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Apparent soil electrical conductivity measurements in agriculture

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Abstract

The field-scale application of apparent soil electrical conductivity (EC_a) to agriculture has its origin in the measurement of soil salinity, which is an arid-zone problem associated with irrigated agricultural land and with areas having shallow water tables. Apparent soil electrical conductivity is influenced by a combination of physico-chemical properties including soluble salts, clay content and mineralogy, soil water content, bulk density, organic matter, and soil temperature; consequently, measurements of EC_a have been used at field scales to map the spatial variation of several edaphic properties: soil salinity, clay content or depth to clay-rich layers, soil water content, the depth of flood deposited sands, and organic matter. In addition, EC_a has been used at field scales to determine a variety of anthropogenic properties: leaching fraction, irrigation and drainage patterns, and compaction patterns due to farm machinery. Since its early agricultural use as a means of measuring soil salinity, the agricultural application of EC_a has evolved into a widely accepted means of establishing the spatial variability of several soil physico-chemical properties that influence the EC_a measurement. Apparent soil electrical conductivity is a quick, reliable, easy-to-take soil measurement that often, but not always, relates to crop yield. For these reasons, the measurement of EC_a is among the most frequently used tools in precision agriculture research for the spatio-temporal characterization of edaphic and

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Abbreviations: CEC, cation exchange capacity; $EC_{1:1}$, laboratory measured electrical conductivity of a 1:1 soil to water extract; EC, soil electrical conductivity; 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; ESP, exchangeable sodium percentage; GIS, geographic information system; GPS, global positioning system; NPS, non-point source; OM, organic matter; PW, per cent water on a gravimetric basis; SAR, sodium adsorption ratio; SLR, spatial 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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anthropogenic properties that influence crop yield. It is the objective of this paper to provide a review of the development and use of EC_a measurements for agricultural purposes, particularly from a perspective of precision agriculture applications. Background information is presented to provide the reader with (i) an understanding of the basic theories and principles of the EC_a measurement, (ii) an overview of various EC_a measurement techniques, (iii) applications of EC_a measurements in agriculture, particularly site-specific crop management, (iv) guidelines for conducting an EC_a survey, and (v) current trends and future developments in the application of EC_a to precision agriculture. Unquestionably, EC_a is an invaluable agricultural tool that provides spatial information for soil quality assessment and precision agriculture applications including the delineation of site-specific management units. Technologies such as geo-referenced EC_a measurement techniques have brought precision agriculture from a 1980's concept to a promising tool for achieving sustainable agriculture.

Keywords: Precision agriculture; Salinity; EC_a; Site-specific management units; Spatial variability; Soil quality

1. Introduction

Over the past three decades, global agriculture has made tremendous progress in expanding the world's supply of food. Even though the world population has doubled over this time period, food production has risen even faster with per capita food supplies increasing from less than 2000 calories per day in 1962 to more than 2500 calories in 1995 (World Resources Institute, 1998). The rise in global food production has been credited to better seeds, expanded irrigation, and higher fertilizer and pesticide use, commonly referred to as the Green Revolution.

The prospect of feeding a projected additional 3 billion people over the next 30 years poses more challenges than encountered in the past 30 years. In the short term, global resource experts predict that there will be adequate global food supplies, but the distribution of those supplies to malnourished people will be the primary problem. Longer term, however, the obstacles become more formidable, though not insurmountable. Although total yields continue to rise on a global basis, there is a disturbing decline in yield growth with some major crops such as wheat and maze reaching a "yield plateau" (World Resources Institute, 1998). Feeding the ever-increasing world population will require a sustainable agricultural system that can keep pace with population growth.

In an effort to feed the world population, agriculture has had detrimental impacts due to the loss of natural habitat, the use and misuse of pesticides and fertilizers, and soil and water resource degradation. By 1990, poor agricultural practices had contributed to the degradation of 38% of the roughly 1.5 billion ha of crop land worldwide and since 1990 the losses have continued at a rate of 5–6 million ha annually (World Resources Institute, 1998). 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 35–40% of the total supply of food and fiber comes from irrigated agriculture (Rhoades and Loveday, 1990). Yet, poor water management on irrigated crop land has resulted in 10–15% of all irrigated land suffering some degree of waterlogging and salinization. In fact, waterlogging and salinization alone represent a significant threat to the world's productivity capacity (Alexandratos, 1995).

Barring unexpected technological breakthroughs, sustainable agriculture is viewed as the most viable means of meeting the food demands of the projected world's population. The concept of sustainable agriculture is predicated on a delicate balance of maximizing crop productivity and maintaining economic stability while minimizing the utilization of finite natural resources and the detrimental environmental impacts of associated agrichemical pollutants. Arguably, the most promising approach for attaining sustainable agriculture, and thereby keeping agricultural productivity apace with population growth, is precision agriculture. Site-specific crop management refers to the application of precision agriculture to crop production.

Conventional farming currently treats a field uniformly, ignoring the naturally inherent variability of soil and crop conditions between and within fields. Ever since the classic paper by Nielson et al. (1973) concerning the variability of field-measured soil water properties, the significance of within-field spatial variability of soil properties has been scientifically acknowledged and documented. However, until recently, with the introduction of global positioning systems (GPS; see Appendix A for a list of abbreviations) and yield-monitoring equipment, documentation of crop yield and soil variability at field-scale was difficult to establish. Now there is well-documented evidence that spatial variability within a field is highly significant and amounts to a factor of 3–4 or more for crops (Birrel et al., 1995; Verhagen et al., 1995) and up to an order of magnitude or more for soils (Corwin et al., 2003a).

Spatial variation in crops is the result of a complex interaction of biological (e.g., pests, earthworms, microbes), edaphic (e.g., salinity, organic matter, nutrients, texture), anthropogenic (e.g., leaching efficiency, soil compaction due to farm equipment), topographic (e.g., slope, elevation), and climatic (e.g., relative humidity, temperature, rainfall) factors. Site-specific crop management aims to manage soils, pests, and crops based upon spatial variations within a field (Larson and Robert, 1991). Specifically, site-specific crop management is the management of agricultural crops at a spatial scale smaller than the whole field by considering local variability with the aim of cost effectively maximizing crop production and making efficient use of agrichemicals to minimize detrimental environmental impacts.

Precision agriculture utilizes rapidly evolving electronic information technologies to modify land management in a site-specific manner as conditions change spatially and temporally (van Schilfgaarde, 1999). 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 Schilfgaarde, 1999). The fundamental components of precision agriculture include newly commercialized technologies of GPS, yield-monitoring, and variable rate agrichemical application combined with adaptation of existing technologies of GIS and remote sensing (e.g., electromagnetic induction, aerial photography, satellite- and airborne multispectral imagery, microwave, and hyperspectral imagery) or rapid invasive soil property measurement technologies (e.g., electrical resistivity, time domain reflectometry) (Plant, 2001).

To manage within-field variability, geo-referenced areas displaying similar behavior with respect to a specified characteristic (e.g., yield potential, leaching potential) must be identified (van Uffelen et al., 1997). It must also be established to what extent and under what conditions these spatial patterns are stable. Yield maps provide information on the integrated effects of the physical, chemical, and biological processes under certain weather conditions (van Uffelen et al., 1997) and provide the basis for implementing site-specific crop management by indicating where varying cropping inputs are needed based upon spatial patterns of crop productivity (Long, 1998). However, the cropping inputs necessary to optimize productivity and minimize environmental impacts can be derived only if it is known what factors gave rise to the observed spatial crop patterns (Long, 1998). Yield maps alone cannot provide information to distinguish between the various sources of variability and cannot provide clear guidelines without information concerning the influence of the variability of weather, pests and diseases, and soil physico-chemical properties on the variability of a crop for a particular year (van Uffelen et al., 1997).

To a varying extent from one field to the next, crop patterns are influenced by edaphic or soil-related properties. Bullock and Bullock (2000) point out that efficient methods for accurately measuring within-field variations in soil physical and chemical properties are important for precision agriculture. The measurement of apparent soil electrical conductivity (EC_a) is a technology that has become an invaluable tool for identifying the soil physico-chemical properties influencing crop yield patterns and for establishing the spatial variation of these soil properties (Corwin et al., 2003b).

Precision agriculture not only requires spatial information to determine *where* and *how much* of an input (e.g., fertilizers, pesticides, irrigation water) to apply, but also requires temporal information to know *when* to apply. To know when to apply an input, particularly when to irrigate, requires real-time measurements of plant and/or soil conditions. Real-time measurements of plant condition, and to a limited extent soil condition, are best obtained with multi- and hyper-spectral imagery. Even though multi- and hyper-spectral imagery are still in their infancy for answering questions related to when inputs should be applied, their potential for answering time-related management questions is greater than for geospatial EC_a measurements. Imagery has the advantage of monitoring plant condition over large areas in a short time frame, whereas EC_a monitors the soil, which must be related back to plant response. However, the problem with imagery has been that in some instances (e.g., water stress) by the time imagery detects a change in plant condition, such as exceeding the wilting point, it may be too late to rectify the condition and damage may have already occurred. Nonetheless, the extremely rapid, landscape-scale measurement of plant response with multi- and hyper-spectral imagery makes it more practical for real-time measurements of plant condition, which are necessary to determine the timing of inputs within a precision agriculture management framework. Spatio-temporal measurements of EC_a are best suited for historical or year-to-year assessments of trend, such as salinization of a soil or reclamation of a salt-affected soil.

It is the objective of this review to provide the reader with (i) an understanding of the basic theories and principles of the EC_a measurement and what it actually measures, (ii) an overview of various EC_a measurement techniques (i.e., electromagnetic induction, electrical resistivity, time domain reflectometry), (iii) applications of EC_a measurements in agriculture, particularly site-specific crop management, (iv) guidelines for conducting an EC_a survey, and (v) current trends and future developments in the application of EC_a to precision agriculture.

2. Basic principles of the $\mathrm{EC_a}$ measurement

A comprehensive and instructive discussion of the theory and principles of the $\mathrm{EC_a}$ measurement is presented by Hendrickx et al. (2002a). An overview of the basic theories and principles is presented herein.

2.1. Theory of the EC_a measurement

Apparent soil electrical conductivity measurements were first used in the mid-1900s in geophysical logging. This resulted in the well-known Archie's empirical law for saturated rocks and sand soils:

$$\mathrm{EC_a} = a\sigma_\mathrm{w}\phi^m \tag{1}$$

where a is an empirical constant, σ_w is the electrical conductivity of the porous media solution ($\mathrm{dS^{-1}}$), φ the porosity ($\mathrm{m^3\,m^{-3}}$), and m the cementation exponent (Archie, 1942).

Three pathways of current flow contribute to the $\mathrm{EC_a}$ of a soil: (i) a liquid phase pathway via dissolved solids contained in the soil water occupying the large pores, (ii) a solid–liquid phase pathway primarily via exchangeable cations associated with clay minerals, and (iii) a solid pathway via soil particles that are in direct and continuous contact with one another (Rhoades et al., 1999a). These three pathways of current flow are illustrated in (Fig. 1). Rhoades et al. (1989) formulated an electrical conductance model that describes the three conductance pathways of $\mathrm{EC_a}$:

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

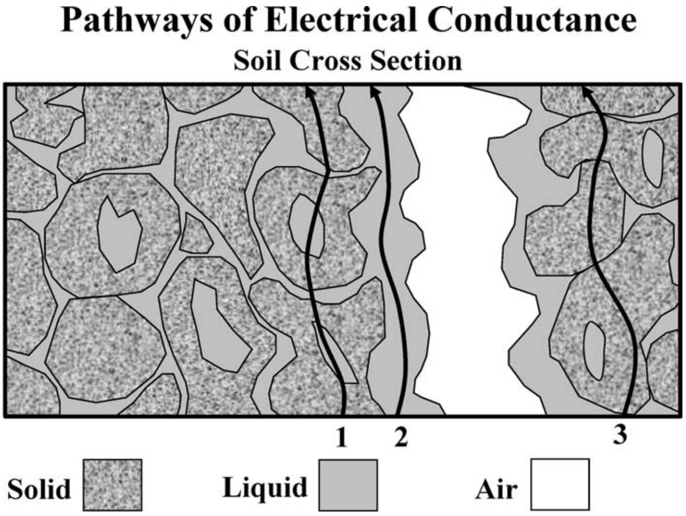

Fig. 1. Three conductance pathways for the $\mathrm{EC_a}$ measurement. Modified from Rhoades et al. (1989).

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the soil–water pathway ($cm^3\,cm^{-3}$) and in the continuous-liquid pathway ($cm^3\,cm^{-3}$), respectively; θ_{ss} and θ_{sc} are the volumetric contents of the surface-conductance ($cm^3\,cm^{-3}$) and indurated solid phases of the soil ($cm^3\,cm^{-3}$), respectively; EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil–water pathway ($dS\,m^{-1}$) and continuous-liquid pathway ($dS\,m^{-1}$); and EC_{ss} and EC_{sc} are the electrical conductivities of the surface-conductance ($dS\,m^{-1}$) and indurated solid phases ($dS\,m^{-1}$), respectively. Eq. (2) was reformulated by Rhoades et al. (1989) into Eq. (3):

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

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

$$\theta_w = \frac{P_W \rho_b}{100} \tag{4}$$

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

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

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

$$EC_W = \left[\frac{EC_e \rho_b S_P}{100\theta_w}\right] \tag{8}$$

where P_W is the per cent water on a gravimetric basis, ρ_b is the bulk density ($mg\,m^{-3}$), S_P 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 is the electrical conductivity of the saturation extract ($dS\,m^{-1}$).

The reliability of Eqs. (3)–(8) has been evaluated by Corwin and Lesch (2003). These equations are reliable except under extremely dry soil conditions. However, Lesch and Corwin (2003) developed a means of extending equations for extremely dry soil conditions by dynamically adjusting the assumed water content function. By measuring EC_a, SP, PW, and ρ_b, and using Eqs. (3)–(8), the EC_e can be estimated. The determination of EC_e is of agricultural importance because traditionally EC_e has been the standard measure of soil salinity used in all salt-tolerance plant studies. Alternatively, EC_a can be estimated by knowing EC_e, SP, PW, and ρ_b. Furthermore, the sensitivity of EC_a can be easily established over the range of values for EC_e, SP, PW, and ρ_b occurring within a field.

2.2. *Factors influencing EC_a*

Because of the three pathways of conductance, the EC_a measurement is influenced by several soil physical and chemical properties: (1) soil salinity, (2) saturation percentage, (3) water content, and (4) bulk density. The quantitative influence of each factor is reflected in Eqs. (3)–(8). The SP and ρ_b are both directly influenced by clay content and organic matter (OM). Furthermore, the exchange surfaces on clays and OM provide a solid–liquid phase pathway primarily via exchangeable cations; consequently, clay content and type, cation exchange capacity (CEC), and OM are recognized as additional factors influencing EC_a measurements. Measurements of EC_a *must* be interpreted with these influencing factors in mind.

Another factor influencing EC_a is temperature. Electrolytic conductivity increases at a rate of approximately 1.9% per °C increase in temperature. Customarily, EC is expressed at a reference temperature of 25 °C for purposes of comparison. The EC (i.e., EC_a, EC_e, or EC_w) measured at a particular temperature, t (in °C), EC_t, can be adjusted to a reference EC at 25 °C, EC_{25}, using the below equations from Handbook 60 (U.S. Salinity Laboratory Staff, 1954):

$$EC_{25} = f_t EC_t \tag{9}$$

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

$$f_t = 0.4470 + 1.4034\,\mathrm{e}^{-t/26.815} \tag{10}$$

3. Apparent soil electrical conductivity in agriculture

3.1. *Original application of the EC_a measurement in agriculture*

The first application of EC_a in agriculture was for the measurement of soil salinity. Research in this area was primarily conducted by Rhoades and colleagues in the 1970's at the USDA-ARS Salinity Laboratory in Riverside, CA. Soil salinity refers to the presence of major dissolved inorganic solutes in the soil aqueous phase, which consist of soluble and readily dissolvable salts including charged species (e.g., Na^+, K^+, Mg^{+2}, Ca^{+2}, Cl^-, $HCO_3{}^-$, $NO_3{}^-$, $SO_4{}^{-2}$ and $CO_3{}^{-2}$), non-ionic solutes, and ions that combine to form ion pairs. 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. Effects of soil salinity are manifested in loss of stand, reduced plant growth, reduced yields, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential making it more difficult for the plant to extract water. Salinity may also cause specific-ion toxicity or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth.

3.2. Measurement of soil salinity

Historically, five methods have been developed for determining soil salinity at field scales: (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 resistivity (ER), (iv) non-invasive measurement of electrical conductance with electromagnetic induction (EM), and most recently (v) in situ measurement of electrical conductance with time domain reflectometry (TDR).

3.2.1. Visual crop observation

Visual crop observation is a quick and economical method, but it has the disadvantage that salinity development is detected after crop damage has occurred. For obvious reasons, the least desirable method is visual observation because crop yields are reduced to obtain soil salinity information. However, remote imagery is increasingly becoming a part of agriculture and potentially represents a quantitative approach to visual observation that may offer a potential for early detection of the onset of salinity damage to plants.

3.2.2. Electrical conductivity of soil solution extracts

The determination of salinity through the measurement of electrical conductance has been well established for decades (U.S. Salinity Laboratory Staff, 1954). It is known that the electrical conductivity of water is a function of its chemical composition. McNeal et al. (1970) were among the first to establish the relationship between electrical conductivity and molar concentrations of ions in the soil solution. Soil salinity is quantified in terms of the total concentration of the soluble salts as measured by the electrical conductivity (EC) of the solution in $\mathrm{dS\,m^{-1}}$. To determine EC, the soil solution is placed between two electrodes of constant geometry and distance of separation (Bohn et al., 1979). At constant potential the current is inversely proportional to the solution's resistance. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. The electrical conductance is a reciprocal of the resistance [Eq. (11)]:

$$\mathrm{EC}_t = \frac{k}{R_t} \tag{11}$$

where EC_t is the electrical conductivity of the solution in $\mathrm{dS\,m^{-1}}$ at temperature t (°C), k the cell constant, and R_t the measured resistance at temperature t.

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

Soil salinity can also be determined from the measurement of the EC of a soil solution ($\mathrm{EC_w}$). Theoretically, $\mathrm{EC_w}$ is the best index of soil salinity because this is the salinity actually experienced by the plant root. Nevertheless, EC_w has not been widely used to express soil salinity for various reasons: (i) it varies over the irrigation cycle as the soil water content changes and (ii) methods for obtaining soil solution samples are too labor, and cost intensive at typical field water contents to be practical for field-scale applications (Rhoades et al., 1999a). For disturbed samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum- or pressure-extraction methods. For undisturbed samples, EC_w can be determined either in the laboratory on a soil solution sample collected with a soil solution extractor or directly in the field using in situ, imbibing-type porous matrix salinity sensors.

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). Because of their small sphere of measurement, neither extractors nor salt sensors adequately integrate spatial variability (Amoozegar-Fard 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 qualitative measurement of soil solutions, but not quantitative measurements unless the field-scale variability is established. Furthermore, salinity sensors demonstrate a response time lag that is dependent upon the diffusion of ions between the soil solution and solution in the porous ceramic, which is affected by (i) the thickness of the ceramic conductivity cell, (ii) the diffusion coefficients in soil and ceramic, and (iii) the fraction of the ceramic surface in contact with soil (Wesseling and Oster, 1973). The salinity sensor is generally considered the least desirable method for measuring EC_w because of its low sample volume, unstable calibration over time, and slow response time (Corwin, 2002).

3.2.3. *Electrical resistivity*

Developments in the measurement of soil EC to determine soil salinity shifted to the measurement of EC_a because of the time and cost of obtaining soil solution extracts and the high local-scale variability associated with small volume soil core samples. The techniques of ER, EM, and TDR measure EC_a.

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 (Fig. 2). These methods were developed in the second decade of the 1900s by Conrad Schlumberger in France and

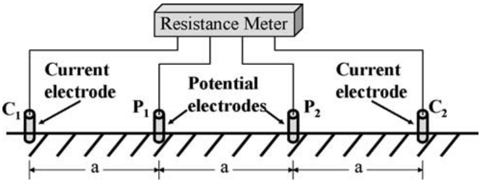

Fig. 2. Schematic showing the electrical resistivity method with an array of four electrodes: two current electrodes (C_1 and C_2) and two potential electrodes (P_1 and P_2). Modified from Rhoades and Halvorson (1977). When electrodes are equally spaced at distance *a*, as shown, the electrode array is called a Wenner array.

Frank Wenner in the United States for the evaluation of ground ER (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 (see Fig. 2; Corwin and Hendrickx, 2002). The depth of penetration of the electrical current and the volume of measurement increase as the inter-electrode spacing, a, increases. For a homogeneous soil, the soil volume measured is roughly πa^3. There are additional electrode configurations that are frequently used, as discussed by Dobrin (1960), Telford et al. (1990), and Burger (1992).

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 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 non-invasive EM measurement. Nevertheless, 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. Furthermore, the $\mathrm{EC_a}$ measurement with ER is linear over depth unlike EM measurements of $\mathrm{EC_a}$, which are a function of a depth-weighted response function. This allows the $\mathrm{EC_a}$ for a discrete depth interval of soil to be easily calculated with a Wenner array by measuring the $\mathrm{EC_a}$ of successive layers for increasing inter-electrode spacings and using the following equation (Barnes, 1952):

$$\mathrm{EC_x} = \mathrm{EC_{a_i}} - \mathrm{EC_{a_{i-1}}} = \left(\frac{\mathrm{EC_{a_i}} a_i - \mathrm{EC_{a_i}} a_{i-1}}{a_i - a_{i-1}} \right) \tag{12}$$

where a_i is the inter-electrode spacing, which equals the depth of sampling, a_{i-1} is the previous inter-electrode spacing, which equals the depth of previous sampling, and $\mathrm{EC_x}$ is the apparent soil electrical conductivity for a specific depth interval. Electromagnetic induction can also measure $\mathrm{EC_a}$ at variable depths determined by the height of the EM instrument above the soil surface, but the depth of penetration is not as easily determined as for ER. Unlike ER, depth profiling of $\mathrm{EC_a}$ with EM is mathematically complex (Borchers et al., 1997; McBratney et al., 2000; Hendrickx et al., 2002b). Measurements of $\mathrm{EC_a}$ at variable depths with EM are usually achieved by positioning the EM instrument at the soil surface in the vertical ($\mathrm{EM_v}$) or horizontal ($\mathrm{EM_h}$) dipole mode, which measures to depths of 0.75 and 1.5 m, respectively.

3.2.4. Electromagnetic induction

A transmitter coil located at one end of the EM instrument induces circular eddy-current loops in the soil with the magnitude of these loops directly proportional to the electrical conductivity 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 soil electrical conductivity, $\mathrm{EC_a}$. The amplitude and phase of the secondary field will differ from those of the primary field as a result of soil

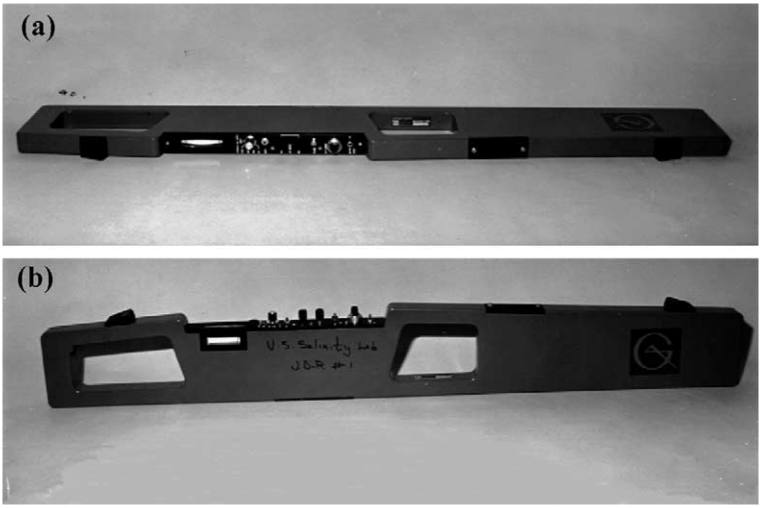

Fig. 3. Handheld Geonics EM-38 electromagnetic soil conductivity meter (a) lying in the horizontal orientation with its coils parallel to the soil surface and (b) lying in the vertical orientation with its coils perpendicular to the soil surface (bottom). Taken from Corwin and Lesch (2003).

properties (e.g., clay content, water content, salinity), spacing of the coils and their orientation, frequency, and distance from the soil surface (Hendrickx and Kachanoski, 2002).

The application of EM measurements of EC_a in soil science first appeared in late 1970's and early 1980's in efforts to measure soil salinity (de Jong et al., 1979; Rhoades and Corwin, 1981; Corwin and Rhoades, 1982; Williams and Baker, 1982). Many of the early efforts concentrated on attempts to measure soil salinity profiles with a series of above-ground EM measurements (Rhoades and Corwin, 1981; Corwin and Rhoades, 1982, 1984, 1990; Slavich, 1990; Cook and Walker, 1992). The two most commonly used EM conductivity meters in soil science and in vadose zone hydrology are the Geonics[i] EM-31 and EM-38. The EM-38 (Fig. 3) has had considerably greater application for agricultural purposes because the depth of measurement corresponds roughly to the root zone (i.e., 1.5 m), when the instrument is placed in the vertical coil configuration. In the horizontal coil configuration, the depth of the measurement is 0.75–1.0 m. The operation of the EM-38 equipment is discussed by McNeill (1980, 1986) and Hendrickx and Kachanoski (2002). The depth of measurement of the EM-31 is approximately 6 m.

3.2.5. Time domain reflectometry

Noborio (2001) provides a timely review of time domain reflectometry (TDR) with a thorough discussion of the theory for the measurement of soil water content (θ) and EC_a; probe configuration, construction, and installation; strengths and limitations. In addition, Wraith (2002) provides an excellent overview of the principles, equipment, procedures, range and precision of measurement, and calibration of TDR.

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[i] Geonics Limited, Mississauga, Ontario, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

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

By measuring ε, θ can be determined through calibration (Dalton, 1992). The ε is calculated with Eq. (13) from Topp et al. (1980),

$$\varepsilon = \left(\frac{ct}{2l}\right)^2 = \left(\frac{l_a}{l v_p}\right)^2 \tag{13}$$

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

By measuring the resistive load impedance across the probe (Z_L), EC_a can be calculated with Eq. (14) from Giese and Tiemann (1975),

$$EC_a = \frac{\varepsilon_0 c}{l}\frac{Z_0}{Z_L} \tag{14}$$

where ε_0 is the permittivity of free space ($8.854 \times 10^{-12}\,\mathrm{F\,m^{-1}}$), Z_0 the probe impedance (Ω), and $Z_L = Z_u[2V_0/V_f - 1]^{-1}$ where Z_u is the characteristic impedance of the cable tester, V_0 the voltage of the pulse generator or zero-reference voltage, and V_f is the final reflected voltage at a very long time. To reference EC_a to 25 °C, Eq. (15) is used:

$$EC_a = K_c f_t {Z_L}^{-1} \tag{15}$$

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

Advantages of TDR for measuring EC_a include (i) a relatively non-invasive nature, (ii) an ability to measure both θ 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) a lack of a calibration requirement for soil water content measurements in many cases (Wraith, 2002). However, because TDR is a stationary instrument where measurements are taken from point-to-point thereby preventing it from mapping at the spatial resolution of ER and EM approaches, it is currently impractical for developing detailed geo-referenced EC_a maps for large areas.

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, and fast enough for the general needs of field-scale soil salinity assessment (Rhoades et al., 1999a). Currently, the use of TDR for field-scale spatial characterization of θ and EC_a distributions are largely limited. Only ER and EM have been widely adapted for detailed spatial surveys consisting of intensive geo-referenced measurements of EC_a at field scales and larger (Rhoades et al., 1999a, 1999b).

3.3. Relationship between EC_a and EC_e

Because EC_e has been the standard measure of salinity used in all salt-tolerance plant studies, a relation between EC_a and EC_e is needed to relate EC_a back to EC_e, which is in turn related to crop yield. Over the past decade research has been directed at developing reliable and efficient conversion techniques from EC_a back to EC_e (Wollenhaupt et al., 1986; McKenzie et al., 1989; Rhoades et al., 1989, 1990, 1991, 1999b; Rhoades and Corwin, 1990; Slavich and Petterson, 1990; Lesch et al., 1992, 1995a, 1995b, 1998; LopezBruna and Herrero, 1996; Rhoades, 1996; Mankin and Karthikeyan, 2002). In the case of converting EC_a measured with EM back to EC_e, most investigators have used non-linear transformations of EM EC_a readings to decrease the errors of the estimates (LopezBruna and Herrero, 1996). However, LopezBruna and Herrero (1996) showed that linear methods of calibration are sufficiently accurate for soil salinity surveys.

3.4. Measurement of other soil physico-chemical properties with EC_a

Measured EC_a is the product of both static and dynamic factors, which include soil salinity, clay content and mineralogy, θ, ρ_b, and temperature. Johnson et al. (2003a) astutely described the observed dynamics of the general interaction of these factors. In general, the magnitude and spatial heterogeneity of EC_a in a field are dominated by one or two of these factors, which will vary from one field to the next making the interpretation of EC_a measurements highly site-specific. In instances where dynamic soil properties (e.g., salinity) dominate the EC_a measurement, temporal changes in spatial patterns exhibit more fluidity than systems that are dominated by static factors (e.g., texture). In texture-driven systems, spatial patterns remain consistent because variations in dynamic soil properties affect only the magnitude of measured EC_a (Johnson et al., 2003a). For this reason, Johnson et al. (2003a) warn that EC_a maps of static-driven systems convey very different information from those of less stable dynamic-driven systems. Furthermore, the application of manure and commercial fertilizer can influence EC_a to the point where texture-dominated systems can be transformed into salt-dominated systems (Johnson et al., 2003a). Although it has not been experimentally evaluated, texture-driven systems will likely be more temporally stable than salinity-driven systems. This has ramifications concerning the delineation of site-specific management units (SSMU) and the frequency with which SSMUs must be redefined.

Numerous EC_a field studies have been conducted that have revealed the site specificity and complexity of spatial EC_a measurements with respect to the particular property influencing the EC_a measurement at that study site. Table 1 is a compilation of various field studies and the associated dominant soil property measured.

3.5. Mobilized EC_a measurement equipment

The EC_a measurement is particularly well suited for establishing within-field spatial variability of soil properties because it is a quick, easy, and reliable measurement that integrates within its measurement the influence of several soil properties that contribute to the electrical conductance of the bulk soil. The EC_a measurement serves as a means of defining spatial patterns that indicate differences in electrical conductance due to the combined con-

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

Soil property	Ref.
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, 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. (1999b), Rhoades et al. (1999b)
Groundwater recharge	Cook and Kilty (1992), Cook et al. (1992), Salama et al. (1994)
Herbicide partition coefficients	Jaynes et al. (1995b)
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)

ductance influences of salinity, water content, texture, and ρ_b. The development of mobile EC_a measurement equipment (McNeill, 1992; Carter et al., 1993; Rhoades, 1993; Jaynes et al., 1993; Cannon et al., 1994; Kitchen et al., 1996; Freeland et al., 2002) has made it possible to produce EC_a maps with measurements taken every few meters.

Mobile EC_a measurement equipment has been developed for both ER and EM geophysical approaches. In the case of ER, by mounting the electrodes to “fix” their spacing,

Fig. 4. Mobile ER equipment developed (a) by Rhoades (1992, 1993) and Carter et al. (1993) and (b) Veris Technologies' commercial equipment.

considerable time for a measurement is saved. A tractor-mounted version of the "fixed-electrode array" has been developed that geo-references the EC_a measurement with a GPS (see Fig. 4a; Carter et al., 1993; Rhoades, 1992, 1993). Veris Technologies[iii] has developed a commercial mobile system for measuring EC_a using the principles of ER (Fig. 4b). In the case of EM, an EM-38 unit has been mounted in a cylindrical non-metallic housing in the front of a mobile spray rig that has adequate clearance to traverse fields with a crop cover (Carter et al., 1993; Rhoades, 1992, 1993). The housing can be raised and lowered to take measurements at the soil surface or at various heights above the soil or to lock into a travel position to go from one measurement site to the next. The housing can also be rotated 90° to take EM_h and EM_v readings at each measurement site. Recently, the

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[iii] Veris Technologies, Salinas, Kansas, USA (www.veristech.com). Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

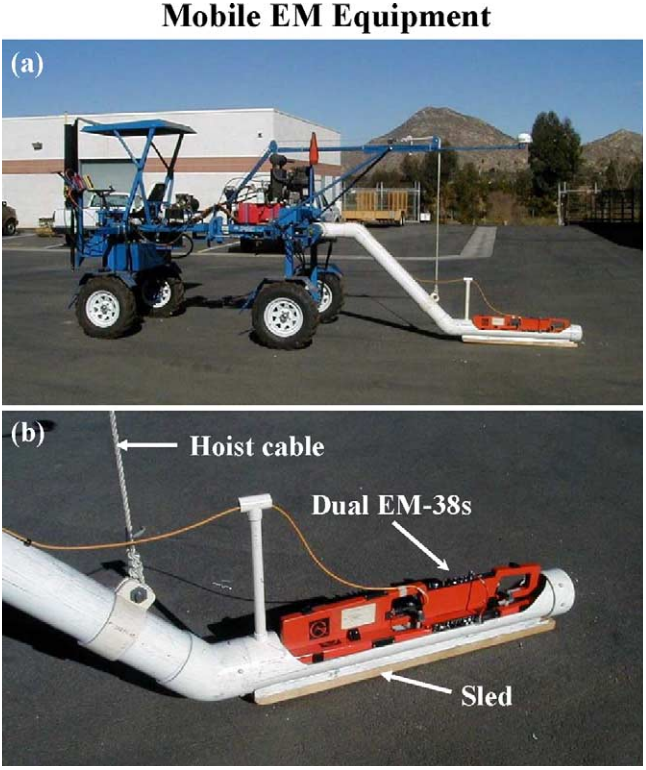

Fig. 5. Mobile dual-dipole EM equipment: (a) complete mobile rig and (b) close-up of sled holding the Geonics dual-dipole EM-38 soil conductivity meter.

mobile EM equipment developed at the Salinity Laboratory was modified by the addition of a dual-dipole EM-38 unit (Fig. 5) in place of the single EM-38 unit. The dual-dipole EM-38 unit permits continuous, simultaneous EC_a measurements in both the horizontal (EM_h) and vertical (EM_v) dipole configurations at time intervals of just a few seconds between readings. Other less costly mobile EM equipment has been developed that carry the EM-38 unit on a non-metallic cart or sled pulled by an all-terrain vehicle or tractor (Jaynes et al., 1993; Cannon et al., 1994; Kitchen et al., 1996; Freeland et al., 2002). These sleds or carts allow continuous EC_a measurements, but in only one dipole position. No commercial mobile system has been developed with EM. The mobile "fixed-electrode array" ER and EM equipment are both well suited for collecting detailed maps of the spatial variability of average root zone soil electrical conductivity at field scales and larger.

4. Applications of EC_a measurements in precision agriculture

Efficient methods for accurately measuring within-field variations in soil physical and chemical properties are a crucial element of precision agriculture (Bullock and Bullock, 2000). The ability to delineate geo-referenced areas within a field that display similar behavior with respect to crop yield potential, referred to as site-specific management units (SSMUs), is difficult due to the complex combination of edaphic, anthropogenic, biological, and meteorological factors that affect crop yield. Four basic approaches have been used to delineate soil management zones for site-specific management including the use of (i) county soil surveys (Robert, 1989), (ii) geostatistical interpolation techniques to estimate the spatial distribution of soil properties from measured data (Mulla, 1991; Corwin et al., 2003b), (iii) yield maps (Eliason et al., 1995; Stafford et al., 1999), and (iv) EC_a or other remote sensing approaches and landscape features, if needed, with soil-landscape models to estimate patterns of soil variability (Bell et al., 1995; Tomer et al., 1995; McCann et al., 1996; Sudduth et al., 1997a; Fleming et al., 1999; Lund et al., 1999; Kravchenko et al., 2000; Johnson et al., 2003b; Corwin et al., 2003b).

Fraisse et al. (2001) point out that the first two approaches for delineating SSMUs suffer from significant limitations. Traditional soil surveys provide only a general understanding of the soil variation influencing crop productivity and are not sufficiently detailed to provide information for within-field recommendations. Geostatistical interpolations require large numbers of soil samples to accurately represent the variability of soil properties, making this approach prohibitively expensive. Long (1998) indicates that yield maps provide the basis for implementing site-specific management by indicating where varying cropping inputs are needed based on spatial patterns of crop productivity, but the cropping inputs necessary to optimize productivity and minimize environmental impacts can be derived only if it is known what factors gave rise to the observed spatial crop patterns. Yield maps alone do not provide this information nor do they by themselves provide the information necessary to differentiate edaphic, anthropogenic, biological, and meteorological factors influencing crop yield and spatial crop patterns. Furthermore, yield-monitoring has not been developed for all crops. In contrast, EC_a measurements can obtain detailed spatial information rapidly and cheaply about soil-related and anthropogenic properties influencing crop yield and spatial crop patterns (Rhoades et al., 1999b; Corwin et al., 2003b). EC_a measurements also provide a viable alternative when yield-monitoring data are not available (Corwin et al., 2003b). Even though ground-truth soil sampling is needed in conjunction with EC_a measurements, EC_a-directed soil sampling can reduce the number of samples to the minimum necessary to describe the variability (Lesch et al., 2000; Corwin and Lesch, 2003; Corwin et al., 2003a; Lesch, 2005).

Soil EC_a has become one of the most reliable and frequently used measurements to characterize field variability for application to precision agriculture due to its ease of measurement and reliability (Rhoades et al., 1999a, 1999b; Corwin and Lesch, 2003). The potential of the spatial measurement of EC_a for predicting crop yield due to soil water differences has been reported by Jaynes et al. (1995a) and Sudduth et al. (1995). It has been previously shown by Kitchen et al. (1999) using boundary line analysis that soil EC_a provides a measure of the within-field soil differences associated with topsoil thickness, which for claypan soils is a measure of root zone suitability for crop growth and yield. Spatial measurements of EC_a can be used as an indicator of yield potential (Jaynes et al., 1993; Sudduth et al., 1995; Kitchen et al., 1999; Johnson et al., 2001; Corwin et al., 2003b). Johnson et al. (2001) classified fields into zones of different production potentials by separating EC_a maps into ranges of EC_a. Corwin et al. (2003b) used spatial EC_a measurements to direct soil sampling with a response surface sample design (Lesch et al., 1995a, 1995b, 2000), which permitted the delineation of SSMUs based on edaphic and anthropogenic properties influencing crop yield. This approach identified areas of soil that could be managed similarly and provided site-specific recommendations to optimize yield.

Landscape position and topographic features are also readily available or easily obtained. Several studies using landscape position and topographic features have shown productivity levels associated with water availability. In general, footslope positions tend to out produce upslope positions, except in areas of poor drainage (Jones et al., 1989; Mulla et al., 1992; Jaynes et al., 1995a; Sudduth et al., 1997b).

Precision agriculture studies relating crop yield directly to EC_a have met with inconsistent results due to the complex interaction of the soil properties that influence the EC_a measurement and the complex interaction of biological, anthropogenic, and meteorological factors that influence yield beyond soil-related factors, thereby confounding results (Corwin and Lesch, 2003). In instances where yield correlates with EC_a, spatial measurements of EC_a can be used in a site-specific crop management context (Corwin and Lesch, 2003). However, it is necessary to establish the soil properties that most significantly influence the EC_a measurements within a field in order to establish the soil properties that are influencing yield. EC_a measurements need ground-truth soil samples to interpret what the EC_a measurements mean at a specific site. Maps of EC_a are used to establish a soil sample design. The physical and chemical analysis of the soil samples potentially provides the spatial information for determining the soil properties that influence crop yield causing within-field yield variation. Corwin and Lesch (2003) suggest two approaches for determining the predominant factors influencing spatial EC_a measurements: (i) simple statistical correlation and (ii) wavelet analysis. Wavelet analysis has been successfully used by Lark et al. (2003) in the analysis of spatial EC_a measurements. Because wavelet analysis is restricted to a regular grid or equal-spaced transect, simple statistical correlations applied to soil samples located with the stochastic statistical sampling design developed by Lesch et al. (1995a, 1995b, 2000) are generally more practical.

Using EC_a maps to direct soil sampling, Johnson et al. (2001) and Corwin et al. (2003a) spatially characterized the overall soil quality of physico-chemical properties thought to affect yield potential. To characterize the soil quality, Johnson et al. (2001) used a stratified soil sampling design with allocation into four geo-referenced EC_a ranges. Correlations were performed between EC_a and the minimum data set of physical, chemical, and biological soil attributes proposed by Doran and Parkin (1996). Their results showed a positive correlation of EC_a with percentage clay, ρ_b, pH, and $EC_{1:1}$ over a soil depth of 0–30 cm, and a negative correlation with soil moisture, total and particulate organic matter, total C and N, microbial biomass C, and microbial biomass N. No relationship of the soil properties to crop yield was determined. Corwin et al. (2003a) characterized the soil quality of a saline-sodic soil using a response surface soil sample design. A positive correlation was found between EC_a and the properties of volumetric water content; EC_e; Cl^-, NO_3^-, SO_4^-, Na^+, K^+, and Mg^{+2} in the saturation extract; SAR; ESP; B; Se; Mo; $CaCO_3$; inorganic and organic C. Most of these properties are associated with soil quality for arid-zone soils. A number of soil properties (i.e., ρ_b; percentage clay; pH_e; SP; HCO_3^- and Ca^{+2} in the saturation extract; exchangeable Na^+, K^+, and Mg^{+2}; As; CEC; gypsum; total N) did not correlate well with EC_a measurements. Neither Johnson et al. (2001) nor Corwin et al. (2003a) actually

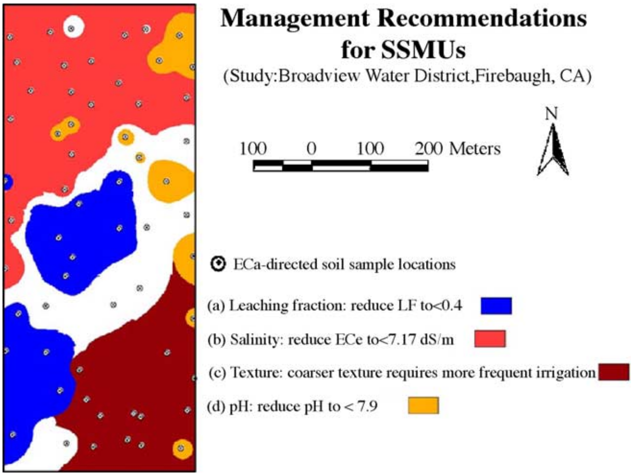

Fig. 6. Site-specific management units for a 32.4 ha cotton field in the Broadview Water District of central California's San Joaquin Valley. Recommendations are associated with the SSMUs for (a) leaching fraction, (b) salinity, (c) texture, and (d) pH.

related the spatial variation in the measured soil physico-chemical properties to crop yield variations.

Corwin et al. (2003b) carried the EC_a-directed soil sampling approach to the next level by integrating crop yield into the approach. Through spatial statistical analysis Corwin et al. (2003b) were able to identify those edaphic and anthropogenic properties influencing the spatial variation of cotton yield on a 32.4 ha field. From this, management recommendations were made that spatially prescribed what could be done to increase cotton yield at those locations with less than optimal yield (Fig. 6). Fig. 6a indicates highly leached zones where the leaching fraction (LF) needs to be reduced to ≤ 0.5. This can be achieved by shortening the lengths of the flood irrigation runs or resorting to sprinkler instead of flood irrigation, which will reduce the high leaching that occurred near irrigation water sources at mid-field and at the southern end. Fig. 6b delineates high salinity areas where the salinity needs to be reduced below the salinity threshold for cotton, which was established at $EC_e = 7.17\,dS^{-1}$ for this field. The salinity levels can also be reduced by shorter flood irrigation runs or using sprinkler irrigation. To maintain optimal available water content distribution, Fig. 6c indicates areas of coarse texture that need more frequent irrigations and areas of fine texture that need less frequent irrigations. Fig. 6d indicates areas where the pH needs to be lowered below a pH of 8 with a soil amendment such as OM. This work brought an added dimension because it delineated within-field units where associated site-specific management recommendations would optimize the yield, but it still fell short of integrating meteorologic, economic, and environmental impact ramifications.

An aspect of precision agriculture that is of critical importance is the mitigation of detrimental environmental impacts through site-specific management practices. The ability to assess, both in real-time and in a prognostic mode, the spatial distribution and fate of a non-point source (NPS) pollutant (e.g., salinity, fertilizers, pesticides, and trace elements) is a key concern in maintaining the delicate balance between crop productivity and the detrimental environmental impacts of NPS pollutants (Corwin et al., 1999a). The majority of studies investigating the reduction in NPS pollution loads to soil and water resources by the implementation of site-specific management practices have been for NO_3-N and pesticide loads in runoff. Much less research has been conducted to evaluate the mitigation of groundwater loads by site-specific management practices, particularly at field scales.

It is through real-time measurements that a continued inventory of a NPS pollutant can determine the extent of the problem and 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 groundwater or drainage tile systems. As demonstrated by Corwin et al. (1999b), Corwin and Lesch (2003), and Corwin et al. (2003a), EC_a measurements have an unquestionable role to play in this evaluation through their capacity to monitor spatio-temporal changes in dynamic soil properties (e.g., salinity) and to define 'stream-tubes', which are valuable in landscape-scale modeling of NPS pollutants in the vadose zone.

Over the past decade, numerous landscape-scale models of NPS pollutants have been developed as indicated in the reviews by Corwin (1996) and Corwin et al. (1997). The preponderance of these models rely on existing databases (e.g., NATSGO, STATSGO, SSURGO) or on estimated data from transfer functions to derive their spatial input data and parameters. Few rely on measured spatial data. The unique aspect of the Corwin et al. (1999b) approach to landscape-scale modeling of a NPS pollutant 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 (1992, 1993). Stream-tubes are non-interactive volumes of soil whose physicochemical properties influencing solute transport are relatively homogenous so that solute transport within the column of soil defined by the stream-tube can be simulated with a 1D 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 use in the modeling of salinity transport through the vadose zone. 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., $\sqrt{[EM_h EM_v]}$), 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 to EM_v ratios exist. These points serve as the centroids of the Thiessen polygons delineating the stream-tubes throughout the area of study. The ratio of EM_h to EM_v is an approximation of the LF and reflective of the soil's hydraulic properties. It is well-documented that the LF is equal to the salinity of the irrigation water divided by the salinity of the drainage water (U.S. Salinity Laboratory Staff, 1954). Within the soil profile an estimate of the LF can be obtained from the salinity at the soil surface divided by the salinity at the bottom of the root zone. Since the EM-38 measures at shallow (EM_h) and deep (EM_v) depths, then the LF is approximated on a relative basis from point to point within a field by EM_h/EM_v. The geometric mean of EM_h and EM_v is a rough measure of the salinity level since an average of the root zone salinity is being determined using the shallow and deep EM measurements. The geometric mean of EM_h and EM_v is reflective of the soil's water soluble chemistry.

5. Guidelines for conducting a field-scale EC_a survey

Geo-referenced measurements of EC_a are potentially useful for determining the spatial distribution of those soil properties influencing EC_a at that particular location. 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 with crop yield, then an EC_a-directed soil sampling approach can be used to identify what soil properties are causing the variability in crop yield (Corwin et al., 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 can be found in Corwin and Lesch (2005a). General guidelines can be gleaned from Corwin and Lesch (2003) and Corwin et al. (2003a, 2003b).

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 for application to site-specific crop management include (i) 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 sample-determined salinity as determined by the electrical conductivity of the saturation extract (EC_e), (vii) spatial statistical analysis, (viii) determination of the dominant soil properties influencing the EC_a measurement at the site of interest, and (ix) GIS development. The basic steps of an EC_a survey include:

(a) define the project's/survey's objective
(b) establish site boundaries
(c) record site metadata
(d) select GPS coordinate system
(e) establish EC_a measurement intensity
(f) geo-reference site boundaries and significant physical geographic features with GPS
(g) measure EC_a (with sporadic measurements of soil temperature at selected depth increments) at the pre-determined spatial intensity and record associated metadata
(h) statistically analyze EC_a data using an appropriate statistical sampling design to establish the soil sample site locations

(i) establish site locations, sample depth increments, number of sites with duplicates or replicates, and associated metadata
(j) analyze the physico-chemical properties of interest as defined by the project's objective
(k) perform a basic statistical analysis of physico-chemical data by depth and by composite depth to establish depth of concern
(l) conduct an exploratory statistical analysis to determine significant physico-chemical properties influencing parameter of concern (e.g., crop yield, crop quality)
(m) formulate a spatial linear regression (SLR) model that relates soil properties (independent variables) to crop yield or crop quality (dependent variable)
(n) adjust this model for spatial auto-correlation, if necessary, using restricted maximum likelihood or some other technique
(o) conduct a sensitivity analysis to establish dominant soil property(ies) influencing yield or quality
(p) create maps of spatial distribution of soil properties

The issue of accuracy in EM measurements of EC_a for precision agriculture is cogently presented by Sudduth et al. (2001). The authors point out that 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 a calibration transect would be periodically taken to adjust for the drift in post-processing of EC_a data. Positional offset can 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.

Even though surveys of EC_a are a quick, easy, reliable, and cost-effective means of characterizing spatial variability of a variety of physico-chemical properties, there are major limitations. Measurements of EC_a by themselves do not directly characterize spatial variability. Actually, EC_a measurements provide limited direct information about the physico-chemical properties that influence yield, effect solute transport, or determine soil quality. Rather, EC_a-survey measurements provide the spatial information necessary to direct soil sampling. It is as a cost-effective tool for directing soil sampling that EC_a-survey measurements are invaluable for characterizing spatial variability. Furthermore, EC_a-directed soil sampling can only spatially characterize soil properties that correlate with and are measured by EC_a.

Apparent soil electrical conductivity is a complex measurement that requires knowledge and experience to interpret. Ground-truth soil samples are obligatory to be able to understand and interpret spatial measurements of EC_a. Without ground-truth soil samples an EC_a survey will be of minimal value. Spatial measurements of EC_a do not supplant the need for soil sampling, but they do minimize the number necessary to characterize spatial variability. Users of EC_a-survey data must exercise caution and be aware of what EC_a is actually measuring at the site of interest.

6. Future needed developments and current trends in the application of EC_a to precision agriculture

Future developments that are needed to better focus current research in the application of EC_a to precision agriculture include protocols and guidelines for (i) conducting an EC_a survey and (ii) delineating SSMUs. There are many previous examples of EC_a surveys applied to precision agriculture or to soil spatial variability characterizations that have been misused, misunderstood, and/or misinterpreted. For this reason, a recent USDA-ARS Precision Agriculture Workshop (Kansas City, MO; 25–27 March 2003) recommended the development of ARS EC_a survey protocols and standard operating procedures. This recommendation prompted the papers by Corwin and Lesch (2005a, 2005b), which provide detailed guidelines for conducting an EC_a survey and interpreting survey results, respectively. Although considerable research has been undertaken and published concerning SSMUs, there is still no accepted protocol or guideline for establishing SSMUs. Obviously, one approach that has received considerable attention is that of developing SSMUs with the use of geo-referenced EC_a measurements. However, even though general guidelines have been developed for the application of EC_a to precision agriculture (Corwin and Lesch, 2003, 2005a), there is still no accepted means of delineating SSMUs. Part of the reason for this may be that there is no agreed upon definition of a SSMU.

It remains unknown whether SSMU boundaries are necessarily the same for different intended goals (i.e., optimize agricultural productivity, minimize the use of natural or man-made resources, and/or minimize detrimental environmental impacts) nor is there reason to believe that they should be the same. Furthermore, SSMUs may differ from year to year. If sustainability is the primary agricultural concern, then a goal of precision agriculture must be to optimize crop productivity and the use of limited natural resources, while minimizing detrimental environmental impacts. Concomitantly, the guidelines for the delineation of SSMUs must reflect this ‘umbrella’ goal. This requires that the definition of a SSMU is based on optimizing physical, chemical, and biological responses that balance crop production with resource use and detrimental environmental impacts while identifying management strategies both spatially and temporally that will balance these concerns economically. At this time, no researcher has delineated SSMUs that have holistically encompassed all these objectives.

Current trends can be found to occur in two areas: (i) the interpretation of the complex interrelationship between spatial EC_a measurements, spatial variation in crop yield, and spatial variation in soil properties measured by EC_a that influence the spatial variation in yield based on a theoretical understanding of EC_a and (ii) the integration of soil-related influences on crop yield as assessed by geo-referenced EC_a measurements with additional spatial influences (e.g., meteorological, economic, and biological) to provide a more holistic evaluation of the concept of site-specific crop management.

The past decade has seen a flurry of observational papers where spatial EC_a measurements are related to yield or to soil properties without concern for what properties are actually being measured and whether or not those properties are influencing a crop’s yield. This disconnect has resulted in inconsistent results and a misunderstanding of the relationship between EC_a and yield. Currently, the trend is toward a greater physical understanding of the EC_a measurement and from this understanding an interpretation of its relationship to a crop’s yield at a specific location and point in time. The measurement of EC_a is no longer a 'black box' measurement to statistically relate to crop yield or to some soil property presumably related to yield. Rather, EC_a measurements are now recognized as a surrogate for deriving the spatial variability of soil properties that may or may not influence a crop's yield. For this reason, EC_a measurements are of limited value without ground-truth soil samples to elucidate their meaning. In situations where EC_a is statistically related to yield, ground-truth soil samples provide a means of interpreting the relationship and of ascertaining site-specific management recommendations that will cost effectively optimize yield.

Most published research regarding spatial measurements of EC_a has only appraised one or two factors related to soil quality or crop yield. However, recent work by Johnson et al. (2001) and Corwin et al. (2003a, 2003b) has shown that EC_a measurements can be used to direct soil sampling to evaluate the spatial variation in overall quality of soil physico-chemical properties that affect yield. This new trend provides the added information needed to make site-specific, soil-related management recommendations that have been absent from previous approaches using EC_a measurements.

Recently, Corwin et al. (2003b) delineated SSMUs based on a response-surface ECa-directed soil sampling that identified the edaphic and anthropogenic factors influencing a crop's (i.e., cotton) yield. Nevertheless, economic, meteorologic, and biologic factors were not taken into account and the intent of the SSMUs was strictly to identify zones that could be managed to increase yield with no consideration given to environmental impacts or economic limitations. This has been beyond the scope of past research because of the limitation of funds that would support a completely holistic, multi-disciplinary approach to a problem that must address economical, environmental, and agricultural issues within a single project. The current state of research is that SSMUs are defined on the basis of a specific objective (e.g., agricultural productivity or mitigation of environmental impacts) rather than a combination of interrelated and interacting objectives.

At this time, no single study has been conducted that evaluates site-specific management from a holistic perspective of environmental, crop productivity, and economical impacts. This task remains as a future goal for agronomists, and soil and environmental scientists. Unquestionably, the application of EC_a measurements to precision agriculture will play a crucial role in future holistic evaluations of the concept of precision agriculture as a viable and sustainable means of meeting the world's future demands for food. The spatial measurement of EC_a is a powerful tool that serves (i) to characterize the spatial heterogeneity of several physico-chemical properties, (ii) to identify edaphic and anthropogenic factors that may influence crop yield, and (iii) to provide a viable approach for delineating areas that behave similarly with respect to water flow and solute transport.

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