Hendrickx et al., 1992). Nevertheless, electrical resistivity has a flexibility that has proven advantageous for field application, i.e., the depth and volume of measurement can be easily changed by changing the spacing between the electrodes. Even though the depth of penetration and volume of measurement by EM can be varied by raising the instrument above the soil surface, it is a complicated matter of determining the subsequent depth and volume of measurement, whereas in the case of the electrical resistivity method, it is a simple calculation to estimate the depth of penetration and the volume of measurement once the interelectrode spacing is adjusted. Both electrical resistivity and EM measure the EC_a . Electrical resistivity measures apparent resistivity.

In homogeneous mediums, resistivity is the reciprocal of conductivity. Resistivity devices convert measurements of apparent resistivity into measurements of apparent conductivity.

Time domain reflectometry (TDR) was initially adapted for use in measuring water content. 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 attenuation of applied signal voltage as it traverses the medium of interest with the relative magnitude of energy loss related to EC_a (Wraith, 2002). The advantages of TDR for measuring EC_a include (i) a relatively noninvasive nature because there is only minor interference with soil processes, (ii) an ability to measure both soil water content and EC_a , (iii) an ability to detect small changes in EC_a under representative soil conditions, (iv) the capability of obtaining continuous unattended measurements, and (v) no need for a calibration of soil water content measurements in many cases (Wraith, 2002).

PRINCIPLES OF EC_a MEASUREMENT

Of all the aforementioned methods of measuring soil salinity, the measurement of EC_a with electrical resistivity and EM is regarded as the most practical for establishing the spatial distribution of soil salinity at field scales and larger (Rhoades et al., 1999b). Measurement

of EC_a with electrical resistivity and EM has the greatest potential for application to precision agriculture because of its reliability, accuracy, large volume of measurement, and relative ease of obtaining the measurement.

Apparent soil electrical conduction in sufficiently moist soils is primarily via salts contained in soil water occupying the larger pores; consequently, measurement of EC of bulk soil is closely related to soil salinity (Rhoades et al., 1999b). However, there is also a contribution by the solid phase to EC_a in moist soils primarily via the exchangeable cations associated with clay minerals (Rhoades et al., 1999b). A third pathway exists through soil particles in direct and continuous contact with one another (Rhoades et al., 1999b). These three pathways of current flow contribute to the EC_a (Fig. 3).

Rhoades et al. (1989) formulated an electrical conductance model that describes the three conductance pathways of EC_a :

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

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the soil water pathway ($\text{cm}^3 \text{cm}^{-3}$) and in the continuous liquid pathway ($\text{cm}^3 \text{cm}^{-3}$), respectively; θ_{ss} and θ_{sc} are the volumetric contents of the surface-conductance

Pathways of Electrical Conductance

Soil Cross Section

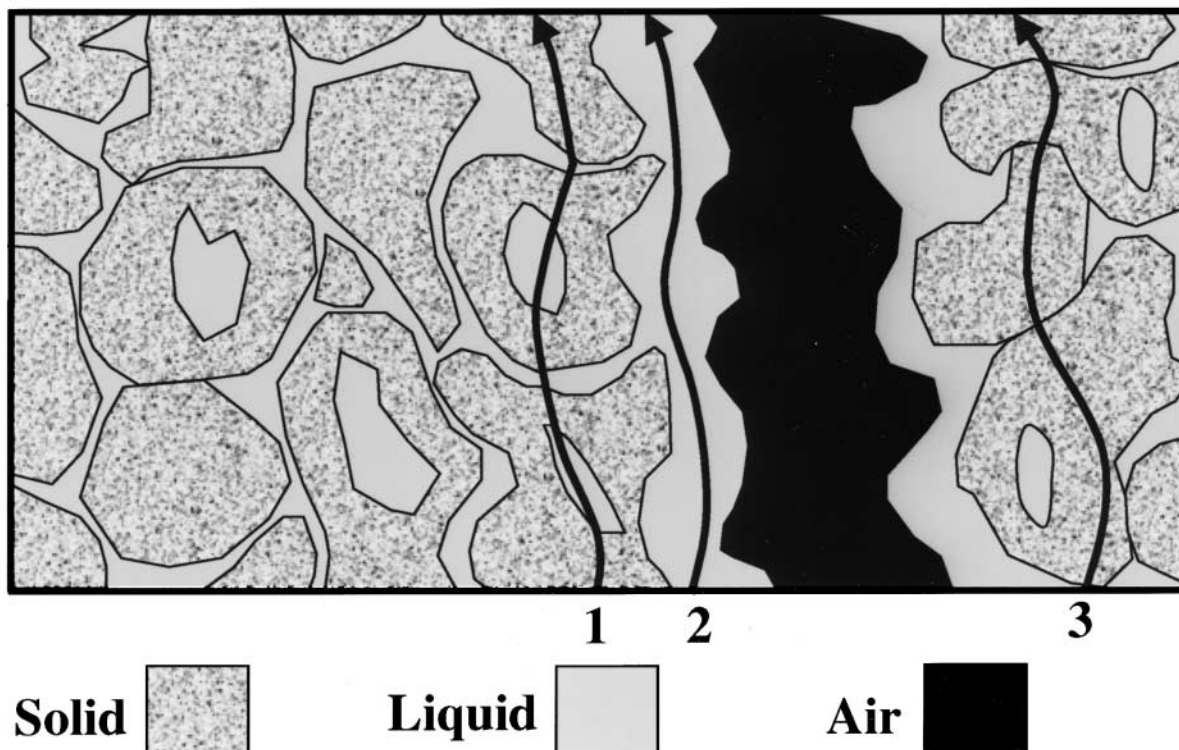


Fig. 3. Soil electrical conductance pathways. 1 = liquid, 2 = solid-liquid, and 3 = solid. Modified from Rhoades et al. (1989).

($\text{cm}^3 \text{cm}^{-3}$) and indurated ($\text{cm}^3 \text{cm}^{-3}$) solid phases of the soil, respectively; EC_{ws} and EC_{wc} are the specific ECs of the soil water pathway (dS m^{-1}) and continuous liquid pathway (dS m^{-1}); and EC_{ss} and EC_{sc} are the ECs of the surface-conductance (dS m^{-1}) and indurated (dS m^{-1}) solid phases, respectively. Equation [2] was reformulated by Rhoades et al. (1989) into Eq. [3]:

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{(\theta_{ss} \cdot EC_{ws}) + (\theta_{ws} \cdot EC_s)} \right] + (\theta_w - \theta_{ws}) \cdot EC_{wc} \quad [3]$$

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

$$\theta_w = (PW \cdot \rho_b)/100 \quad [4]$$

$$\theta_{sw} = 0.639\theta_w + 0.011 \quad [5]$$

$$\theta_{ss} = \rho_b/2.65 \quad [6]$$

$$EC_{ss} = 0.019(SP) - 0.434 \quad [7]$$

$$EC_w = \left[\frac{(EC_e \cdot \rho_b \cdot SP)}{100 \cdot \theta_w} \right] \quad [8]$$

where PW is the percentage water on a gravimetric basis, ρ_b is the bulk density (Mg m^{-3}), SP is the saturation percentage, EC_w is average EC of the soil water assuming equilibrium (i.e., $EC_w = EC_{ws} = EC_{wc}$), and EC_e is the EC of the saturation extract (dS m^{-1}). By measuring soil EC_e , SP, PW, and ρ_b and using Eq. [3] through [8], the EC_a can be estimated. Very simply, Eq. [3] through [8] indicate that EC_a is a function of the soil physical and chemical properties of (i) soil salinity, (ii) SP, (iii) water content, and (iv) bulk density. The SP and bulk density are both closely associated with clay content.

Another factor influencing EC_a is temperature. 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 for purposes of comparison. The EC measured at a particular temperature t , EC_t , can be adjusted to a reference EC at 25°C, EC_{25} , using the below relation from Handbook 60 (U.S. Salinity Lab. Staff, 1954):

$$EC_{25} = f_t \cdot EC_t \quad [9]$$

where f_t is a temperature conversion factor. Approximations for the temperature conversion factor are available in polynomial form (Stogryn, 1971; Wraith and Or, 1999) or other equations such as Eq. [10] by Sheets and Hendrickx (1995):

$$f_t = 0.4470 + 1.4034e^{-t/26.815} \quad [10]$$

Traditionally, EC_e has been the standard measure of salinity used in all salt-tolerance plant studies. As a result, a relation between EC_a and EC_e was needed to relate EC_a back to EC_e , which is in turn related to crop yield. Over the past two decades, research has been directed at developing reliable and efficient conversion techniques from EC_a back to EC_e (Williams and Baker, 1982; McNeill, 1980, 1986; McKenzie et al., 1989;

Rhoades, 1992, 1996; Rhoades and Corwin, 1990; Rhoades et al., 1989, 1990, 1991, 1999a; Slavich, 1990; Cook and Walker, 1992; Diaz and Herrero, 1992; Yates et al., 1993; Lesch et al., 1992, 1995a, 1995b, 1998).

METHODS AND EQUIPMENT FOR GEOREFERENCED MEASUREMENT OF EC_a

Indirect methods for the determination of soil salinity depend on a measurement of EC_a using electrical resistivity (i.e., Wenner array), EM, or TDR. Although TDR has been demonstrated to compare closely with other accepted methods of EC_a measurement (Heimovaara et al., 1995; Mallants et al., 1996; Spaans and Baker, 1993; Reece, 1998), it is still not sufficiently simple, robust, or fast enough for the general needs of field-scale assessment of soil salinity (Rhoades et al., 1999a). Only electrical resistivity (specifically, the Wenner array) and EM have been adapted for the georeferenced measurement of EC_a at field scales and larger (Rhoades et al., 1999a, 1999b).

Electrical Resistivity

Electrical resistivity methods introduce an electrical current into the soil through current electrodes at the soil surface, and the difference in current flow potential is measured at potential electrodes that are placed in the vicinity of the current flow. 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 ground electrical resistivity (Burger, 1992; Telford et al., 1990).

The electrode configuration is referred to as a Wenner array when four electrodes are equidistantly spaced in a straight line at the soil surface, with the two outer electrodes serving as the current, or transmission, electrodes and the two inner electrodes serving as the potential, or receiving, electrodes (Fig. 4). The depth of penetration of the electrical current and the volume of measurement depend on the interelectrode spacing. The larger the spacing is, the deeper the measurement and larger the volume of measurement. The resistivity, ρ , measured with the Wenner array is (Burger, 1992):

$$\rho = 2\pi a \Delta V / i = 2\pi a R \quad [11]$$

where V is the voltage (V), a is the interelectrode spacing, i is the electrical current (A), and R is the measured resistance (ω). Because the EC_a is the inverse of R , then Eq. [11] becomes:

$$EC_a = 1/2\pi a R \quad [12]$$

The volume of measurement with the Wenner array is roughly between the two inner potential electrodes from the soil surface to a depth of roughly the interelectrode spacing, a . For a homogeneous soil, the soil volume measured is roughly πa^3 . Other electrode configurations are frequently used, and the equations for these configurations are discussed by Burger (1992), Dobrin (1960), and Telford et al. (1990).

The basic equipment for measuring EC_a with the

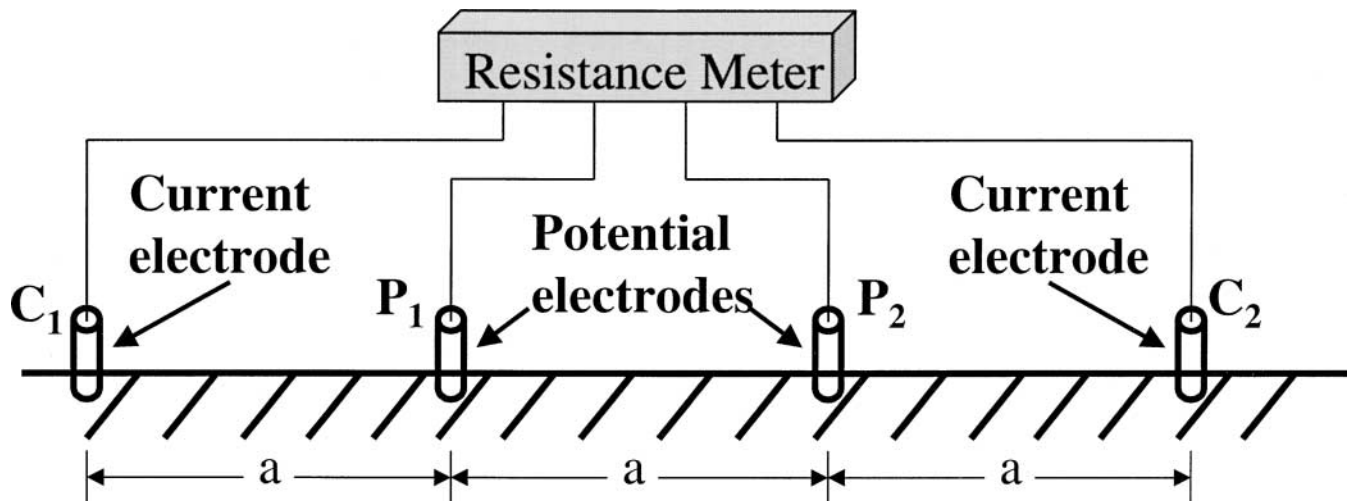


Fig. 4. Schematic of Wenner array electrodes. C_1 and C_2 represent the current electrodes, P_1 and P_2 represent the potential electrodes, and a represents the interelectrode spacing. Modified from Rhoades and Halvorson (1977).

Wenner array technique (Fig. 5) includes an electrical current source, a resistance meter, four metal electrodes, connecting wire, measuring tape, and a soil thermometer (Rhoades and Halvorson, 1977). The current source can be a hand-cranked generator or battery powered, which should measure from 0.1 to 1000 ω . The electrodes can be made from any noncorrosive conductive metal (e.g., stainless steel, copper, brass). The connecting wire should be flexible, well-insulated, multistranded, 12- to 18-gauge wire. Detailed instructions concerning electrode construction and information concerning the resistivity meters can be found in Rhoades and Halvorson (1977).

By mounting the four electrodes to *fix* their interelectrode spacing, considerable time for a handheld measurement is saved (Fig. 6; Rhoades and Halvorson, 1977). An interelectrode spacing of 1 to 1.5 m is particularly useful in instances where the Wenner array is used in conjunction with the EM-38 electromagnetic conductivity meter because the penetration depths of the EM-38 in the vertical and horizontal coil configurations are 0.75 and 1.5 m, respectively. However, a Wenner array with

a 1.5-m interelectrode spacing would result in a cumbersome 4.5-m span.

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 the following equation from Barnes (1952) for resistors in parallel:

$$EC_x = EC_{a_i - a_{i-1}} - \frac{(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} \cdot a_{i-1})}{(a_i - a_{i-1})} \quad [13]$$

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 previous sampling. A detailed discussion of the Wenner array electrical resistivity technique can be found in Corwin and Hendrickx (2002).

A mobilized, tractor-mounted version of the *fixed-electrode array* (Fig. 7) has been developed that georeferences the EC_a measurement with a GPS (Carter et al., 1993; Rhoades, 1992, 1993). The fixed-electrode array is a particularly appealing approach for field applications because of the relative ease of measurement and the large volume of soil that can be measured. However,

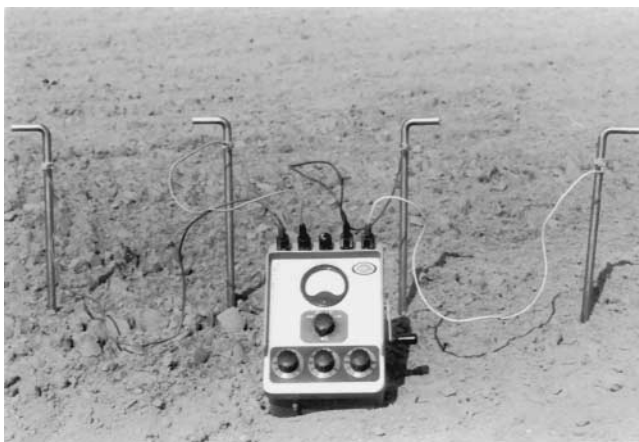


Fig. 5. Equipment layout of the Wenner array technique. Taken from Rhoades and Oster (1986).

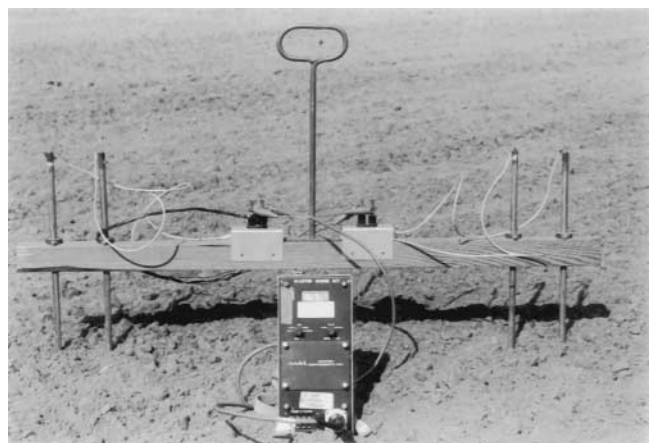


Fig. 6. Electrodes mounted in a fixed array.



Fig. 7. Mobile fixed-array equipment for the continuous measurement of apparent soil electrical conductivity.

because of the large volume of measurement and the complex localized spatial variability of pore geometry, water content, and salinity, which influence the measurement of EC_a , some error is introduced, making it difficult to calibrate EC_a , as measured with this equipment, to EC_w or EC_e as determined for soil samples taken at the sites of the EC_a measurements. The error is a consequence of the difference in volumes of measurement between the EC_a measurement and the soil core sample used to determine the associated EC_w or EC_e . The calibration problem is also of concern for EM. The mobile, fixed-electrode array equipment is particularly well suited for collecting detailed maps of the spatial variability of average root-zone soil EC at field scales and larger.

Veris Technologies¹ has developed a commercial system for measuring EC_a using the principles of the Wen-

¹ Veris Technologies, Salina, KS, USA (www.veristech.com; verified 27 Jan. 2003). Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

ner array. The Veris unit consists of six coulter electrodes. Coulter electrodes no. 2 and 5 are the current electrodes. Two sets of electrode arrays enable simultaneous measurement of two soil depths: 0 to 0.3 m and 0 to 0.9 m. When connected to a GPS, a georeferenced map of EC_a for precision agriculture applications is prepared.

Electromagnetic Induction

Apparent soil electrical conductivity can be measured remotely with EM. An EM transmitter coil located at one end of the instrument induces circular eddy-current loops in the soil (Fig. 8). The magnitude of these loops is directly proportional to the EC of the soil 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 bulk soil EC, EC_a . The receiver coil measures amplitude and phase of the secondary magnetic field. 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, and salinity), spacing of the coils and their orientation, frequency, and distance from the soil surface (Hendrickx and Kachanoski, 2002).

The two most commonly used EM conductivity meters in soil science and in vadose zone hydrology are the Geonics² EM-31 and EM-38. 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. The EM-38 has an intercoil spacing of 1 m, which results in a penetration

² Geonics, Limited, Mississauga, ON, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

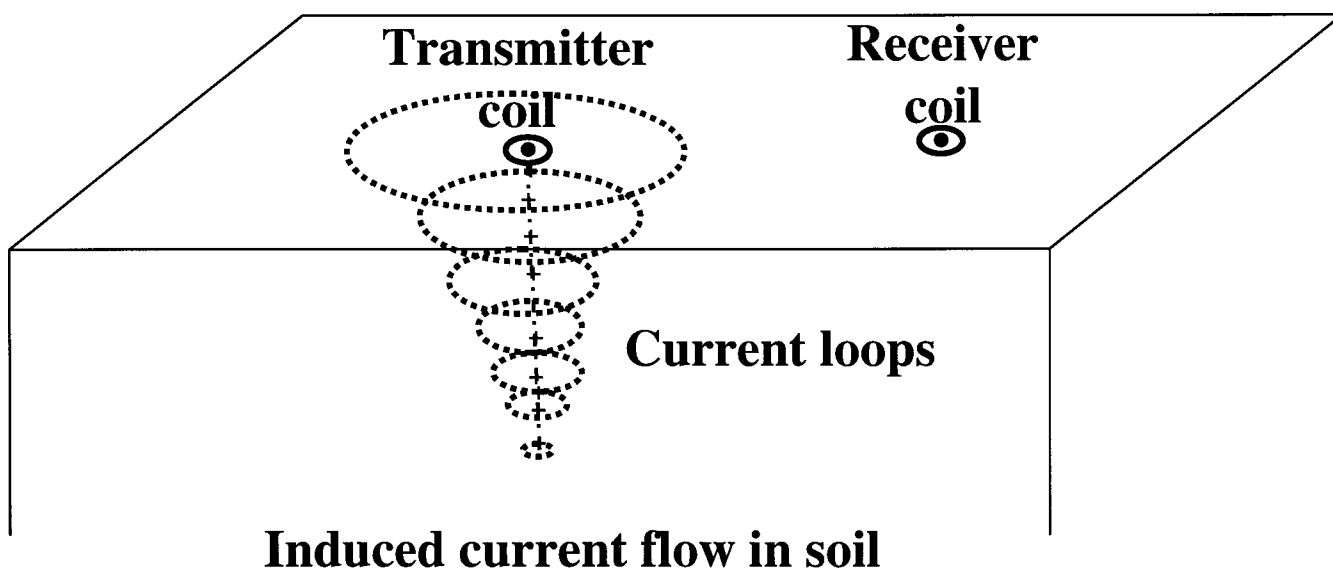


Fig. 8. Principle of operation of the electromagnetic soil conductivity meter.

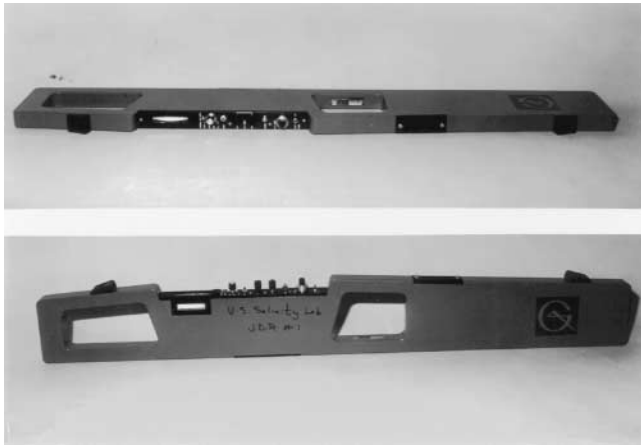


Fig. 9. Handheld Geonics EM-38 electromagnetic soil conductivity meter (top) lying in the horizontal orientation with its coils parallel to the soil surface and (bottom) lying in the vertical orientation with its coils perpendicular to the soil surface.

depth of roughly 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Fig. 9). The EM-38 has had considerably greater application for precision agriculture because the root zone extends roughly to 1.5 m. A detailed discussion of the equipment and its operation can be found in Hendrickx and Kachanoski (2002).

The EC_a measured by EM at $EC_a < 100 \text{ mS m}^{-1}$ is given by (McNeill, 1980)

$$EC_a = \frac{4}{2\pi\mu_0 f_s^2} \left(\frac{H_s}{H_p} \right) \quad [14]$$

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 ($4\pi \cdot 10^{-7} \text{ H m}^{-1}$); and s is the intercoil spacing (m).

Mobile EM equipment developed at the Salinity Laboratory (Carter et al., 1993; Rhoades, 1993) is available for the appraisal of soil salinity and other soil properties (e.g., water content and clay content) using an EM-38. The drawback of this early mobile EM equipment was that it produced a point EC_a measurement for the vertical (EM_v) and horizontal (EM_h) coil configurations rather than a continuous-stream reading of EC_a as with the mobile fixed-array equipment; consequently, all EC_a maps were grid maps. The drawback relates to the inability of the EM-38 meter to measure and record data simultaneously in each dipole orientation. The measurement of soil salinity with EM relies on both horizontal and vertical dipole measurements at each observation point to qualitatively evaluate the salinity distribution profile. However, data can be recorded continuously with the EM-38 meter if surveys are conducted in one dipole orientation. This is commonly done in the Midwest where other towed units that have been developed. In these instances, the concern is not with mapping salinity, but usually with mapping clay, water content, or both. Recently, the mobile EM equipment developed at the Salinity Laboratory has been modified by the addition of a dual-dipole EM-38 unit (Fig. 10). The dual-dipole EM-38 meter simultaneously records data in both dipole orientations at time intervals of just a few seconds between readings. A close-up of the sled that houses the dual-dipole EM-38 is provided in Fig. 11. The mobile EM equipment is suited for the detailed mapping of



Fig. 10. Mobile dual-dipole electromagnetic induction equipment for the continuous measurement of apparent soil electrical conductivity.

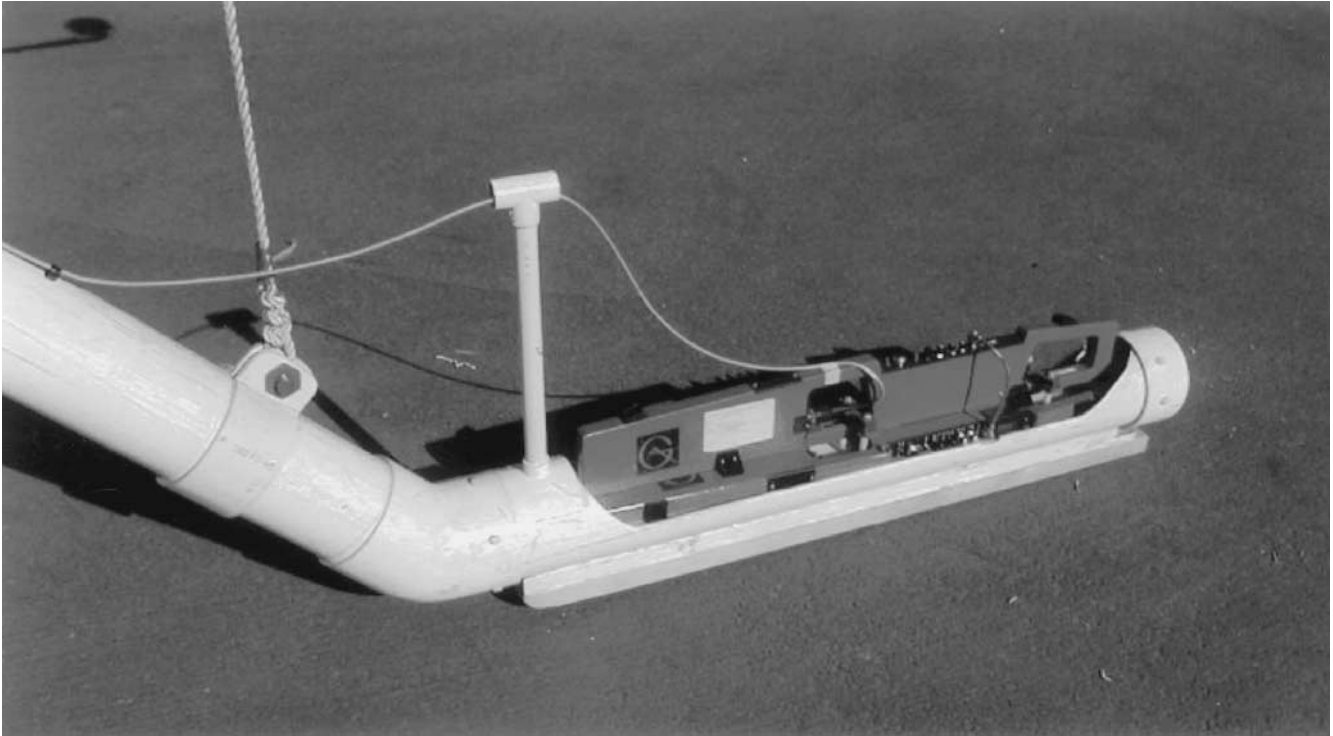


Fig. 11. Close-up of the sled that houses the dual-dipole EM-38 for the mobile electromagnetic induction vehicle.

EC_a and correlated soil properties at specified depth intervals through the root zone. The advantages of the mobile dual-dipole EM equipment over the mobile fixed-array resistivity equipment are that (i) the EM technique is noninvasive, so it can be used in dry 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; (ii) the EM technique provides information for the vertical profiling of EC_a rather than just a single integrated EC_a although the Veris unit does provide two depths; and (iii) stream tubes can be delineated (see Modeling Soil Salinity in a Geospatial Context section). A disadvantage of the EM approach would be that the EC_a is a depth-weighted value that is nonlinear. This depth-weighted nonlinearity is shown in Fig. 12, which illustrates the cumulative relative contributions of all soil EC, $R(z)$, for a homogeneously conductive material below a normalized depth of z based on Eq. [15] and [16] from McNeill (1980) for vertical and horizontal dipoles, respectively:

$$R_v(z) = 1/(4z^2 + 1)^{1/2} \quad [15]$$

$$R_h(z) = (4z^2 + 1)^{1/2} - 2z \quad [16]$$

STANDARD OPERATING PROCEDURE FOR A FIELD-SCALE EC_a SURVEY FOR PRECISION AGRICULTURE APPLICATIONS

The standard operating procedure for field-scale EC_a surveys applied to precision agriculture includes four steps: (i) an initial intensive EC_a survey, (ii) a soil sample design based on the intensive EC_a survey, (iii) a stochas-

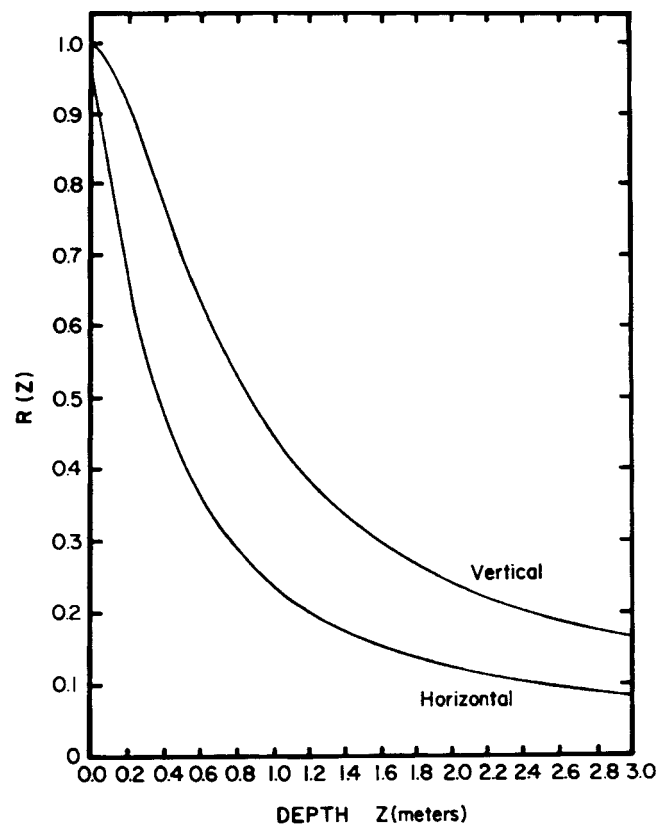


Fig. 12. Cumulative relative contribution of all soil electrical conductivity, $R(z)$, below various depths for the EM-38 apparent soil electrical conductivity reading when the device is held in a horizontal (parallel) and vertical (perpendicular) position. Taken from McNeill (1980).

Mobile Wenner EC_a Survey Broadview Water District - 1996

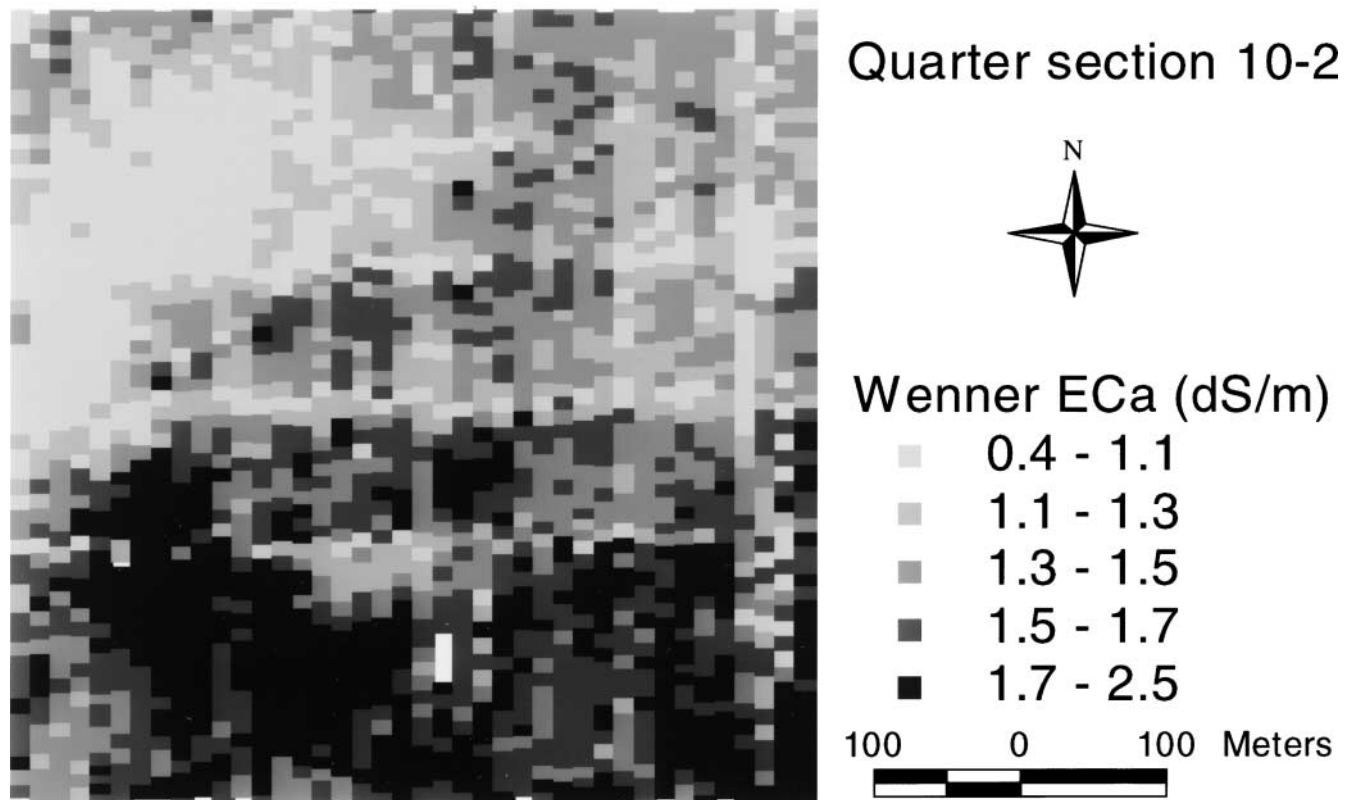


Fig. 13. Detailed mobile Wenner apparent soil electrical conductivity (EC_a) survey of Quarter Section 10-2 (roughly 70 ha) of the Broadview Water District in the San Joaquin Valley of central California.

tic and/or deterministic calibration of EC_a to soil sample-determined EC_e, and (iv) a determination of the dominant soil properties influencing the EC_a measurement at the site of interest. The following is a brief description of each step.

Mobile EC_a Survey and Soil Sample Design

An initial intensive EC_a survey with either mobile electrical resistivity or EM equipment is conducted and used to establish soil core sampling locations needed for calibration and understanding the dominant soil properties influencing EC_a. Depending on the level of detail desired, from 100 to several thousand spatial measurements of EC_a are taken generally in regularly spaced traverses across the field of interest. The use of mobile EM equipment has one slight advantage over the use of mobile resistivity equipment, which is the ability to take measurements on dry and stony soils. Figures 13 and 14 show representative EC_a surveys using mobile Wenner array and mobile EM-38 equipment, respectively.

Once a georeferenced, intensive EC_a survey is conducted, the data can be used to establish the locations of the soil core sample sites that will be used for calibrating EC_a to soil sample EC_e. To establish the locations

where soil cores are to be taken, a software package (ESAP) developed by Lesch et al. (1995a, 1995b, 2000) is used. 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. 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 for validation of the EC_a measurements. This is done with a response-surface sampling design. The EC_a measurements are subsequently transformed using an EC_a-to-EC_e calibration into predicted salinity data throughout the entire survey area using the sample soil salinity data in conjunction with spatially based statistical modeling techniques.

Stochastic and/or Deterministic Calibration of EC_a to EC_e

Soil salinity, as conventionally expressed in terms of EC_e, can be inferred from EC_a by two approaches: a deterministic and a stochastic approach (Rhoades et al., 1999b). The preferred approach will vary with the size of the area to be assessed, availability of equipment, and the specific objectives. In the deterministic approach,

Broadview Water District - 1991

EMv Measurements

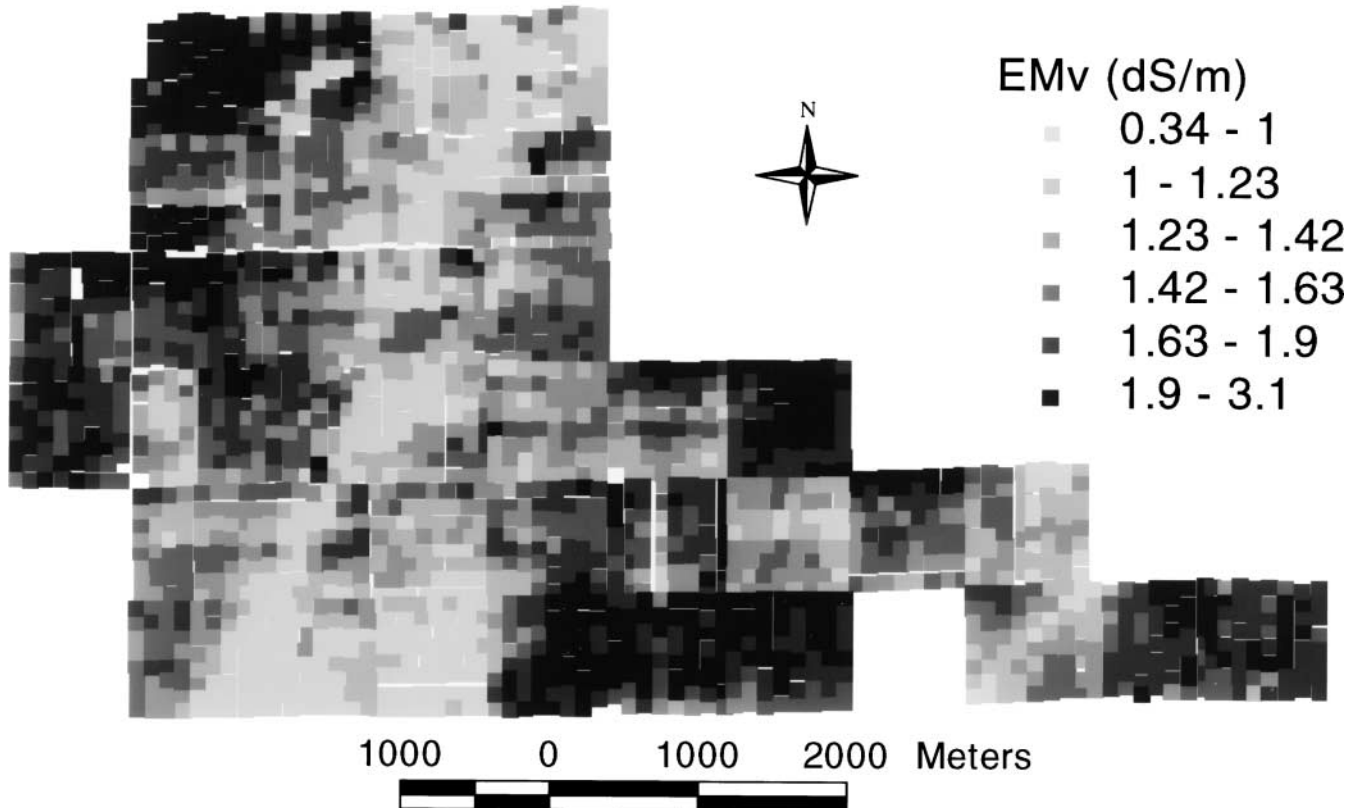


Fig. 14. Mobile EM-38 apparent soil electrical conductivity survey of 2396 ha of the Broadview Water District. EM_v, electromagnetic induction measurement in the vertical coil-mode configuration.

either theoretically or empirically determined models are used to convert EC_a into salinity (EC_e). Deterministic models are *static*; i.e., all model parameters are considered known, and no EC_e data need to be determined. For example, Eq. [3], developed by Rhoades et al. (1989), is a deterministic approach. The deterministic approach is the preferred approach to use when significant, localized variations in soil type exist in the field. This approach typically requires knowledge of additional soil properties (e.g., soil water content, SP, bulk density, temperature, etc.). In the stochastic approach, statistical modeling techniques such as spatial regression or co-kriging are used to directly predict the soil salinity from EC_a survey data. In this approach, the models are *dynamic*; i.e., the model parameters are estimated using soil sample data collected during the survey. This calibration is developed by acquiring soil salinity data (or other soil property data, such as SP, texture, bulk density, etc.) from a small percentage of the sensor measurement sites and estimating an appropriate stochastic prediction model for each depth increment using the paired soil sample and EC_a measurement data. Then, using the remaining sensor data in conjunction with the established model, the soil salinity levels (or other similarly

calibrated properties) are predicted at all of the remaining nonsampled measurement locations. The stochastic and deterministic calibration approaches are described in detail by Lesch et al. (1995a, 1995b, 2000) and incorporated into the ESAP software (Lesch et al., 2000).

Typically, when an EC_a survey is performed, the EC_a data are used to estimate the values of one or more soil variables influencing EC_a . For example, estimates of spatial soil salinity pattern, soil texture, or water-holding capacity may be desired. To facilitate this estimation process, the soil variables are *calibrated* to the EC_a survey information with a stochastic approach. As mentioned in the previous section (Mobile EC_a Survey and Soil Sample Design), ESAP optimizes the sample design by selecting sites that optimize estimation of a calibration or prediction model (i.e., an equation that can be used to predict the values of soil variables from the EC_a survey data). The prediction model is an ordinary regression model. To use an ordinary regression model to predict the values of a spatial data set, ESAP addresses issues of spatial correlation and collinearity.

Apparent soil electrical conductivity can be converted into estimated soil salinity (i.e., EC_e) using a determinis-

tic conversion algorithm. First, raw EC_a data are converted into depth-specific EC_a . Next, these EC_a data are converted into estimated soil salinity data using Eq. [3] through [8], originally developed by Rhoades et al. (1989).

Determination of the Dominant Soil Properties Influencing the EC_a Measurement

The fact that EC_a is a function of several soil properties (i.e., soil salinity, texture, and water content) is often overlooked in the application of EC_a measurements obtained with EM and electrical resistivity to precision agriculture. Precision agriculture studies relating EC_a to crop yield have met with inconsistent results due to the fact that a combination of factors influence EC_a measurements to varying degrees across units of management, thereby confounding interpretation. These factors include soil salinity, water content, SP, and bulk density. In areas of saline soils, salinity dominates the EC_a measurements, and interpretations are often more straightforward. To use spatial measurements of EC_a in a precision agriculture context, it is necessary to understand what factors are most significantly influencing the EC_a measurements within the field of study. There are two approaches for determining the predominant factors influencing EC_a measurement: (i) simple statisti-

cal correlation and (ii) wavelet analysis. Even though wavelet analysis is a powerful tool for determining the dominant complex interrelated factors influencing EC_a measurement, it requires data on a regular grid or equal-spaced transect. Grid or equal-spaced transect sampling schemes are not as practical for determining spatial distributions of soil salinity from EC_a measurements as the stochastic statistical approach developed by Lesch et al. (1995a, 1995b, 2000).

Table 1 is a compilation of correlation data for six field study sites where EC_a surveys were performed for the purpose of salinity appraisal. The table shows the variation in the influence of various soil properties on EC_a for different field locations. In all cases, the surveys were performed as discussed in the above standard operating procedure. An intensive EC_a survey was performed, followed by selection of 6 to 20 sites for soil core sampling. An analysis was performed on the soil cores for various physicochemical properties (e.g., SP, salinity, and water content). A calibration and the correlations in Table 1 were determined using the EC_a survey and soil sample data. The *predicted* correlation column corresponds to the correlation between the predicted EC_a using Eq. [3] through [8] and the specified soil property (salinity, texture, and θ_w) while the *observed* correlation column corresponds to the correlation be-

Table 1. Means and ranges of the soil factors [electrical conductivity of the saturated soil paste extract (EC_e ; $ds\ m^{-1}$), saturation percentage (SP), and total volumetric water content (θ_w ; $cm^3\ cm^{-3}$), and the correlations of $\ln(EM_{avg})^\dagger$ with $\ln(EC_e)$, SP and θ_w for six field-scale surveys.

Field	Soil factors (EC_e , SP, and θ_w)		Predicted correlation \ddagger	Observed correlation \S
	Mean	Range		
Coachella Valley wheat field				
$\ln(EM_{avg})$ and $\ln(EC_e)$	2.33	0.85–6.64	0.87	0.87
$\ln(EM_{avg})$ and SP	40.4	36.5–45.8	0.76	0.78
$\ln(EM_{avg})$ and θ_w	0.24	0.18–0.32	0.73	0.77
Coachella Valley sorghum field				
$\ln(EM_{avg})$ and $\ln(EC_e)$	10.1	5.37–16.8	0.83	0.88
$\ln(EM_{avg})$ and SP	57.0	51.0–61.1	0.06	–0.20
$\ln(EM_{avg})$ and θ_w	0.38	0.33–0.41	0.19	0.25
Broadview Water District (quarter sections 16-2 and 16-3)				
$\ln(EM_{avg})$ and $\ln(EC_e)$	3.65	1.61–8.19	0.68	0.62
$\ln(EM_{avg})$ and SP	50.3	33.2–85.0	0.79	0.84
$\ln(EM_{avg})$ and θ_w	0.31	0.21–0.39	0.81	0.86
Fresno cotton field				
$\ln(EM_{avg})$ and $\ln(EC_e)$	5.42	1.28–9.57	0.92	0.87
$\ln(EM_{avg})$ and SP	79.4	59.3–103.0	0.60	0.71
$\ln(EM_{avg})$ and θ_w	0.28	0.22–0.33	–0.49	–0.65
Coachella Valley–Kohl Ranch field				
$\ln(EM_{avg})$ and $\ln(EC_e)$	11.8	3.73–22.9	0.94	0.94
$\ln(EM_{avg})$ and SP	63.3	59.7–66.7	–0.31	–0.33
$\ln(EM_{avg})$ and θ_w	0.33	0.30–0.36	0.72	0.76
$\ln(EM_{avg})$ and $\ln(SAR)\ \$	23.2	5.55–40.2	0.88	0.89
$\ln(EM_{avg})$ and $\ln(B)\#$	1.44	0.52–2.57	0.87	0.91
Broadview Water District (quarter section 10-2)				
$\ln(EM_{avg})$ and $\ln(EC_e)$	2.66	0.90–5.69	0.81	0.80
$\ln(EM_{avg})$ and SP	55.4	40.6–67.4	0.54	0.49
$\ln(EM_{avg})$ and θ_w	0.38	0.29–0.42	0.58	0.59
$\ln(EM_{avg})$ and $\rho_b\ddagger\ddagger$	1.35	1.26–1.44	–0.38	–0.35
$\ln(EM_{avg})$ and sand $\ddagger\ddagger$	25.5	8.35–49.9	–0.39	–0.38
$\ln(EM_{avg})$ and silt $\ddagger\ddagger$	39.3	26.3–51.6	0.38	0.42
$\ln(EM_{avg})$ and clay $\ddagger\ddagger$	35.3	23.8–44.5	0.35	0.29

\dagger EM_{avg} , the geometric mean of the vertical and horizontal electromagnetic induction readings.

\ddagger The correlation between the predicted apparent soil electrical conductivity using Eq. [3] through [8] and the specified soil property (salinity, texture, volumetric water content).

\S The correlation between the measured apparent soil electrical conductivity and the specified soil property.

$\|\$ SAR, sodium adsorption ratio.

$\#$ B, boron ($mg\ kg^{-1}$).

$\ddagger\ddagger$ ρ_b , bulk density ($g\ cm^{-3}$).

$\ddagger\ddagger$ Units: %.

tween the measured EC_a and the specified soil property. The fact that the predicted correlations are in most cases the same as the observed correlations shows that the model by Rhoades et al. (1989) is fairly robust. Only in the case of the Coachella sorghum [*Sorghum bicolor* (L.) Moench] field does the model appear to show some weakness. Even more convincing evidence of the robustness of the Rhoades et al. (1989) model is the high correlation between the predicted EC_a , as reflected by $\ln(EC'_a)$, and the observed EC_a , as reflected by $\ln(EM_{avg})$, in Table 2. However, the observed correlations in Table 1 are the most significant because this column shows what soil properties are influencing the EC_a reading most.

The following is a discussion of the six EC_a surveys presented in Table 1.

Coachella Valley Wheat (*Triticum aestivum* L.) Field

This is an example of a survey where the salinity represented by $\ln(EC_c)$, the soil texture reflected by the SP, and the θ_w correlate with the EM data, which is represented as $\ln(EM_{avg})$, where EM_{avg} is the geometric mean of the vertical and horizontal EM readings (i.e., $\sqrt{EM_v \cdot EM_h}$). In this field, Eq. [3] through [8] correctly predict the correlations and correctly predict that salinity will correlate best with the averaged EM data. The reason why all three soil properties correlate well with the EM data is because all three soil properties are highly correlated with each other (Table 2).

Coachella Valley Sorghum Field

This field is an example of where only salinity correlates well with the EM data. Equations [3] through [8] correctly predict this condition even though the calcu-

lated correlation between the $\ln(EM_{avg})$ and the $\ln(EC'_a)$, where EC_a is calculated from Eq. [3] through [8], is less than ideal ($r = 0.85$). Note from Table 2 that neither the soil texture nor θ_w correlate much at all with salinity, with $r = -0.10$ and $r = 0.28$, respectively. It is this lack of correlation with salinity and because the texture and water content exhibit minimal sample variation (i.e., sample range for SP is 51.0–61.1%; sample range for θ_w is 0.33–0.41 $cm^3 cm^{-3}$) that they correlate so poorly with the EM data, with $r = -0.20$ and $r = 0.25$, respectively (Table 1).

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

These combined quarter sections display large variability in soil texture (SP ranges from 33.2–85.0%) and water content (θ_w ranges from 0.21–0.39 $cm^3 cm^{-3}$) sample data, with relatively minimal salinity variation (80% of the samples fell below the mean value of 3.65 $dS m^{-1}$). Equations [3] through [8] correctly predict that both the texture and EM and water content and EM correlation levels will be higher than the salinity and EM correlation level (Table 1). Equations [3] through [8] tend to slightly overestimate the influence of salinity and underestimate the texture and water content influences (Table 1).

Fresno Cotton (*Gossypium hirsutum* L.) Field

Equations [3] through [8] correctly predict a negative correlation between EM data and water content and also correctly predict the order of the degree of correlation between the EM data and each soil property although the influence of soil water content again appears to be underestimated (Table 1).

Table 2. Correlation matrix of soil properties and calculated correlation between $\ln(EM_{avg})$ and $\ln(EC'_a)$ for the six field-scale apparent soil electrical conductivity (EC_a) surveys.[†]

Field	$\ln(EC_c)$ ‡	SP§	θ_w ¶	Correlation between $\ln(EM_{avg})$ and $\ln(EC'_a)$
Coachella Valley wheat field				0.90
$\ln(EC_c)$	1.00	0.69	0.66	
SP		1.00	0.91	
θ_w			1.00	
Coachella Valley sorghum field				0.85
$\ln(EC_c)$	1.00	-0.10	0.28	
SP		1.00	-0.47	
θ_w			1.00	
Broadview Water District (quarter sections 16-2 and 16-3)				0.96
$\ln(EC_c)$	1.00	0.23	0.33	
SP		1.00	0.82	
θ_w			1.00	
Fresno cotton field				0.96
$\ln(EC_c)$	1.00	0.38	-0.37	
SP		1.00	-0.78	
θ_w			1.00	
Coachella Valley-Kohl Ranch field				0.95
$\ln(EC_c)$	1.00	-0.39	0.72	
SP		1.00	-0.04	
θ_w			1.00	
Broadview Water District (quarter section 10-2)				0.95
$\ln(EC_c)$	1.00	0.08	0.14	
SP		1.00	0.91	
θ_w			1.00	

[†] EM_{avg} is the geometric mean, and EC'_a is the calculated EC_a using Eq. [3]–[8] from Rhoades et al. (1989).

[‡] EC_c , electrical conductivity of the saturated soil paste extract.

[§] SP, saturation percentage.

[¶] θ_w , total volumetric water content.

Coachella Valley–Kohl Ranch Field

This field displays excellent agreement between predicted and observed EM–soil property correlations (Table 1). Salinity correlates very well, water content correlates fairly well, and soil texture exhibits weak negative correlation, indicating that the dominant soil properties influencing the EM reading are salinity and water content. In addition, two secondary properties, sodium adsorption ratio and B, were measured. The fact that these correlated quite well with the EM data suggests the close association of these properties with salinity in this particular field because the EM reading does not directly measure sodium adsorption ratio or B.

Broadview Water District (Quarter Section 10-2)

Equations [3] through [8] do an excellent job of predicting both the sign and magnitude of each EM–soil property correlation (Table 1). The dominant soil property influencing the EM reading is salinity.

From this discussion of six typical EC_a surveys for agricultural soils in the arid Southwest, what is known about the interrelationship of soil properties influencing the EC_a measurement? First, Eq. [3] through [8] describe how various soil properties (salinity, texture, and water content) interact to influence the EC_a signal data and highlight the fact that this interaction can be quite complex. However, there appears to be consistent, high positive correlation between the EC'_a (i.e., the calculated EC_a using Eq. [3]–[8]) and EM data (see Table 2), implying that Eq. [3] represents a reasonable model. Therefore, we can get a good idea of how well EM survey data will correlate with a specific soil property by determining how well this same soil property correlates with EC'_a data.

Second, it is clear that the innercorrelation structure of the various primary soil properties (EC_e , SP, and θ_w) determines how well each property ultimately correlates with the EC_a signal data. However, the variability of each soil property also influences the final correlation estimates because increased variability in any given soil property directly translates into increased variation in the EC_a data. Obviously, one may encounter many diverse types of innercorrelation structures and/or different degrees of specific soil property variation, as shown in Tables 1 and 2. Thus, the ultimate correlation between the EC_a signal data and any specific soil property may be quite different from field to field. For example, this effect is clearly evident in the $\ln(EM_{avg})$ and SP correlation estimates shown in Table 1 where the observed estimates range from -0.33 to 0.84 .

Finally, with respect to EC_e data, the best scenario for the prediction of salinity from EC_a signal data occurs when the (EC_e , SP, and θ_w) cross-correlation estimates are all positive and high (i.e., near 1) and/or the SP and θ_w variation is minimal. However, in all of the scenarios shown here, Eq. [3] can be successfully used to explain why certain soil properties correlate well with EC_a signal data in some survey scenarios but not in others.

MODELING SOIL SALINITY IN A GEOSPATIAL CONTEXT

Spatial measurements of EC_a are not only of value to precision agriculture from the perspective of real-time inventories of soil salinity, but they're also of value in forecasting spatio-temporal changes in salinity status based on existing conditions and subsequent imposed scenarios. Assessment encompasses both real-time measurements and model predictions. The ability to assess, both in real time and in a prognostication mode, the spatial distribution and fate of a nonpoint source (NPS) pollutant, such as soil salinity, is a key concern in maintaining the delicate balance between crop productivity and the detrimental environmental impacts of NPS pollutants. This balance is a cornerstone of sustainable agriculture (Corwin et al., 1999a). It is through real-time measurements that a continued inventory of a constituent (e.g., salinity) can be maintained to determine the extent of the problem and to evaluate changes, whether for better or worse, that gauge the effect of ameliorative actions (Corwin et al., 1999a). Model predictions set the stage for posing *what if* scenarios that serve a preventative role by suggesting management actions that will alter the occurrence of detrimental conditions before they manifest (Corwin et al., 1999a). A key aspect of precision agriculture is minimizing detrimental environmental impacts. Landscape-scale solute transport modeling can serve as a crucial component of precision agriculture by providing feedback concerning solute loading to ground water or drainage tile systems.

Soil and ground water quality affected by salinity depend on spatially distributed properties that influence salt transport. The phenomenon of salt transport through the vadose zone (i.e., the zone extending from the soil surface to the ground water table) is affected by the temporal variation in irrigation water quality and the spatial variability of plant water uptake and soil chemical and physical properties. Coupling a GIS to a salt transport model potentially offers a means of dealing with the complex spatial heterogeneity of soils, which influences the intricate biological, chemical, and physical processes of transient-state salt transport in the vadose zone (Corwin, 1996).

Modeling the movement and accumulation of salinity is a spatial problem well suited for the integration of a salt transport model with GIS (Corwin, 1996). A GIS serves as a spatial database to organize, manipulate, and display the complex spatial data used by a deterministic model to describe the regional-scale distribution of soil salinity and salt loading to ground water. Coupling of the spatial data-handling capabilities of a GIS with a one-dimensional salt transport model offers the advantage of utilizing the full information content of spatially distributed data to analyze solute movement on a field scale in three dimensions (Corwin, 1996). As a visualization and analysis tool, GIS is capable of manipulating both spatially referenced input and output parameters of the model.

The basic components of a NPS pollutant model (NPS pollutants, such as salinity and pesticides, are spread over a wide area, as opposed to point source pollutants,

which are located at a specific site or point, such as a toxic spill) are model, GIS, and data (Corwin et al., 1997). These components depend on the advanced information technologies of a GPS, GIS, geostatistics, remote sensing, solute transport modeling, neural networks, transfer functions, fuzzy logic, hierarchical theory, and uncertainty analysis (Corwin et al., 1999a).

Published work by Corwin and his colleagues (Corwin and Rhoades, 1988; Corwin et al., 1989, 1995, 1996, 1999b) reflects the current trend in the application of GIS-based models to simulate the transport of NPS pollutants in the vadose zone at field, basin, and regional scales (Corwin, 1996; Corwin et al., 1997, 1999a). These models are specifically designed to account for the spatio-temporal variability of the properties and conditions influencing soil salinity accumulation and transport. Two different GIS-based approaches are described for predicting the areal distribution of salinity. The first approach couples a regression model of salinity development to a GIS of soil salinity development factors (i.e., permeability, leaching fraction, and ground water EC) for the Wellton–Mohawk Irrigation District near Yuma, AZ, over the study period 1968–1973 (Corwin and Rhoades, 1988; Corwin et al., 1989). The regression model predicts the composite salinity of the root zone (i.e., top 60 cm.). Areas of low, medium, and high salinization potential are delineated for the entire 44 000-ha irrigation district. Measured salinity data verified that 86% of the predicted salinity categories was accurately predicted. The second approach *loosely coupled* the one-dimensional, transient-state solute transport model, TETrans, to the GIS ARC/INFO (Corwin et al., 1999b). Slightly less than 2400 ha of the Broadview Water District located on the west side of central California's San Joaquin Valley was used as the test site to evaluate the integrated GIS–transport model over the study period 1991–1996 (Corwin et al., 1999b).

The unique aspect of the Corwin et al. (1999b) approach to landscape-scale modeling of a NPS pollutant (i.e., salinity) in the vadose zone is the delineation of *stream tubes* from EC_a measurements taken on a grid with the mobile EM-38 equipment developed by Carter et al. (1993) and Rhoades (1993). Stream tubes are non-interactive volumes of soil whose physicochemical properties influencing solute transport are relatively homogeneous so that solute transport within the column of soil defined by the stream tube can be simulated with a one-dimensional solute transport model. Corwin et al. (1999b) first proposed the use of an intensive EM survey measuring EC_a as a means of delineating stream tubes. For field sites where EC_a is closely correlated with soil salinity, stream tubes can be delineated based on EM_h and EM_v measurements of EC_a . From the geometric mean of EM_h and EM_v (i.e., $\sqrt{EM_h \cdot EM_v}$), quantiles can be defined. The ratio of EM_h to EM_v (i.e., EM_h/EM_v) is determined, and within each quantile, the points are selected where the low and high EM_h/EM_v ratios exist. These points serve as the centroids of the Thiessen polygons delineating the stream tubes throughout the area of study.

A GIS is used to define the spatial location of the stream tubes with their associated solute transport prop-

erty attributes. TETrans uses the GIS as a spatial database from which to draw its input data. Simulations are presented over a 5-yr period, 1991–1996. Display maps show spatial distributions of soil salinity profiles to a depth of 1.2 m, irrigation efficiencies, drainage amounts, and salt loading to ground water over the 2396-ha study area. These maps provide a potential precision agriculture tool for making irrigation management decisions to minimize the environmental impact of salinity on soil and ground water. The first approach is best suited for areas where steady-state conditions are approximated while the second approach can be used under transient-state conditions.

SUMMARY

As the world's population continues to grow, humankind is faced with the onerous task of meeting the world's food demand. This can only be accomplished with sustainable agriculture. Sustainable agriculture requires a delicate balance between crop production, natural resource use, environmental impacts, and economics. The goal of sustainable agriculture is to optimize food production while maintaining economic stability, minimizing the use of natural resources and minimizing impacts on the environment. Precision agriculture stands as one of the potential means of attaining sustainable agriculture. The future of precision agriculture rests on the reliability, reproducibility, and understanding of the technological developments on which it is based.

Assessing the impact of salinity at regional and localized scales is a key component to achieving sustainable agriculture. Assessment involves the determination of change in salinity over time, which can be measured in real time or predicted with a model. Real-time measurements reflect activities of the past, whereas model predictions are glimpses into the future based on a simplified set of assumptions. Both means of assessment are valuable; however, the advantage of prediction is that it can be used to alter the occurrence of detrimental conditions before they develop. Forecasting information from model simulations is used in decision-making strategies designed to sustain agriculture. This information permits an alteration in the management strategy before the development of levels of soil salinity that detrimentally impact either agricultural productivity of the soil or quality of the ground water.

The ability to locate the sources of soil salinity within irrigated landscapes and to model the migration of salt through the vadose zone to obtain an estimate of salt loading to drainage and ground water is an essential tool in precision agriculture to combat degradation of our soil and water resources. This information is valuable for selecting alternate crops or alternate irrigation management practices to maintain crop productivity while minimizing the environmental impacts of salinity.

The need for a means of measuring soil salinity in the root zone in a quick, reliable, and cost-effective manner resulted in the development of mobile electrical resistivity and EM techniques to measure EC_a . However, the measurement of EC_a is complicated by the influence of several soil properties aside from soil salin-

ity, including soil texture, temperature, and water content. For this reason, it is necessary to determine the dominant soil properties influencing the EC_a measurement at each field of interest to interpret what information is being conveyed by a map of EC_a . From a precision agriculture perspective, when maps of EC_a are properly understood, they (i) provide a graphic inventory of the scope of the soil salinity problem, (ii) provide useful spatial information concerning soil texture and water content, (iii) provide information for crop selection, (iv) identify potential areas in need of improved irrigation and drainage management, and (v) provide a means of monitoring spatio-temporal changes in soil properties that potentially influence crop production.

Because precision agriculture is an outgrowth of technological developments such as the EC_a measurement, the future of precision agriculture rests on a complete understanding of these technologies. The fruition of the precision agriculture application of EC_a maps will likely come from future plant indicator approaches where combinations of data inputs including airborne spectral imagery, EC_a measurements with mobile EM, and plant and soil sampling based on response-surface sample design strategies are manipulated, organized, and displayed with GIS, image analysis, and spatial statistical analysis to create maps of soil salinity, soil texture and available water.

ACKNOWLEDGMENTS

The authors thank Dr. Newell Kitchen (USDA-ARS, University of Missouri) for his hard work in organizing the symposium "Use of Soil Electrical Conductivity in Precision Agriculture" at the 2000 ASA-CSSA-SSSA annual meetings (8 Nov. 2000 in Minneapolis, MN) where this invited paper was initially presented.

REFERENCES

- Amoozegar-Fard, A., D.R. Nielsen, and A.W. Warrick. 1982. Soil solute concentration distributions for spatially varying pore water velocities and apparent diffusion coefficients. *Soil Sci. Soc. Am. J.* 46:3-9.
- Barnes, H.E. 1952. Soil investigation employing a new method of layer-value determination for earth resistivity interpretation. *Highw. Res. Board, Bull.* 65:26-36.
- Biggar, J.W., and D.R. Nielsen. 1976. Spatial variability of the leaching characteristics of a field soil. *Water Resour. Res.* 12:78-84.
- Burger, H.R. 1992. Exploration geophysics of the shallow subsurface. Prentice Hall PTR, Upper Saddle River, NJ.
- Carter, L.M., J.D. Rhoades, and J.H. Chesson. 1993. Mechanization of soil salinity assessment for mapping. ASAE Paper no. 931557. Proc. 1993 ASAE Winter Meet., Chicago, IL. 12-17 Dec. 1993. ASAE, St. Joseph, MI.
- Cook, P.G., and G.R. Walker. 1992. Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. *Soil Sci. Soc. Am. J.* 56:1015-1022.
- Corwin, D.L. 1996. GIS applications of deterministic solute transport models for regional-scale assessment of non-point source pollutants in the vadose zone. p. 69-100. *In* D.L. Corwin and K. Loague (ed.) Applications of GIS to the modeling of non-point source pollutants in the vadose zone. SSSA Spec. Publ. 48. SSSA, Madison, WI.
- Corwin, D.L. 2002a. Measurement of solute concentration using soil water extraction: Suction cups. p. 1261-1266. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.
- Corwin, D.L. 2002b. Measurement of solute concentration using soil water extraction: Porous matrix sensors. p. 1269-1273. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.
- Corwin, D.L., M.L.K. Carrillo, P.J. Vaughan, J.D. Rhoades, and D.G. Cone. 1999b. Evaluation of a GIS-linked model of salt loading to groundwater. *J. Environ. Qual.* 28:471-480.
- Corwin, D.L., and J.M.H. Hendrickx. 2002. Indirect measurement of solute concentration: Electrical resistivity—Wenner array. p. 1282-1287. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.
- Corwin, D.L., K. Loague, and T.R. Ellsworth. 1997. Modeling non-point source pollutants in the vadose zone with GIS. *Environ. Sci. Technol.* 31(8):2157-2175.
- Corwin, D.L., K. Loague, and T.R. Ellsworth. 1999a. Assessing non-point source pollution in the vadose zone with advanced information technologies. p. 1-20. *In* D.L. Corwin, K. Loague, and T.R. Ellsworth (ed.) Assessment of non-point source pollution in the vadose zone. Geophysical Monogr. 108. AGU, Washington, DC.
- Corwin, D.L., and J.D. Rhoades. 1988. The use of computer-assisted mapping techniques to delineate potential areas of salinity development in soils: II. Field verification of the threshold model approach. *Hilgardia* 56(2):8-32.
- Corwin, D.L., J.D. Rhoades, and P.J. Vaughan. 1996. GIS applications to the basin-scale assessment of soil salinity and salt loading to groundwater. p. 295-313. *In* D.L. Corwin and K. Loague (ed.) Applications of GIS to the modeling of non-point source pollutants in the vadose zone. SSSA Spec. Publ. 48. SSSA, Madison, WI.
- Corwin, D.L., J.D. Rhoades, P.J. Vaughan, and S.M. Lesch. 1995. Salt-loading assessment methodology for managing soil salinity. p. 35-38. *In* Clean water—clean environment—21st century. Vol. II: Nutrients. Proc. Conf., Kansas City, MO. 5-8 Mar. 1995. ASAE, St. Joseph, MI.
- Corwin, D.L., M. Sorensen, and J.D. Rhoades. 1989. Field-testing of models which identify soils susceptible to salinity development. *Geoderma* 45:31-64.
- Dalton, F.N., W.N. Herkelrath, D.S. Rawlins, and J.D. Rhoades. 1984. Time-domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe. *Science* 224:989-990.
- Das, B.S., J.M. Wraith, and W.P. Inskeep. 1999. Soil solution electrical conductivity and nitrate concentrations in a crop root zone estimated using time-domain reflectometry. *Soil Sci. Soc. Am. J.* 63: 1561-1570.
- Diaz, L., and J. Herrero. 1992. Salinity estimates in irrigated soils using electromagnetic induction. *Soil Sci.* 154:151-157.
- Dobrin, M.B. 1960. Introduction to geophysical prospecting. McGraw-Hill Book Co., New York.
- 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.
- Haines, B.L., J.B. Waide, and R.L. Todd. 1982. Soil solution nutrient concentrations sampled with tension and zero-tension lysimeters: Report of discrepancies. *Soil Sci. Soc. Am. J.* 46:658-661.
- Hart, G.L., and B. Lowery. 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., A.G. Focke, W. Bouten, and J.M. Verstraten. 1995. Assessing temporal variations in soil water composition with time domain reflectometry. *Soil Sci. Soc. Am. J.* 59:689-698.
- Hendrickx, J.M.H., B. Baerends, Z.I. Raza, M. Sadig, and M. Akram Chaudhry. 1992. Soil salinity assessment by electromagnetic induction of irrigated land. *Soil Sci. Soc. Am. J.* 56:1933-1941.
- Hendrickx, J.M.H., and R.G. Kachanoski. 2002. Indirect measurement of solute concentration: Nonintrusive electromagnetic induction. p. 1297-1306. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.
- Kachanoski, R.G., E. Pringle, and A. Ward. 1992. Field measurement of solute travel time using time domain reflectometry. *Soil Sci. Soc. Am. J.* 56:47-52.
- Lesch, S.M., J. Herrero, and J.D. Rhoades. 1998. Monitoring for temporal changes in soil salinity using electromagnetic induction techniques. *Soil Sci. Soc. Am. J.* 62:232-242.
- Lesch, S.M., J.D. Rhoades, and D.L. Corwin. 2000. ESAP-95 Version 2.01R: User manual and tutorial guide. Res. Rep. 146. USDA-ARS George E. Brown, Jr., Salinity Lab., Riverside, CA.
- Lesch, S.M., J.D. Rhoades, L.J. Lund, and D.L. Corwin. 1992. Mapping

- soil salinity using calibrated electromagnetic measurements. *Soil Sci. Soc. Am. J.* 56:540–548.
- Lesch, S.M., D.J. Strauss, and J.D. Rhoades. 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques: I. Statistical prediction models: A comparison of multiple linear regression and cokriging. *Water Resour. Res.* 31:373–386.
- Lesch, S.M., D.J. Strauss, and J.D. Rhoades. 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques: II. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. *Water Resour. Res.* 31:387–398.
- Mallants, D., M. Vanclooster, M. Meddahi, and J. Feyen. 1994. Estimating solute transport in undisturbed soil columns using time-domain reflectometry. *J. Contam. Hydrol.* 17:91–109.
- Mallants, D., M. Vanclooster, N. Toride, J. Vanderborght, M.Th. Van Genuchten, and J. Feyen. 1996. Comparison of three methods to calibrate TDR for monitoring solute movement in undisturbed soil. *Soil Sci. Soc. Am. J.* 60:747–754.
- Marion, G.M., and K.L. Babcock. 1976. Predicting specific conductance and salt concentration in dilute aqueous solutions. *Soil Sci.* 122:181–187.
- McKenzie, R.C., W. Chomistek, and N.F. Clark. 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. *Can. J. Soil Sci.* 69:25–32.
- McNeill, J.D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Tech. Note TN-6. Geonics Limited, Mississauga, ON, Canada.
- McNeill, J.D. 1986. Rapid, accurate mapping of soil salinity using electromagnetic ground conductivity meters. Tech. Note TN-18. Geonics Limited, Mississauga, ON, Canada.
- Nissen, H.H., P. Moldrup, and K. Henriksen. 1998. Time domain reflectometry measurements of nitrate transport in manure-amended soil. *Soil Sci. Soc. Am. J.* 62:99–109.
- 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.
- Rhoades, J.D. 1978. Monitoring soil salinity: A review of methods. p. 150–165. *In* L.G. Everett and K.D. Schmidt (ed.) *Establishment of water quality monitoring programs*. Vol. 2. Am. Water Resour. Assoc., San Francisco.
- Rhoades, J.D. 1992. Instrumental field methods of salinity appraisal. p. 231–248. *In* G.C. Topp, W.D. Reynolds, and R.E. Green (ed.) *Advances in measurement of soil physical properties: Bringing theory into practice*. SSSA Spec. Publ. 30. SSSA, Madison, WI.
- Rhoades, J.D. 1993. Electrical conductivity methods for measuring and mapping soil salinity. *Adv. Agron.* 49:201–251.
- Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved salts. p. 417–435. *In* D.L. Sparks et al. (ed.) *Methods of soil analysis*. Part 3. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.
- Rhoades, J.D., F. Chanduvi, and S. Lesch. 1999a. Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. *FAO Irrig. and Drain. Paper 57*. Food and Agric. Organ. of the United Nations, Rome.
- Rhoades, J.D., and D.L. Corwin. 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., D.L. Corwin, and S.M. Lesch. 1991. Effect of soil EC_e -depth profile pattern on electromagnetic induction measurements. *Res. Rep. 125*. U.S. Salinity Lab., Riverside, CA.
- Rhoades, J.D., D.L. Corwin, and S.M. Lesch. 1999b. Geospatial measurements of soil electrical conductivity to assess soil salinity and diffuse salt loading from irrigation. p. 197–215. *In* D.L. Corwin, K. Loague, and T.R. Ellsworth (ed.) *Assessment of non-point source pollution in the vadose zone*. Geophysical Monogr. 108. AGU, Washington, DC.
- Rhoades, J.D., and A.D. Halvorson. 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, CA.
- Rhoades, J.D., and J. Loveday. 1990. Salinity in irrigated agriculture. p. 1089–1142. *In* B.A. Stewart and D.R. Nielsen (ed.) *Irrigation of agricultural crops*. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.
- Rhoades, J.D., N.A. Manteghi, P.J. Shouse, and W.J. Alves. 1989. Soil electrical conductivity and soil salinity: New formulations and calibrations. *Soil Sci. Soc. Am. J.* 53:433–439.
- Rhoades, J.D., and J.D. Oster. 1986. Solute content. p. 985–1006. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.
- Rhoades, J.D., P.J. Shouse, W.J. Alves, N.M. Manteghi, and S.M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. *Soil Sci. Soc. Am. J.* 54:46–54.
- Sheets, K.R., and J.M.H. Hendrickx. 1995. Non-invasive soil water content measurement using electromagnetic induction. *Water Resour. Res.* 31:2401–2409.
- Slavich, P.G. 1990. Determining EC_e -depth profiles from electromagnetic induction measurements. *Aust. J. Soil Res.* 28:443–452.
- Smith, C.N., R.S. Parrish, and D.S. Brown. 1990. Conducting field studies for testing pesticide leaching models. *Int. J. Environ. Anal. Chem.* 39:3–21.
- Spaans, E.J.A., and J.M. Baker. 1993. Simple baluns in parallel probes for time domain reflectometry. *Soil Sci. Soc. Am. J.* 57:668–673.
- Stogryn, A. 1971. Equations for calculating the dielectric constant of saline water. *IEEE Trans. Microwave Theory Tech.* 19:733–736.
- Telford, W.M., L.P. Gledart, and R.E. Sheriff. 1990. *Applied geophysics*. 2nd ed. Cambridge Univ. Press, New York.
- U.S. Salinity Laboratory Staff. 1954. *Diagnosis and improvement of saline and alkali soils*. USDA Handb. 60. U.S. Gov. Print. Office, Washington, DC.
- Vanclouster, M., D. Mallants, J. Diels, and J. Feyen. 1993. Determining local scale solute transport parameters using time domain reflectometry (TDR). *J. Hydrol. (Amsterdam)* 148:93–107.
- van Schilfgaarde, J. 1999. Is precision agriculture sustainable? *Am. J. Altern. Agric.* 14(1):43–46.
- Ward, A.L., R.G. Kachanoski, and D.E. Elrick. 1994. Laboratory measurements of solute transport using time domain reflectometry. *Soil Sci. Soc. Am. J.* 58:1031–1039.
- Wesseling, J., and J.D. Oster. 1973. Response of salinity sensors to rapidly changing salinity. *Soil Sci. Soc. Am. Proc.* 37:553–557.
- Williams, B.G., and G.C. Baker. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. *Aust. J. Soil Res.* 20:107–118.
- Wraith, J.M. 2002. Indirect measurement of solute concentration: Time domain reflectometry. p. 1289–1297. *In* J.H. Dane and G.C. Topp (ed.) *Methods of soil analysis*. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.
- Wraith, J.M., S.D. Comfort, B.L. Woodbury, and W.P. Inskeep. 1993. A simplified waveform analysis approach for monitoring solute transport using time-domain reflectometry. *Soil Sci. Soc. Am. J.* 57:637–642.
- Wraith, J.M., and D. Or. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development. *Water Resour. Res.* 35:361–369.
- Yates, S.R., R. Zhang, P.J. Shouse, and M.Th. Van Genuchten. 1993. Use of geostatistics in the description of salt-affected lands. p. 283–304. *In* D. Russo and G. Dagan (ed.) *Water flow and solute transport in soils: Developments and applications*. Adv. Ser. in Agric. 20. Springer-Verlag, New York.