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Characterizing soil spatial variability with apparent soil electrical conductivity

I. Survey protocols

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Abstract

Spatial characterization of the variability of soil physico-chemical properties is a fundamental element of (i) soil quality assessment, (ii) modeling non-point source pollutants in soil, and (iii) site-specific crop management. Apparent soil electrical conductivity (EC_a) is a quick, reliable measurement that is frequently used for the spatio-temporal characterization of edaphic (e.g., salinity, water content, texture, and bulk density) and anthropogenic (e.g., leaching fraction) properties. It is the objective of this paper to provide the protocols for conducting a field-scale EC_a survey (Part I) and apply these protocols to a soil quality assessment in central California's San Joaquin Valley (Part II). The protocols are comprised of eight general steps: (i) site description and EC_a survey design; (ii) EC_a data collection with mobile GPS-based equipment; (iii) soil sampling design; (iv) soil core sampling; (v) laboratory analysis; (vi) calibration of EC_a to EC_e; (vii) spatial statistical analysis; (viii) GIS database development and graphic display. For each outlined step, detailed discussion and guidelines

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Abbreviations: CEC, cation exchange capacity; DPPC, dual pathway parallel conductance model; $EC_{25\,^\circ C}$, electrical conductivity at 25 ° C; EC_a, apparent soil electrical conductivity; EC_e, electrical conductivity of the saturation extract; EC_w, electrical conductivity of the soil solution; EM, electromagnetic induction; EM_h, electromagnetic induction measurement in the horizontal coil-mode configuration; EM_v, electromagnetic induction measurement in the vertical coil-mode configuration; ER, electrical resistivity; ESAP, ECe sampling, assessment and prediction software; ESP, exchangeable sodium percentage; GIS, geographic information system; GPS, global positioning system; IDW, inverse distance weighting; K_s, saturated hydraulic conductivity; LF, leaching fraction; NPS, non-point source; OM, organic matter; PW, percent water on a gravimetric basis; SAR, sodium adsorption ratio; SLRspatial linear regression; SP, saturation percentage; SSMU, site-specific management unit; TDR, time domain reflectometry; USDA-ARS, United States Department of Agriculture-Agricultural Research Service

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were presented. The developed protocols provide the guidelines to assure reliability, consistency, and compatibility of EC_a survey measurements and their interpretation.
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1. Introduction

The heterogeneity of soil physico-chemical properties has been known since the classic study of Nielsen et al. (1973), which characterized the spatial variability of soil-water properties for a 150 ha field at the University of California's West Side Field Station in the San Joaquin Valley. The characterization of soil spatial variability is fundamental to the understanding of landscape-scale processes of soils. Delineation of the spatial variation of soil properties is a crucial element of (i) non-point source (NPS) pollutant transport in the vadose zone, (ii) soil quality assessment, and (iii) site-specific crop management.

The spatial measurement of apparent soil electrical conductivity (EC_a) is one means of delineating spatial variation. Because of reliability, ease of measurement, and ability to detect a variety of soil properties, spatial EC_a measurements have become a common tool used for field and landscape-scale studies related to edaphic properties. Spatial surveys of EC_a have become widely used by a variety of scientists to spatially characterize soil salinity and nutrients (e.g., NO_3^-), texture-related properties, bulk density related properties such as compaction, organic matter (OM) related properties, and a variety of other soil properties (see Table 1; Corwin and Lesch, 2005a).

Geo-referenced EC_a measurements have been correlated to associate yield-monitoring data with mixed results (Jaynes et al., 1993; Sudduth et al., 1995; Kitchen et al., 1999; Johnson et al., 2001; Corwin et al., 2003b). These mixed results are due to confounding factors that complicate the relationship between EC_a measurements and variations in crop yield. As pointed out by Corwin and Lesch (2003), crop yield inconsistently correlates with EC_a due to (i) the influence of soil properties (e.g., salinity, water content, texture, etc.) that are measured by EC_a, but may or may not influence yield within a particular field, (ii) a temporal component of yield variability that is poorly captured by a state variable such as EC_a, and (iii) confounding climatic factors.

Nevertheless, in instances where yield correlates with EC_a, maps of EC_a are useful for devising soil sampling schemes to identify soil properties influencing yield within a field (Corwin et al., 2003b). When used as a means of directing soil sampling design, geo-referenced measurements of EC_a have been shown by investigators to be a reliable, rapid means of establishing the spatial variability of soil physico-chemical properties associated with the leaching of NPS pollutants (Corwin et al., 1999), soil quality (Johnson et al., 2001; Corwin et al., 2003a), and variations in crop yield (Corwin et al., 2003b).

Because previous studies have varied in their approach of obtaining and interpreting spatial EC_a measurements, a recent USDA-ARS workshop on precision agriculture (Kansas City, MO, 25–27 March 2003) concluded that protocols for conducting geo-referenced field-scale EC_a surveys and guidelines for interpreting the EC_a measurements are needed to assure reliability, consistency, and compatibility of data. It is the objective of this paper

Table 1
Compilation of literature measuring EC_a with geophysical techniques (ER or EM) that have been categorized according to soil-related properties that were either directly or indirectly measured by EC_a

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

Taken from Corwin and Lesch (2005a).

to (i) describe the GPS-based equipment used to conduct an EC_a survey and (ii) outline a detailed set of protocols for conducting a field-scale EC_a survey that is used to direct a soil sampling design to characterize soil spatial variability for use in soil quality assessment and site-specific crop management.

2. Mobilized EC_a-measurement equipment

A detailed description of the theory, operation, and construction of electrical resistivity (ER) and electromagnetic induction (EM) instrumentation is provided by Rhoades et al. (1999b) and Hendrickx et al. (2002a). Mobilized EC_a-measurement equipment, ER or EM instrumentation, has been in use for over a decade for the purpose of mapping and monitoring field-scale spatial soil salinity patterns (Rhoades, 1992, 1993). More recently these mobilized systems have been used to spatially characterize soil condition by mapping a variety of physico-chemical properties including salinity, water content, texture, bulk density (Johnson et al., 2001; Corwin et al., 2003a). The design of a mobilized EC_a measurement system consists of four basic components: (i) EC_a measurement sensor, (ii) global positioning system (GPS), (iii) hardware interfacing, and (iv) transport platform.

Three types of EC_a measurement sensors are available: (i) invasive four-electrode ER sensors, (ii) noninvasive EM sensors, and (iii) time domain reflectometry (TDR) sensors. Invasive ER and noninvasive EM sensors are the most popular sensors because the commercial development of a TDR sensor for use on a mobile apparatus has not yet occurred. Invasive four-electrode sensors can take the form of either insertion probes or surface arrays with the latter being the configuration used for mobilized EC_a measurement systems. Examples of invasive ER four-electrode sensors configured as fixed-surface arrays include the equipment developed by Rhoades (1992, 1993) and Carter et al. (1993) and the commercial sensor technology used in the Veris 3100 system[1] (Veris Technologies, Salina, KS). Commercial examples of EM sensors include the Geonics EM-31 and EM-38 soil conductivity meters (see footnote 1) (Geonics Ltd., Mississauga, Ont., Canada), both of which can be easily mobilized, but the EM-38 has been the primary instrument of choice for soil quality and site-specific crop management applications because its depth of penetration most closely corresponds to the root zone (i.e., 0 to 1–1.5 m).

There are two basic GPS systems that can be used in mobile EC_a-measurement equipment: (i) self-contained systems and (ii) stand-alone GPS receivers that require external data logging. The difference between the two is not in the GPS receiver technology, but in the interfacing. Self-contained GPS systems include data loggers and software programs that allow the user to record, modify, and/or store GPS coordinate data independent of attached sensors or hardware interfacing. Stand-alone GPS receivers typically must be connected to a microprocessor or electronic controller in order to store and/or process GPS coordinate data. The Trimble Pathfinder Pro-XRS and Trimble Ag132 GPS systems are examples of available commercial GPS systems.

Hardware interfacing is needed to link the EC_a measurement sensor data with associated GPS coordinate data and control the timing of the data acquisition. The complexity of the hardware interface depends on the type and number of sensors and the extent of real-time data processing; consequently, the hardware interface tends to be system specific and expensive. However, in a simple mobile EC_a measurement system with a single electrical conductivity meter (i.e., single EM-38) the hardware interface can be omitted by direct output of real-

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[1] Mention of trademark or proprietary products does not constitute an endorsement or guarantee/warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be available.

time sensor data through an RS-232 serial connection with the data capture capability of the GPS system. The Veris system comes complete with interfacing and recording hardware, only requiring the user to plug in a compatible GPS receiver.

The final component of the mobile EC_a measurement system is the transport platform, which consists of either tow-able or self-mobilized platforms. Pickups, all-terrain vehicles (ATVs), and tractors have been used to tow EC_a-measurement sensors. The fixed-array four electrode (Rhoades, 1992, 1993) and Veris 3100 (Lund et al., 1999; Sudduth et al., 1999) are examples of ER sensor platforms that are towed. Simple non-metallic platforms have also been developed to tow EM instrumentation (Jaynes et al., 1993; Cannon et al., 1994; Kitchen et al., 1996; Freeland et al., 2002). An example of a self-mobilized platform includes a modified hydraulic-driven spray tractor with insertion-type, four-electrode EC_a sensors located on the rig's undercarriage that are driven into the ground with the hydraulic system, and a non-metallic cylinder located at the front end that houses an EM-38, which is raised, lowered, and rotated 90E with the hydraulic system (Rhoades, 1992, 1993; Carter et al., 1993). In general, motorized platforms are more sophisticated, versatile, and expensive to develop than tow-able platforms.

System integration can be dedicated or autonomous. In a dedicated system all EC_a measurement sensors and GPS equipments are integrated directly into the transport platform. This system relies on extensive hardware interfacing and a central computer or controller to manage the data acquisition and data storage. In an autonomous system the GPS receiver and each EC_a measurement sensor can be easily removed from the platform and used independently. The Trimble Pathfinder Pro-XRS is an example of an autonomous system, whereas the Trimble Ag132 GPS is a dedicated system.

Surveys of EC_a to characterize soil spatial variability are used as spatial information to direct a soil sampling scheme that will provide the necessary ground-truth information to establish the spatial distribution of those soil properties correlated with EC_a within a field. For this reason, the inclusion of soil sampling equipment directly onto the platform is advantageous. The addition of soil sampling equipment allows the platform to serve as both an EC_a survey system and a soil sampling rig, which increases the versatility of the system. Figs. 1 and 2 illustrate the components of a GPS-based mobile EC_a measurement system developed at the George E. Brown Jr. Salinity Laboratory. The system consists of a dual-dipole EM-38 that simultaneously measures vertical (EM_v) and horizontal (EM_h) electromagnetic induction EC_a (see Fig. 1b), a Giddings soil core sampler (see footnote 1) mounted on the front of the rig (see Fig. 1c), and a Trimble Pro-XL GPS system (see Fig. 2). The Trimble Pro-XL GPS system consists of a MC-V datalogger, TANS receiver, battery pack, and dome antenna (see Fig. 2).

3. Protocols for conducting a field-scale EC_a survey and soil sampling

Geo-referenced measurements of EC_a are useful for establishing the spatial distribution of those soil properties influencing EC_a within a field. In instances where EC_a correlates with a particular soil property, an EC_a-directed soil sampling approach will establish the spatial distribution of that property with an optimum number of site locations to characterize the variability and keep labor costs minimal (Corwin et al., 2003a). Also, if EC_a is correlated

Fig. 1. Mobile EM equipment: (a) complete rig; (b) close-up of sled holding the Geonics dual-dipole EM-38 soil electrical conductivity meter; (c) close-up of Giddings soil core sampler.

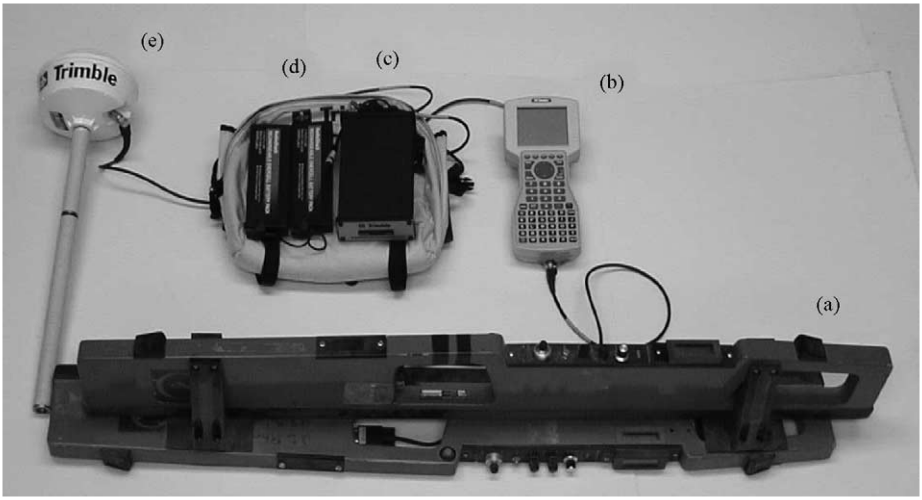

Fig. 2. Connection between (a) dual-dipole EM-38 meter and Trimble MC-V Pro-XL system consisting of (b) MC-V datalogger, (c) TANS receiver, (d) battery pack, and (e) dome antenna.

with crop yield, then an EC_a-directed soil sampling approach can be used to identify those soil properties that are causing variability in crop yield (Corwin et al., 2003b). General EC_a survey guidelines can be derived from Corwin and Lesch (2003) and Corwin et al. (2003a, 2003b). Details for conducting a field-scale EC_a survey for the purpose of characterizing the spatial variability of soil properties influencing soil quality or crop yield variation are provided herein.

The purpose of an EC_a survey from a soil quality perspective is to establish the within-field variation of soil properties that influence the field's intended use (e.g., agricultural productivity, environmental protection, waste recycling, etc.). The purpose of an EC_a survey from a site-specific crop management perspective is to establish the within-field variation of soil properties influencing the variation in crop yield. The basic elements of a field-scale EC_a survey applied to soil quality assessment and site-specific crop management include (i) site description and EC_a survey design, (ii) geo-referenced EC_a data collection, (iii) soil sample design based on geo-referenced EC_a data, (iv) soil sample collection, (v) physico-chemical analysis of pertinent soil properties, (vi) if soil salinity is a primary concern, development of a stochastic and/or deterministic calibration of EC_a to soil salinity as determined by the electrical conductivity of the saturation extract (EC_e), (vii) spatial statistical analysis, and (viii) geographic information system (GIS) database development. The basic steps within each component are outlined in Table 2.

3.1. EC_a survey design and geo-referenced EC_a data collection

An initial EC_a survey with either mobile ER or EM equipment is conducted and used to establish soil core sampling locations needed for calibration and/or characterization of the spatial distribution of soil properties correlated with 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 three advantages over the use of mobile ER equipment: (i) the ability to take measurements on dry and stony soils, (ii) the ability to traverse growing crops, and (iii) the ability to traverse fields with beds and furrows. Under dry soil conditions the physical contact needed between ER electrodes and soil for continuous electrical current flow is difficult to maintain. Stony soils are damaging to the ER electrodes. Growing crops and bed–furrow systems pose a problem for ER equipment because of contact problems with the invasive electrodes. The coulters or insertion probes of ER equipment are on a fixed-height or limited-height adjustable platform that cannot clear most crops nor are they easily adjusted to conform to abrupt changes in microtopography as found in bed–furrow systems. In contrast, EM equipment is easily designed so the platform clears most crop canopies and the EM-38 slides down furrows.

Prior to physically conducting the EC_a survey, the survey's objective(s) must be defined based upon the project goals and available resources (e.g., manpower, funding, analytical capabilities, etc.). Pre-survey design tasks including site boundary definition, recording of site metadata, and selection of the GPS coordinate system and datum should be performed. The survey's objectives and resources will determine the measurement intensity of the survey (i.e., spacing between EC_a measurements). Measurement intensities generally vary from every 3 to 5 m for intense surveys used in detailed field-scale studies to 75–100 m

Table 2
Outline of steps for an EC_a field survey

1. Site description and EC_a survey design
    - (a) Record site metadata
    - (b) Define the project's/survey's objective
    - (c) Establish site boundaries
    - (d) Select GPS coordinate system
    - (e) Establish EC_a measurement intensity

2. EC_a data collection with mobile GPS-based equipment
    - (a) Geo-reference site boundaries and significant physical geographic features with GPS
    - (b) Measure geo-referenced EC_a data at the pre-determined spatial intensity and record associated metadata

3. Soil sample design based on geo-referenced EC_a data
    - (a) Statistically analyze EC_a data using an appropriate statistical sampling design to establish the soil sample site locations
    - (b) Establish site locations, depth of sampling, sample depth increments, and number of cores per site

4. Soil core sampling at specified sites designated by the sample design
    - (a) Obtain measurements of soil temperature through the profile at selected sites
    - (b) At randomly selected locations obtain duplicate soil cores within a 1 m distance of one another to establish local-scale variation of soil properties
    - (c) Record soil core observations (e.g., mottling, horizonation, textural discontinuities, etc.)

5. Laboratory analysis of appropriate soil physico-chemical properties defined by project objectives

6. If needed, stochastic and/or deterministic calibration of EC_a to EC_e or to other soil properties (e.g., water content and texture)

7. Spatial statistical analysis to determine the soil properties influencing EC_a and/or crop yield
    - (a) Soil quality assessment
        - (1) Perform a basic statistical analysis of physico-chemical data by depth increment and by composite depth over the depth of measurement of EC_a
        - (2) Determine the correlation between EC_a and physico-chemical soil properties by composite depth over the depth of measurement of EC_a
    - (b) Site-specific crop management (if EC_a correlates with crop yield, then)
        - (1) Perform a basic statistical analysis of physico-chemical data by depth increment and by composite depths
        - (2) Determine the correlation between EC_a and physico-chemical soil properties by depth increment and by composite depths
        - (3) Determine the correlation between crop yield and physico-chemical soil properties by depth and by composite depths to determine depth of concern (i.e., depth with consistently highest correlation, whether positive or negative, of soil properties to yield) and the significant soil properties influencing crop yield (or crop quality)
        - (4) Conduct an exploratory graphical analysis to determine the relationship between the significant physico-chemical properties and crop yield (or crop quality)
        - (5) Formulate a spatial linear regression (SLR) model that relates soil properties (independent variables) to crop yield or crop quality (dependent variable)
        - (6) Adjust this model for spatial auto-correlation, if necessary, using restricted maximum likelihood or some other technique
        - (7) Conduct a sensitivity analysis to establish dominant soil property influencing yield or quality
        - (8) GIS database development and graphic display of spatial distribution of soil properties

for basin-scale studies of thousands of hectares. Typically, an 18 ha field can be surveyed with mobile EC_a equipment in one to two 8 h work days at a 5 m spacing, which results in roughly 7200 EC_a measurements. This level of survey intensity provides a map of spatial variation sufficiently detailed to meet nearly any intended purpose.

3.2. Soil sample design based on geo-referenced EC_a data

Once a geo-referenced EC_a survey is conducted, the data are used to establish the locations of the soil core sample sites for (i) calibration of EC_a to soil sample EC_e and/or (ii) 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 model-based sampling schemes can be used. 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. Model-based sampling schemes are far less common, although some statistical research has been performed in this area (Royall, 1988). Specific model-based sampling approaches that have direct application to agricultural and environmental survey work are described by McBratney and Webster (1983), Russo (1984) and Lesch et al. (1995b).

The sampling approach introduced by Lesch et al. (1995b) is specifically designed for use with ground-based soil EC_a data. This sampling approach attempts to optimize the estimation of a regression model (i.e., minimize the mean square prediction error produced by the calibration function), while simultaneously insuring that the independent regression model residual error assumption remains approximately valid. This in turn allows an ordinary regression model to be used to predict soil property levels at all remaining (i.e., non-sampled) 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 remotely sensed EC_a data. Indeed, many types of ground, airborne, and/or satellite-based remotely sensed data are often collected specifically because one expects this data to correlate strongly with some parameter of interest (e.g., crop stress, soil type, soil salinity, etc.), but the exact parameter estimates (associated with the calibration model) may still need to be determined via some type of site-specific sampling design. The response-surface approach explicitly optimizes this site selection process.

A user-friendly software package (ESAP) developed by Lesch et al. (2000), which uses a response-surface sampling design, has proven to be particularly effective in delineating spatial distributions of soil properties from EC_a survey data (Corwin and Lesch, 2003; Corwin et al., 2003a, 2003b). The ESAP software package identifies the optimal locations for soil sample sites from the EC_a survey data. These sites are selected based on spatial statistics to reflect the observed spatial variability in EC_a survey measurements. Generally, 6–20 sites are selected depending on the level of variability of the EC_a measurements for a site. The optimal locations of a minimal subset of EC_a survey sites are identified to obtain soil samples.

Once the number and location of the sample sites have been established, the depth of soil core sampling, sample depth increments, and number of sites where duplicate or replicate core samples should be taken are established. The depth of sampling should be the same at each sample site and should extend over the depth of penetration by the EC_a-measurement equipment used. For instance, the Geonics EM-38 measures to a depth of roughly 0.75–1.0 m in the horizontal coil configuration (EM_h) and 1.2–1.5 m in the vertical coil configuration (EM_v). Sample depth increments are flexible and depend to a great extent on the study objectives. A depth increment of 0.3 m has been commonly used at the 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 physico-chemical analyses. Depth increments should be the same from one sample site to the next. The number of duplicates or replicates taken at each sample site are 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.

3.3. *Soil core sampling*

General soil core sampling protocols (Peterson and Calvin, 1996) and associated quality control and quality assurance procedures (Klestra and Bartz, 1996) should be followed. Soil cores are acquired to the same depth and over the same depth increments at all the selected sites. Soil cores are taken directly over the location of the EC_a measurement. As the cores are taken, soil temperature through the profile can be measured at selected sites, if needed. During sampling, attention should be taken to avoid including any dry, loose soil that may be present at the surface. Dry, loose topsoil is not reflected in the EC_a measurement because it has only residual moisture content making it non-conductive.

The extent of the spatio-temporal variation of soil temperature determines the overall significance of soil temperature as a factor influencing EC_a measurements. Customarily, electrical conductivity is expressed at a reference temperature of 25 °C. Electrolytic conductivity increases at a rate of approximately 1.9% per °C increase in temperature. For comparison purposes, if the spatio-temporal variations in soil temperature are greater than 10 °C, then temperature data is needed to adjust the electrical conductivity to the reference temperature of 25 °C. The following equation expresses electrical conductivity at a standard reference temperature of 25 °C:

$$EC_{25^\circ C} = f_T EC_T \tag{1}$$

where $EC_{25^\circ C}$ is the electrical conductivity at the reference temperature of 25 °C, f_T the temperature conversion factor, and EC_T the electrical conductivity at temperature T (°C). An approximation equation for the temperature conversion factor has been derived by Sheets and Hendrickx (1995):

$$f_T = 0.4470 + 1.4034\exp\left(-\frac{T}{26.815}\right) \tag{2}$$

Duplicate or replicate samples are collected at a minimum of 4–6 of the sample sites within a study area. The primary and replicate soil core samples are taken within a 0.5–1.0 m radius. If the field consists of beds and furrows, all primary and replicate samples are acquired from the same respective locations of the bed–furrow.

An appropriate identification system for labeling the soil samples should be established. Any metadata associated with each sample site and the samples such as observations about the depth to water table, abrupt changes in soil texture, horizonation, mottling, color change, surface crusting, etc. should be recorded. All soil samples should be placed in sealed, air-tight containers to minimize the loss of moisture, which would affect water content measurements. The soil samples should be immediately placed in an insulated storage container (refrigerated, if possible) for protection and keep the samples cool.

3.4. Laboratory analysis of soil physico-chemical properties

General quality control and quality assurance protocols for laboratory analysis should be followed (Klestra and Bartz, 1996). Soil samples should be analyzed as soon as possible after their collection. All soil sample preparation and analyses should be conducted following scientifically accepted procedures such as those outlined in the Soil Science Society of America's Methods of Soil Analysis (Sparks, 1996; Dane and Topp, 2002) and the United States Department of Agriculture's Handbook 60 (U.S. Salinity Laboratory Staff, 1954).

The appropriate analyses will depend upon the objective of the study. There is general agreement by soil scientists upon recommended minimum data sets of soil parameters that should be used to quantify soil quality including biological (microbial biomass, potentially mineralizable N, and soil respiration), chemical (pH, EC_e, OM, N, P, and K) and physical (texture, bulk density, depth of rooting, infiltration, and water holding capacity) parameters (Bouma, 1989; Larson and Pierce, 1991, 1994; Arshad and Coen, 1992; Doran and Parkin, 1994, 1996). However, soil quality is a function of the intended use of the soil; consequently, the appropriate soil properties to assess quality will vary accordingly. Corwin et al. (2003a) found the following properties appropriate for assessing quality of a salt-affected, sodic soil used for agricultural production: EC_e; pH; anions (HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) in the saturation extract; trace elements (B, Se, As, Mo) in the saturation extract; lime ($CaCO_3$); gypsum ($CaSO_4$); cation exchange capacity (CEC); exchangeable Na^+, K^+, Mg^{2+}, and Ca^{2+}; ESP (exchangeable sodium percentage); SAR; saturated hydraulic conductivity (K_s); and leaching fraction (LF). Site-specific crop management applications generally require a knowledge of those soil physico-chemical properties influencing the yield of a specific crop and impacting the environment. For instance, for an irrigated, arid zone soil on the San Joaquin Valley's west side, Corwin et al. (2003b) found pH, B, NO_3 and N, Cl^-, EC_e, LF, gravimetric water content, ρ_b, % clay, and saturation percentage (SP) to be the most significant soil properties when considering edaphic influences on within-field variations in cotton production.

3.5. Stochastic and/or deterministic calibration of EC_a to EC_e or to other soil properties

Apparent soil electrical conductivity can be calibrated to any soil property that significantly influences the EC_a measurement such as salinity, water content, clay content, SP, bulk density (ρ_b), and OM. As previously mentioned, there are numerous studies that document the relationships between soil electrical conductivity and various soil physical and chemical properties, including soil salinity (Rhoades, 1992, 1996; Rhoades et al., 1989; Lesch et al., 1995a; Williams and Baker, 1982), clay content (Williams and Hoey, 1987), depth to clay layers (Doolittle et al., 1994), nutrient status (Sudduth et al., 1995), and moisture content (Kachanoski et al., 1988), just to list a few. Additionally, there are articles documenting the use of conductivity survey information to determine salt loading and field irrigation efficiency (Rhoades et al., 1997; Corwin et al., 1999) and for estimating deep drainage (Triantafilis et al., 2003). All the data analysis and interpretation presented in these papers can be classified into two data modeling categories: deterministic and stochastic.

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

Traditionally, universal kriging models have been viewed as an extension of the ordinary kriging technique and used primarily to account for large-scale (non-stationary) trends in spatial data. However, this modeling technique can be easily generalized to model ancillary survey data (such as EM-38 data) when this data correlates well with some spatially varying soil property of interest (e.g., soil salinity). This generalization is commonly referred to as a “spatial linear model” or “spatial random field model” in the statistical literature (Christensen et al., 1992). This modeling approach requires the estimation of a regression equation with a spatially correlated error structure. This type of model probably represents the most versatile and accurate statistical calibration approach, provided enough calibration sample sites are collected ($n \geq 50$) to ensure a good estimate of the correlated error structure.

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

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

A more common interpretation technique used, particularly in salinity inventorying work, is to employ some form of deterministic EC_a-to-salinity model (i.e., an equation which converts EC_a to EC_e based on knowledge of other soil properties). One model of this type that has been shown to be useful is the DPPC (dual pathway parallel conductance) model developed by Rhoades et al. (1989, 1990) and extended by Lesch and Corwin (2003). This model is based on the idea that electrical conductivity of soil can be modeled as a multi-pathway parallel electrical conductance equation. This model has been shown to be applicable to a wide range of typical agricultural situations (Corwin and Lesch, 2003). The DPPC model demonstrates that soil electrical conductivity can be reduced to a nonlinear function of five soil physico-chemical properties: EC_e, SP, volumetric soil water content, Δ_b, and soil temperature. In Rhoades et al. (1990) the DPPC model was used to estimate field soil salinity levels based on EC_a survey data and measured or inferred information about the remaining soil physical properties. Corwin and Lesch (2003) and Lesch et al. (2000) showed that this model can also be used to assess the degree of influence that each of these soil properties has on the acquired EC_a-survey data.

Soil salinity, as conventionally expressed in terms of the electrical conductivity of the saturated-paste extract, EC_e, can be determined from EC_a in two ways: 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, either theoretically or empirically determined models convert EC_a into EC_e. Deterministic models are “static” (i.e., all model parameters are considered known and no EC_e data needs to be determined). For example, Eq. (3) from the DPPC model of Rhoades et al. (1989) is a deterministic approach:

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

where $\theta_w = \theta_{ws} + \theta_{wc}$ = total volumetric water content (cm^3 cm^{-3}); θ_{ws} and θ_{wc} are the volumetric soil water content in the soil-water pathway (cm^3 cm^{-3}) and in the continuous-liquid pathway (cm^3 cm^{-3}), respectively; θ_{ss} the volumetric content of the surface-conductance (cm^3 cm^{-3}); EC_{ws} and EC_{wc} the specific electrical conductivities of the soil-water pathway (dS m^{-1}) and continuous-liquid pathway (dS m^{-1}); and EC_{ss} the electrical conductivity of the surface-conductance (dS m^{-1}). Soil EC_a is converted into estimated soil salinity (i.e., EC_e) using Eqs. (3)–(8) originally developed by Rhoades et al. (1989):

$$\theta_w = \frac{(PW \cdot \rho_b)}{100} \tag{4}$$

$$\theta_{ws} = 0.639\theta_w + 0.011 \tag{5}$$

$$\theta_{ss} = \frac{\rho_b}{2.65} \tag{6}$$

$$EC_{ss} = 0.019(SP) - 0.434 \tag{7}$$

$$EC_w = \left[\frac{EC_e \cdot \rho_b \cdot SP}{100 \cdot \theta_b}\right] \tag{8}$$

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

The deterministic approach is the preferred approach when significant, localized variations in soil type exist in the field. However, this approach typically requires knowledge of additional soil properties (e.g., soil water content, SP, ρ_b, temperature, etc.). In instances where extensive soil property information is lacking, the stochastic approach is more appropriate. 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). The calibration is developed by acquiring soil salinity data (or other soil property data such as SP, texture, ρ_b, etc.) from a small percentage of the EC_a measurement sites and estimating an appropriate stochastic-prediction model for each depth increment using the paired soil sample and EC_a data. Using the remaining EC_a data in conjunction with the established model, the soil salinity levels (or other calibrated properties) are predicted at all of the remaining non-sampled, 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).

3.6. *Spatial statistical analysis to determine the soil properties influencing EC_a and/or crop yield*

In the past, the fact that EC_a is a function of several soil properties (i.e., soil salinity, texture, and water content) has sometimes been overlooked in the application of EC_a measurements to site-specific crop management. In areas of saline soils, salinity dominates the EC_a measurements and interpretations are often straightforward. However, in areas other than arid zone soils, texture and water content or even OM may be the dominant properties measured by EC_a. To use spatial measurements of EC_a in a soil quality or site-specific crop management context, it is necessary to understand what factors are most significantly influencing the EC_a measurements within the field of study. There are two commonly used approaches for determining the predominant factors influencing EC_a measurement: (1) wavelet analysis and (2) simple statistical correlation.

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

EC_a measurements as the statistical and graphical approach first developed by Lesch et al. (1995a, 1995b, 2000).

The most practical means of interpreting and understanding the tremendous volume of spatial data from an EC_a survey is through statistical analysis and graphic display. Details describing the statistical and graphical approach for determining the predominant soil property influencing EC_a measurements are found in Corwin and Lesch (2003). For a soil quality assessment a basic statistical analysis of all physico-chemical data by depth increment provides an understanding of the vertical profile distribution. A basic statistical analysis consists of the determination of the mean, minimum, maximum, range, standard deviation, standard error, coefficient of variation, and skewness for each depth increment (e.g., 0–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m) and by composite depth (e.g., 0–1.2 m) over the depth of measurement of EC_a. In the case of EC_a measured with ER (e.g., Veris or fixed-array four electrode equipment), the composite depth over the depth of measurement of EC_a is based on the spacing between the electrodes, while in the case of EM-38 measurements of EC_a the composite depth for the EM_h measurement is about 0–0.75 to 1.0 m and 0–1.2 to 1.5 m for EM_v. The calculation of the correlation coefficient between EC_a and mean value of each physico-chemical soil property by depth increment and composite depth over multiple sample sites determines those soil properties that correlate best with EC_a and those soil properties that are spatially represented by the EC_a-directed sampling design. Those properties that are not correlated with EC_a are not spatially characterized with the EC_a-directed sampling design indicating that a design-based sampling scheme such as stratified random sampling is probably needed to better spatially characterize these soil properties.

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

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

3.7. *GIS development and graphic display of spatial distribution of soil properties*

The organization, manipulation, and graphic display of spatial soil and EC_a data is best accomplished with a geographic information system (GIS). Spatial soil property data are entered into any of the several GIS software packages such as ArcView or ArcGIS (see footnote 1). Once the spatial data is entered, maps of the soil physico-chemical properties can be easily prepared. A variety of interpolation techniques such as inverse-distance-weighting (IDW) interpolation and various kriging approaches can be used. Previous studies comparing interpolation methods for mapping soil properties have found mixed results. In some instances kriging has been found to perform the best (Laslett et al., 1987; Warrick et al., 1988; Leenaers et al., 1990; Kravchenko and Bullock, 1999) and in others IDW has been found superior (Weber and Englund, 1992; Wollenhaupt et al., 1994; Gotway et al., 1996). A common means of determining which method is the best to use for a particular spatial data set is to use the statistical approach of jackknifing to establish the interpolation method that minimizes the prediction error (Isaaks and Srivastava, 1989).

4. Additional considerations

There are a number of additional issues to consider in an EC_a survey that may have subtle effects on the reliability and accuracy of the EC_a measurements. These effects relate to factors that are easily overlooked, but may collectively mean the difference between useful and unreliable data.

4.1. *Accuracy issues concerning EM measurements*

The issue of accuracy in EM measurements of EC_a for precision agriculture is addressed by Sudduth et al. (2001). The authors point out that over time the EM-38 sensor is subject to drift, which can contribute a significant fraction of the within-field EC_a variation. A study by Robinson et al. (2004) indicated that the drift observed in the EM-38 is likely due to temperature effects on the EM-38 sensor and that a simple reflective shade over the sensor could reduce drift effects considerably. However, an added precaution would be to conduct regular "drift runs" where repeated data is periodically acquired along a transect to adjust for the drift in the post-processing of EC_a data. Drift runs are conducted in the morning, noon, and late afternoon to provide a range of diurnal temperature effects on the EM instrument. The variations in drift provide the basis for adjusting the EC_a measurements.

Positional offset can also be a problem due to both the distance from the sensor to the GPS antenna and the data acquisition system time lags. Sudduth et al. (2001) found that the sensitivity of EC_a to variations in sensor operating speed and height was relatively minor. Nevertheless, mobile EC_a equipment should not be operated at speeds higher than $10\,km\,h^{-1}$ to minimize positional offset effects.

4.2. Factors influencing within-field EC_a variations and EC_a-survey and soil-sampling strategies to account for their occurrence

Variation of EC_a within a field is due to spatial variation in soil properties influencing EC_a. The spatial heterogeneity of these soil properties is the consequence of the interaction of (i) soil formation processes, (ii) meteorologic processes, and (iii) anthropogenic influences. Soil formation processes are the result of complex interactions between biological, physical, and chemical mechanisms acting on a parent material over time and influenced by topography. Meteorologic processes directly and indirectly influence soil formation processes. Anthropogenic influences are typically related to management practices including leaching fraction and irrigation water quality. To implement an efficient EC_a survey and associated soil sampling plan to reliably characterize spatial variability, an awareness and understanding of the factors influencing within-field EC_a variations are crucial. Suggestions for EC_a surveys and sampling strategies are provided to account for the occurrence of the deterministic and stochastic mechanisms that create local and within-field EC_a variations.

4.2.1. EC_a variation with salinity

In semi-arid regions where saline seeps occur due to shallow water tables and in arid agricultural areas, salinity is generally the soil property that dominates the EC_a measurement. Salinity accumulation occurs where evaporation or evapotranspiration exceed irrigation and/or precipitation. The predominant mechanism causing the accumulation of salt in irrigated agricultural soils is loss of water through evapotranspiration, leaving ever increasing concentrations of salts in the remaining water. Unlike texture or bulk density, which are static properties of soils, salinity is a dynamic property. It varies temporally and spatially with depth and across the landscape and exhibits high variation across a field and moderate to high local-scale variability (Corwin et al., 2003a). Local-scale variation determined from near-surface furrow samples acquired 0.5 m apart can vary anywhere from 10 to 100% due to micro-scale soil composition characteristics and/or fluctuations in preferential water flow.

Electromagnetic induction instrument readings tend to average out this local-scale variation. The degree to which this averaging occurs depends directly upon the instrument's "foot print" (i.e., the volume of soil incorporated into the signal response). For example, an EM-38 signal will be influenced by any electrically conductive material within about 1–2 m of the instrument (both laterally and vertically). Hence, it is typically assumed to have about a 1.5 m foot print.

Because the volume of soil measured by the EM-38 is so much larger than the volume obtained by conventional soil sampling techniques, an estimate of the degree of local-scale salinity variation needs to be acquired for calibration model purposes and for soil quality assessments of spatial variability. Such an estimate can be acquired by obtaining duplicate or replicate sample cores within a 1 m radius at some of the calibration sites during the soil sampling process. The replicate cores can then be used to estimate the local-scale salinity variation (referred to as the "nugget variation" in geostatistical models and as the "pure error estimate" in spatial regression models). The measured salinity data from these cores can be used to construct a residual autocorrelation test, known as a "lack-of-fit" test, for assessing the spatial residual independence assumption (Lesch et al., 1995a). Techniques for estimating the local-scale salinity variation and performing residual lack-of-fit tests are described in Lesch et al. (1995a).

In a typical 12–16 site calibration sampling design, replicate sample cores are commonly taken at 4–6 of the calibration sites. These 4–6 sites can either be chosen at random (from amongst the 16 sites) or selected throughout the survey area. Additionally, the core separation spacing should be the same at all sites and both the primary and replicate cores should always come from the same location with respect to the bed–furrow environment (i.e., both from the bed, or both from the furrow).

Variations in salinity through the soil profile also influence the EC_a measurement. This influence is particularly complex when EC_a is measured with EM because the depth-weighted response function of the instrument (e.g., EM-31 or EM-38) is non-linear. The depth-weighted nonlinearity is shown in Fig. 3, which illustrates the cumulative relative contributions to EC_a [i.e., R(z)] for a homogeneously conductive material below a normalized depth of z based on Eqs. (9) and (10) from McNeill (1980) for vertical and horizontal

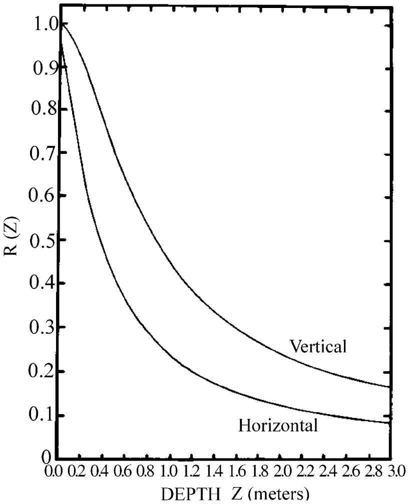

Fig. 3. Cumulative relative contribution of all soil electrical conductivity, $R(z)$, below various depths for the EM-38 apparent soil electrical conductivity reading when the device is held in a horizontal (parallel) and vertical (perpendicular) position. Taken from McNeill (1980).

dipoles, respectively:

$$R_v(z) = \frac{1}{(4z^2 + 1)^{1/2}} \tag{9}$$

$$R_h(z) = (4z^2 + 1)^{1/2} - 2z \tag{10}$$

When considering 0.3 m depth increments through the soil profile, the greatest response for EM_h occurs over the 0–0.3 m depth increment and over the 0.3–0.6 m depth increment for EM_v. Nevertheless, it is possible to determine the general shape of the salinity profile by the relative magnitudes of the EM_h and EM_v readings at a point in the field. For salinity-driven EC_a surveys, if $EM_h > EM_v$, then the salinity profile is inverted and decreases with depth; if $EM_h < EM_v$; then salinity increases; if salinity is uniform, then $EM_h \approx EM_v$.

4.2.2. EC_a variation with water content

Soil water content variations affect EC_a measurements. Like salinity, soil water content is a dynamic soil property that varies with depth and across the landscape, generally with moderate to high local-scale variability. In areas under uniform irrigation management practices, the degree of spatial water content variability is typically minimal provided significant soil texture variation is not present. However, some fields demonstrate gradual trends in water content across the extent of the field, which may be due to gradual changes in shallow water table levels close to the depth of penetration of measurement or to abrupt textural discontinuities, or due to non-uniformity of water application (e.g., flood irrigation has a trend of high to low from the head water to tail water ends of a field, respectively). In instances where gradual changes in the soil water content level occur, trend surface parameters in the regression model can be used.

Like salinity, variations in the water content through the soil profile influence the EC_a measurement and this influence is particularly complex when using EM. As with salinity, it is possible to determine the general profile shape of water content. For fields where water content is the dominant soil property influencing the EC_a measurement, if water content decreases with depth, then $EM_h > EM_v$; if water content increases, then $EM_h < EM_v$; if water content uniform, then $EM_h \approx EM_v$.

It is important to remember that if the water content of the soil drops too low (e.g., <0.10 $cm^3\,cm^{-3}$), then the EM signal readings can become seriously dampened. In most practical applications, reliable EM signal data will be obtained when the soil is at or near field capacity. Surveying dry areas should be avoided. This is especially true for surveys that use ER, which requires close contact between the electrodes and soil that can only be attained when the soil is moist.

4.2.3. EC_a variation induced by changes in soil texture

Soil texture can cause extremely complex spatial patterns of EC_a. Under a uniform irrigation distribution, water content will generally coincide with texture. Soils higher in sand have lower water contents than soils higher in clay. Minimal complexities in spatial patterns of EC_a occur (i) when there is minimal soil texture variability, (ii) when the texture changes are smooth and gradual across the field, or (iii) when the texture, water content, and salinity variations are strongly correlated.

4.2.4. EC_a variation induced by other soil properties

Other physical soil properties also affect the EC_a survey readings to various degrees. These properties include OM, magnetic susceptibility, and temperature. Significant variation in these properties needs to be present before any meaningful influence upon the EC_a signal reading occurs. With respect to temperature, a 1 °C change in temperature throughout the entire soil profile typically causes no more than a 2% change in the EM-38 signal readings. Since soil temperature fluctuations below 0.3 m in the soil profile occur rather slowly, the entire survey process can usually be completed before a significant change in the bulk-average soil profile temperature occurs. Magnetic susceptibility is seldom a factor except for soils high in free iron oxides. Apparent soil electrical conductivity variation related to OM has been investigated by Jaynes (1996).

4.2.5. EC_a variation with depth

The variation of EC_a with depth is primarily due to gradations in salinity, texture, and water content through the soil profile. Soil salinity levels can change quite rapidly with depth; it is not unusual in some arid zone areas to see relative salinity profile levels fluctuate by an order of magnitude within the top meter of soil. Water content tends to increase with depth and will vary according to textural distribution. Textural distribution is mainly a consequence of soil formation processes. However, anthropogenic effects can result in increased uniformity of texture within the plow layer or can produce other localized variations. Salinity will vary in the soil profile primarily from the process of leaching with plant, chemical, and topographic effects contributing to variations.

Devising a sampling scheme that accounts for temporal and depth variations while maintaining accurate and consistent sampling depths throughout a survey area is critical. Without prior knowledge of the distribution of salinity, water content, and texture within a profile, it can be difficult to infer the appropriate sample depth design. For this reason, soil cores should be acquired to a depth of at least 1.2–1.5 m at each sample site. If resources permit, each core can be sliced into subsamples, thereby facilitating the estimation of prediction functions (regression models) for multiple sample depths.

Electrical resistivity and EM techniques are both well suited for field-scale applications because their volumes of measurement are large, which reduces the influence of local-scale variability. However, ER has a flexibility that has proven advantageous for field application, i.e., the depth and volume of measurement can be easily changed by altering the spacing between the electrodes. This allows the EC_a for a discrete depth interval of soil to be easily calculated with a fixed-array four electrode by measuring the EC_a of successive layers for increasing inter-electrode spacings and using the following equation (Barnes, 1952; Telford et al., 1976):

$$\mathrm{EC}_x = \mathrm{EC}_{a_i} - \mathrm{EC}_{a_{i-1}} = \left(\frac{EC_{a_i} a_i - EC_{a_{i-1}} a_{i-1}}{a_i - a_{i-1}} \right) \tag{11}$$

where a_i is the inter-electrode spacing, which equals the depth of sampling, a_{i-1} the previous inter-electrode spacing, which equals the depth of previous sampling, and EC_x the apparent soil electrical conductivity for a specific depth interval.

Electromagnetic induction can also measure EC_a at variable depths determined by the height of the EM instrument above the soil surface. Unlike ER, depth profiling of EC_a with EM is mathematically complex (Borchers et al., 1997; McBratney et al., 2000; Hendrickx et al., 2002b). Measurements of EC_a at variable depths with EM are usually achieved by positioning the EM instrument at various heights above the soil surface in either the vertical (EM_v) or horizontal (EM_h) dipole mode (Rhoades and Corwin, 1981; Corwin and Rhoades, 1982). Though not required, the measurement of EC_a near the soil surface (i.e., top 0.25–0.5 m) along with spatially associated larger soil volume EC_a measurements with EM equipment can be used to increase the accuracy of the fitted prediction functions that define EC_a profile variation (Lesch et al., 1992). Insertion four-electrode probes and small, hand-held fixed-arrays are both very useful for measuring the soil EC_a within the first 0.25–0.5 m of topsoil.

One sampling strategy commonly used in association with an EC_a survey is to acquire soil samples at each sample site in 0.3 m increments, typically down to a depth of either 1.2 or 1.5 m. When sampling by hand (i.e., using a hand auger), each soil sample can be removed individually. If a drill rig is available, then the entire core is usually bored at one time and then split into subsamples after being brought to the surface. To minimize temporal changes that may occur in dynamic soil properties such as water content and salinity, EC_a surveys and associated soil sampling are conducted when the soil is at or near field capacity (i.e., water content of soil after free drainage has occurred, generally 3 and 4 days following an irrigation).

4.2.6. EC_a variation induced by surface topography

Surface topography plays a significant role in influencing spatial EC_a variation. Slope and aspect will determine the level and location of runoff and infiltration, which will influence the variation in water content and salinity at local scales and larger. Areas where the slope is steep tend to have lower water content than areas where a depression occurs. All other factors being equal, flat areas tend to be more spatially uniform in areal variation of water content. The influence of surface topography on salinity distribution coincides with the influence of surface topography on water flow gradients, which result in salt transport.

The bed–furrow environment is an example of surface topography that can have subtle local-scale variation effects. The bed–furrow topography can be a source of considerable water and salinity variation, particularly over the cropping season. A percentage of the irrigation water applied to a furrow will move laterally and upwards into adjacent beds due to capillary flow. This water movement in turn will carry near-surface soluble salts up into the bed. In flood irrigated fields the relative difference between the near-surface furrow and bed salinity levels can become pronounced over time.

Fig. 4 displays the geometrical distribution of soil salinity throughout the near-surface bed–furrow environment within a fixed-bed, flood-irrigated cotton field in the Coachella Valley, California (sampled in 1992). The high mean salinity level was 23.2 dS m^{-1} throughout the bed–furrow; the ratio of bed to furrow near-surface salinity levels was 4:1. At the low level (5.8 dS m^{-1}) this ratio actually increased to 8:1. Fig. 4 indicates that the overall mean

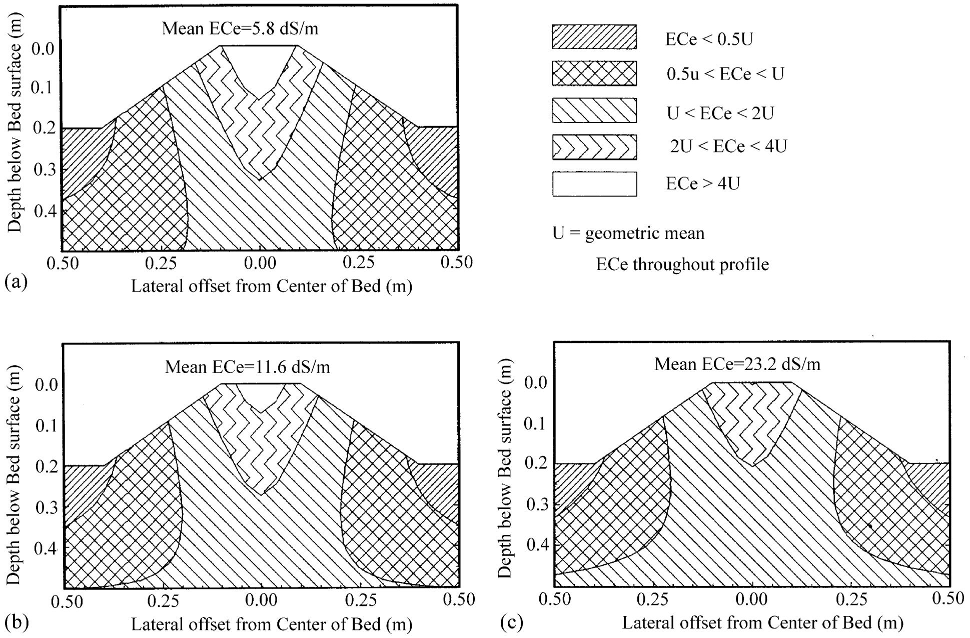

Fig. 4. Two-dimensional salinity distribution within the bed–furrow.

salinity level would have been very poorly estimated by samples acquired either only in the furrows or in the bed. In this particular survey, it took 14 soil samples at each sample site to adequately describe the two-dimensional pattern of salinity present within the bed–furrow environment. The main point conveyed by Fig. 4 is that more extensive sampling schemes must be considered for bed–furrow systems, if knowledge of the two-dimensional salinity and/or water content distributions is an essential objective of the survey. However, if a detailed knowledge of the two-dimensional distributions of a bed–furrow system is unnecessary, then there is a critical need for consistency with respect to soil core locations. In these instances, all soil cores should be sampled from the same place within the bed–furrow. Furthermore, the EC_a survey data, particularly from EM equipment, and soil sample cores should be acquired from exactly the same location within the bed–furrow. For example, if the EC_a data are acquired over the furrows, then the soil samples should also be acquired from the furrows.

Composite or bulk sampling strategies for averaging variations in a bed–furrow system are generally not recommended. In composite sampling, soil samples would be acquired from both bed and furrow locations and then mixed together in an effort to obtain a more “representative” sample. Composite samples are not recommended for two reasons. First, it doubles the field work without providing any knowledge of the two-dimensional, bed–furrow salinity distribution and second, it often introduces more variability into the sample data (through poor mixing processes) than it removes through averaging.

Irrigated, agricultural land is typically laser-leveled to improve irrigation efficiency. Various leveling designs are used, depending on the method of irrigation and the agricultural crop under production. The three most common designs include dead leveling, single-slope leveling, and dual slope leveling. All these three designs create a theoretical plane that can be written mathematically as:

$$\text{Surface elevation} = \alpha_0 + \alpha_1 x + \alpha_2 y \tag{12}$$

where x and y represent the physical (x, y) coordinates, and the α_0, α_1 and α_2 coefficients the primary and secondary slopes of the field. Eq. (12) is referred to as a first-order trend surface equation. The regression relationship between the geo-referenced EC_a measurements and soil properties (i.e., salinity, water content, texture) influencing the EC_a measurement can be influenced by gradual changes in salinity, water content, and/or texture across the survey area due to changes in elevation. These gradual changes in salinity, water content, and/or texture due to elevation can be taken into account through the inclusion of a first-order or second-order trend surface equation in the regression analysis.

If an EC_a survey is conducted on non-graded farmland, which exhibits significant local variation in surface elevation, then it will usually be necessary to conduct a surface elevation survey along with the EC_a survey. This elevation data can then be directly incorporated into any regression analyses relating EC_a to soil properties or into the sample design strategy.

4.2.7. EC_a variation induced by traffic patterns

Another source of potential EC_a variation arises from soil compaction caused by repetitive traffic patterns of heavy agricultural equipment. In many fields, heavy equipment is consistently driven down the same set of furrows when performing tillage and cultivation operations over the growing season. This leads to a systematic pattern of compaction in a subset of furrows throughout the field.

Fig. 5 displays the EM-38 horizontal (EM_h) readings acquired in 1991 along 30 adjacent furrows in a buried drip-irrigated cotton field (Westlands Water District, California) subject to repetitive traffic influences. In this case the traffic pattern induced a clearly cyclic pattern in the EM_h readings; the highest conductivity readings consistently occurred in the compacted furrows where ρ_b was characteristically higher near the soil surface.

The data shown in Fig. 5 is atypical. In general, compaction induced cyclic patterns do not have such pronounced effects on EC_a. Nonetheless, caution should be taken to systematically avoid taking EC_a measurements down compacted furrows, particularly with EM equipment. Excessive soil compaction will nearly always have at least some effect on the ρ_b, soil salinity, and water content levels. Random surveying (and sampling) of both compacted and non-compacted furrows in the same field will introduce variability that should be avoided whenever possible. A simple, but effective, means of determining furrows that have been compacted by repeated traffic from heavy equipment is by pushing a long screwdriver or rod into the furrow to determine if the resistance is greater than adjacent furrows.

4.2.8. EC_a variation induced by irrigation management practices

Irrigation management has a pronounced effect on determining areal and profile EC_a distributions within a field. The amount and frequency of irrigation will directly influence

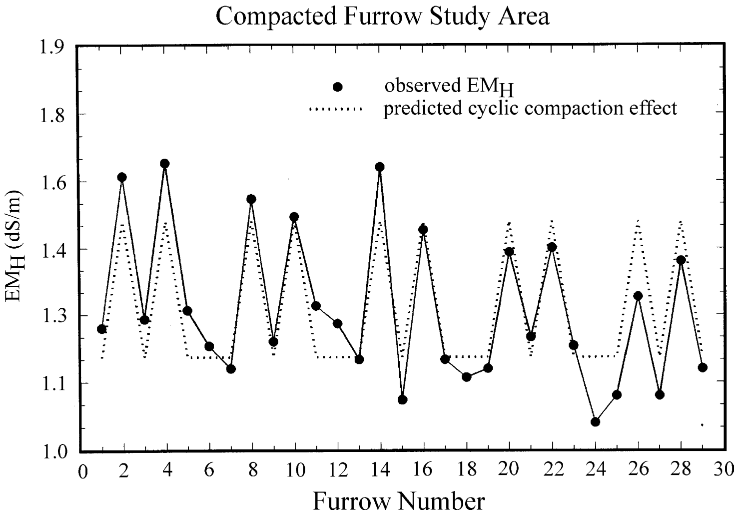

Fig. 5. Variations of EC_a due to compaction from repeated heavy equipment operation on a drip-irrigated cotton field.

the movement of water and soluble salts through the profile and across the field. The water content of the soil during the EC_a survey will be at least partially determined by the elapsed time from the last irrigation event, the presence or absence of a crop, and if present, the maturity of the crop.

Since a change in irrigation management (e.g., drip, sprinkler, or flood irrigation) can seriously affect the three-dimensional salinity and water content distributions within a field, it is important to avoid conducting an EC_a survey (and/or soil sampling) for an area under more than one irrigation management strategy. This means that any survey area must be restricted to farmland under similar irrigation management practices. Each survey must be conducted entirely within a single, homogeneous irrigation management area. The failure to restrict EM readings to an area under a single water management strategy can result in serious regression model and sample design bias with inflated errors that corrupt the entire surveying process.

5. Conclusions

All landscape-scale environmental and agricultural studies involving soil require a spatial and often times a temporal knowledge of soil physico-chemical properties. Surveys of EC_a provide one of the most reliable and comprehensive means for obtaining this spatio-temporal information. The development of mobile EC_a equipment has made it possible to characterize spatial variability of a variety of physico-chemical properties both rapidly and cost effectively. Nevertheless, previous surveys have met with inconsistent results at times due to the inexperience of the researcher and/or the lack of a standardized set of EC_a survey protocols. Concomitantly, the ability to use EC_a survey information in a comparative sense from one site to another and between different researchers or to collectively build a database comprised of EC_a measurements from multiple locations by multiple researchers requires a framework that standardizes the collection of EC_a survey and associated spatial edaphic information. The outlined protocols for conducting EC_a surveys provide a means of characterizing the spatial variability of soil physico-chemical properties that can be used in site-specific crop management, landscape-scale modeling of non-point source pollutants in the vadose zone, and soil quality assessment. Guidelines are also presented for understanding and interpreting EC_a survey measurements. It is the intent of the developed protocols to improve the reliability, consistency, and compatibility of EC_a survey measurements and their interpretation for characterizing spatial variability of soil physico-chemical properties.

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