Protocols and Guidelines for Field-scale Measurement of Soil Salinity Distribution with EC_a-Directed Soil Sampling

Dennis L. Corwin[1] and Scott M. Lesch[2]
[1]USDA-ARS, U.S. Salinity Laboratory, 450 West Big Springs Road, Riverside, CA 92507-4617 USA
Email: Dennis.Corwin@ars.usda.gov
[2]Riverside Public Utilities - Resource Division, 3435 14th St., Riverside, CA 92501 USA

ABSTRACT

Soil salinity is a spatially complex and dynamic property of soil that influences crop yields when the threshold salinity level is exceeded. The mapping and monitoring of soil salinity is necessary for reclamation, crop selection, and site-specific irrigation management of salt-affected soils in the arid and semi-arid agricultural regions of the world. Because of its spatial and temporal heterogeneity, soil salinity is difficult to map and monitor at field scales. There are various methods for characterizing soil salinity variability, but none of these approaches has been as extensively investigated and is as reliable and cost effective as apparent soil electrical conductivity (EC_a) directed soil sampling. Geospatial measurements of EC_a are well-suited for characterizing soil salinity spatial distribution because they are reliable, quick, and easy to take with GPS-based mobilized EC_a measurement equipment. However, EC_a is influenced by a variety of soil properties, which makes the measurement of soil salinity at field scale problematic. It is the goal of this review and analysis paper to provide an overview of the field-scale characterization of soil salinity distribution using EC_a-directed soil sampling. Guidelines, special considerations, protocols, and strengths and limitations are presented for characterizing spatial and temporal variation in soil salinity using EC_a-directed soil sampling. Original data is presented showing the critical importance of conducting EC_a surveys at or near field capacity ($\geq$70% of field capacity). A case study of a 32.4-ha field in San Jacinto, California, is provided as an example to demonstrate the effectiveness of generating soil salinity maps. Land resource managers, farmers, extension specialists, and Natural Resource Conservation Service field staff are the beneficiaries of field-scale maps of soil salinity.

Introduction

Of the 13.2×10^9 ha of land surface on the earth, only 1.5×10^9 ha is cultivated and 23% of the cultivated land is estimated to be salt-affected, which comprises about 10% of the total arable land (Massoud, 1981). Irrigated agriculture, which accounts for 35–40% of the world's total food and fiber, is adversely affected by soil salinity on roughly half of all irrigated soils (totaling about 250 million ha), with over 20 million ha severely affected by salinity worldwide (Rhoades and Loveday, 1990).

The accumulation of soil salinity can result in reduced plant growth, reduced yields, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential, making it more difficult for the plant to extract water. Salinity may also cause specific-ion toxicity (*e.g.,* Na^+ ion toxicity) or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth. Because of the potential detrimental impacts of soil salinity accumulation and its ubiquitous association with irrigated agriculture, salinity is a crucial soil chemical property that is routinely measured and monitored. Without doubt, salinity is a critical agricultural concern for arid and semi-arid soils throughout the world.

Soil salinity is a dynamic property that is spatially and temporally complex in nature. Figure 1 visually indicates the spatially complex salinity patterns that exist at field scale. The dynamic nature of soil salinity makes mapping and monitoring of salinity a difficult challenge. Mapping and monitoring soil salinity at field scale requires a rapid, reliable, easy means of taking geospatial measurements. The use of soil samples to measure salinity at field scales is impractical because

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Figure 1. Aerial view of a typical salt-affected field, showing the complex spatial patterns of salinity.

of the need for hundreds or even thousands of grid samples. The use of soil samples to measure salinity at field scales is only practical when sampling is directed to minimize the number of samples that reflect the range and variability of salinity within the area of study. This can be achieved using easily measured spatial information that is strongly correlated to soil salinity as a means of directing where to take the fewest samples. Two potential sources of correlated spatial information used to direct where soil samples should be taken to measure soil salinity as characterized by the electrical conductivity of the soil saturation extract (EC_e) are: 1) visual crop observations and 2) geospatial measurements of EC_a with mobile electrical resistivity (ER) or electromagnetic induction (EMI) equipment.

Visual crop observation is a quick method, but it has a distinct disadvantage, *i.e.,* salinity development is detected after crop damage has occurred; consequently, crop yield must be sacrificed to locate areas of salinity development. Furthermore, visual crop observations cannot reliably identify low and moderate levels of salinity. For management purposes, an understanding of the spatial distribution of low and moderate salinity levels is just as important as knowing the location of high salinity. In addition, decreases in crop yield are not necessarily the consequence of only salt accumulation. Crops respond to a variety of anthropogenic (*e.g.,* irrigation uniformity, farm equipment traffic), edaphic (*e.g.,* salinity, water content, texture, organic matter), biological (*e.g.,* disease, nematodes), meteorological (*e.g.,* precipitation, humidity, temperature), and topographical (*e.g.,* slope, elevation, microrelief) factors, any of which can cause yield reduction. Because of the variety of factors influencing crop yield and quality, the use of visual crop observations to assess soil salinity is not definitive and can be extremely misleading.

Associated with visual crop observation, but considered a distinct potential approach, is the use of multi- and hyper-spectral imagery. Even though the use of remote imagery has tremendous potential, at this point it is still in its infancy and is restricted to research since protocols have not been developed for general application to mapping and monitoring salinity. The research that has been done in the use of remote imagery to map soil salinity is largely site specific in nature and is not sufficiently developed to have broad application. At present, only the use of geospatial measurements of EC_a can provide reliable, accurate maps of salinity at field scale. Even so, remote imagery will undoubtedly play a future role in mapping salinity, particularly at regional scales. The potential of remote imagery in regional-scale mapping of soil salinity is readily apparent in the recent work of Lobell *et al.* (2010).

Since its early agricultural use for measuring soil salinity, the application of EC_a has evolved into a widely accepted means of establishing the spatial variability of several soil physical and chemical properties that influence the EC_a measurement, aside from soil salinity (Corwin and Lesch, 2003, 2005a). Corwin and Lesch (2005a) provide a compilation of literature pertaining to the soil physical and chemical properties that are either directly or indirectly measured by EC_a.

Because the geospatial measurement of EC_a is a complex spatially measured property of soil that reflects the influence of several soil physical and chemical properties (including soil salinity, clay content and mineralogy, water content, bulk density, organic matter, and cation exchange capacity), it is rarely used to map a single property but rather is used as a surrogate for general spatial variability of those soil physical and chemical properties that are spatially correlated with EC_a. As such, geospatial measurements of EC_a are used to direct soil sampling as a means of characterizing spatial variability of those soil properties that correlate with EC_a at that particularly study site. Characterizing spatial variability with EC_a-directed soil sampling is based on the notion that when EC_a correlates with a soil property or properties, then spatial EC_a information can be used to identify sites that reflect the range and variability of the property or properties.

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). Details for conducting a field-scale EC_a survey for the purpose of characterizing the spatial variability of soil properties can be found in Corwin and Lesch (2005b). General guidelines appear in Corwin and Lesch (2003) and Corwin *et al.* (2003a, 2003b).

Table 1. Compilation of literature using EC_a to measure soil salinity at laboratory, plot, and field scales.

Scale of study	References
Laboratory and plot scales site within a field)	(or singleHalvorson and Rhoades (1976), Rhoades *et al.* (1976), Rhoades and Corwin (1981), Corwin and Rhoades (1982, 1984),Wollenhaupt *et al.* (1986), Rhoades *et al.* (1989b, 1990), Corwin and Rhoades (1990), Slavich and Petterson (1990), Hanson and Kaita (1997), Johnston *et al.* (1997)
Field scale (or larger spatial extent)	de Jong *et al.* (1979), Cameron *et al.* (1981), Williams and Baker (1982), Greenhouse and Slaine (1983), van der Lelij (1983), Williams and Hoey (1987), Rhoades and Corwin (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), Mankin *et al.* (1997), McKenzie *et al.* (1997), Rhoades *et al.* (1997, 1999a, 1999b), Triantafilis *et al.* (2001), Triantafilis *et al.* (2002), Mankin and Karthikeyan (2002), Herrero *et al.* (2003), Paine (2003), Kaffka *et al.* (2005), Lesch *et al.* (2005), Kinal *et al.* (2006), Amezketa (2007), Akramkhanov *et al.* (2008), Urdanoz *et al.* (2008), Zheng *et al.* (2009)

The mapping of soil salinity at field scale with EC_a-directed soil sampling has a unique set of considerations that was not specifically nor comprehensively addressed in the prior protocols developed by Corwin and Lesch (2005b). It is the objective of this review and analysis paper to provide an overview of the field-scale characterization of soil salinity distribution using EC_a-directed soil sampling. Protocols, guidelines, special considerations, and strengths and limitations are discussed for characterizing spatial and temporal variation in soil salinity using EC_a-directed soil sampling. The protocols and guidelines are an enhancement and update of those originally presented by Corwin and Lesch (2003, 2005b) with a focus on soil salinity. Original data are presented showing the critical importance of conducting EC_a surveys at or near field capacity. A case study is presented covering a range of field-scale salinities to demonstrate the effectiveness of generating soil salinity maps using EC_a-directed soil sampling. Basic introductory material is presented in the Appendix to provide background reference information useful for understanding the relationship between EC_a and soil salinity, which is crucial to the interpretation of geo-referenced EC_a measurements for the purpose of mapping soil salinity.

Complexity of the EC_a Measurement

The interpretation of EC_a measurements is not trivial because of the complexity of current flow in the bulk soil. Numerous EC_a studies have been conducted that have revealed the site specificity and complexity of geospatial EC_a measurements with respect to the particular property or properties influencing the EC_a measurement at the study site. Corwin and Lesch (2005a) provide a compilation of EC_a studies and the associated dominant soil property or properties measured by EC_a for that study. More pertinent to the issue of soil salinity, Table 1 provides an update of the field studies that have used EC_a to measure and/or map soil salinity.

The advantages of the EC_a measurement are that it is rapid, reliable, and easy to take, which have made it an ideal field measurement tool, but because of the multiple pathways of conductance it is often difficult to interpret. Corwin and Lesch (2003) provided guidelines for the use of EC_a in agriculture by identifying the complexities of the EC_a measurement and how to deal with them. Three parallel pathways of current flow contribute to the EC_a measurement: 1) a liquid phase pathway via salts contained in the soil water occupying the large pores, 2) a solid pathway via soil particles that are in direct and continuous contact with one another, and 3) a solid-liquid pathway primarily via exchangeable cations associated with clay minerals (Rhoades *et al.,* 1999b). To measure soil salinity, the electrical conductance of only the soil solution is required; consequently, EC_a measures more than just soil salinity. In fact, EC_a is a measure of anything conductive within the volume of measurement and is influenced, whether directly or indirectly, by any edaphic property that affects bulk soil conductance.

Because of the pathways of conductance, EC_a is influenced by a complex interaction of edaphic properties including salinity, saturation percentage (SP), water content, bulk density (Δ_b), organic matter (OM), cation exchange capacity (CEC), clay content and mineralogy, and temperature. The SP and Δ_b are both directly influenced by clay content and OM (Stiven and Khan, 1966; Rhoades *et al.,* 1990; Gavlak *et al.,* 2003). Furthermore, the exchange surfaces on clays and OM provide a solid-liquid phase pathway primarily via exchangeable cations; consequently, clay content (and mineralogy), CEC, and OM are recognized as factors influencing EC_a measurements. Measurements of EC_a *must* be interpreted with these influencing factors in mind.

From a pore-scale perspective, electrolyte conduction through pores dominates over surface conduction when a high concentration of electrolyte occupies the pores. However, when the electrolyte concentration is dilute in the pore fluid, the effects of clay and surface conduction become important (Boadu and Seabrook, 2006). Variations in the electrical response of soils over a broad range of frequencies provide information on the pore geometry, pore surface area as well as the amount and nature of the pore fluids. However, the amount and distribution of clay, as well as the concentration of an electrolyte in the pore fluid, influence spectral electrical response measurements in a complex way that is not separable, but coupled (Boadu and Seabrook, 2006). It is the inseparable influence of soil properties on EC_a, particularly at $EC_a < 2$ dS m^{-1}, that causes the field-scale mapping of salinity solely from geospatial EC_a measurements to be problematic, necessitating the collection of ground-truth soil samples to calibrate EC_a to those properties influencing EC_a at a particular site.

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

The inseparable influences of the soil properties effecting EC_a is a complication that can be dealt with on a pedon scale using the models of Rhoades *et al.* (1990) and Lesch and Corwin (2003). At field scale the effects are best separated out statistically on a field-by-field basis using soil samples obtained from an EC_a-directed soil sampling design to develop a regression model to calibrate EC_a to a target property, such as salinity, water content, clay, etc. (Lesch *et al.,* 2005). In practice, the fitted regression model for salinity (or log salinity) adjusts for the impact of clay and/or water content by direct calibration. By adopting a direct calibration approach, one can optimally adjust for confounding soil property effects, while simultaneously obtaining an assessment of the accuracy and usefulness of the fitted model.

EC_a-Directed Soil Sampling Protocols for Field-scale Soil Salinity Assessment

Corwin and Lesch (2003, 2005b) developed protocols and guidelines for characterizing soil spatial variability from EC_a-directed soil sampling, but recent research data has refined these protocols and guidelines, particularly with regard to field-scale soil salinity assessment. The basic steps are provided and a detailed discussion of the protocols can be found in Corwin and Lesch (2005b). Table 2 presents enhancements to the protocols developed by Corwin and Lesch (2005b) specifically tuned to the application of mapping soil salinity at field scale.

The modification of these overarching protocols to measure and map soil salinity at field scale specifically is an effort to minimize soil property effects outside the target property of soil salinity, and to avoid the confounding influence of soil condition effects. This is represented schematically in Fig. 2 where soil property effects are primary influences on the EC_a measurement and soil condition effects are secondary influences. Soil property effects include water content, bulk density, temperature, and texture (*i.e.,* sand, silt, and clay), while soil condition effects are influences such as metal, surface roughness, soil compaction, and surface geometry (*e.g.,* presence of beds and furrows). Accurate maps of soil salinity will not be obtained using EC_a-directed sampling unless the primary influences are understood and the secondary influences are minimized.

Enhancements to EC_a-Directed Soil Sampling Protocols

The EC_a survey should be designed (Step 1 in Table 2) in a manner that will avoid edge effects, *i.e.,* a buffer area around of the edge of the field should be made where no EC_a measurements are taken. This is particularly important for EC_a surveys that are characterizing the spatial distribution of dynamic soil properties such as salinity and water content. This will eliminate the possibility of sampling sites being selected near the edge, which are areas where unrepresentative extremes may commonly occur. Edge effects can be the consequence of a variety of processes and are common to agricultural fields where the boundary of the field has a sharp transition and the anthropogenic, meteorological, biological, and

Table 2. Outline of steps to conduct an EC_a field survey to map soil salinity. Modified from Corwin and Lesch (2005b) specifically for mapping soil salinity.

1. Site description and EC_a survey design
   - a. record site metadata
   - b. define the project's/survey's objective (*e.g.,* inventorying, spatio-temporal monitoring, site-specific management, etc.)
   - c. establish site boundaries
   - d. select GPS coordinate system
   - e. establish EC_a measurement intensity (*i.e.,* number and location of traverses and space between EC_a measurements with careful consideration of edge effects)
   - f. minimize secondary influences on EC_a (*e.g.,* compaction, surface roughness and geometry, metal)
   - g. special EC_a survey design considerations
     - (1) presence of beds and furrows: perform separate surveys for the beds and for the furrows
     - (2) vineyards with metal trellising
       - (a) maximize distance from metal for surveys with EMI
       - (b) place an insulator between metal posts and trellis wires to break the conductance loop from the soil to the posts along the wires and back into the soil (this applies to both ER and EMI surveys)
     - (3) presence of drip lines: perform separate EC_a surveys over and between drip lines
     - (4) variations in surface geometry or roughness: perform separate surveys with separate sampling designs for each area differing in surface roughness or surface geometry
     - (5) temporal studies
       - (a) reference all EC_a measurement to 25°C or
       - (b) conduct EC_a surveys at same time of day and same day of year
2. EC_a data collection with mobile GPS-based equipment
   - a. conduct drift runs when using EMI to determine the effect of ambient temperature on EMI instrumentation
   - b. geo-reference site boundaries and significant physical geographic features with GPS
   - c. assure that water content at study site is at or near field capacity ($\geq$70% field capacity) throughout the field (if water content is $<$70%, then do not conduct EC_a survey)
   - d. measure geo-referenced EC_a data at the pre-determined spatial intensity and record associated metadata
   - e. keep speed of mobile GPS-based equipment $<$10 km hr^{-1} to reduce GPS positional errors
3. Soil sample design based on geo-referenced EC_a data
   - a. statistically analyze EC_a data using an appropriate statistical sampling design (*i.e.,* model- or design-based sampling design) to establish the soil sample site locations
   - b. establish site locations, depth of sampling, sample depth increments, and number of cores per site ($>$100 soil samples are desirable but the total number of samples is largely determined by the resources available to analyze the soil properties of concern)
4. Soil core sampling at specified sites designated by the sample design
   - a. obtain measurements of soil temperature through the profile at selected sites
   - b. at randomly selected locations obtain duplicate soil cores within a 1-m distance of one another to establish local-scale variation of soil salinity (and other soil properties) for 20% or more of the sample locations
   - c. record soil core observations (*e.g.,* temperature, color, $CaCO_3$, gleying, organic matter, mottling, horizonation, textural discontinuities, etc.)
5. Laboratory analysis of soil salinity and other EC_a-correlated soil properties relevant to the project objectives
6. Stochastic and/or deterministic calibration of EC_a to EC_e (and to other soil properties, *e.g.,* water content, SP, etc.)
7. Spatial statistical analysis to determine the soil properties influencing EC_a
   - a. perform a basic statistical analysis of soil salinity (and other relevant soil properties) by depth increment and by composite depth over the depth of measurement of EC_a
   - b. determine the correlation between EC_a and salinity (and between EC_a and other soil properties) by composite depth over the depth of measurement of EC_a
8. GIS database development
9. Graphic display of spatial distribution of soil salinity (and other properties correlated to EC_a) using various interpolation methods (*e.g.,* inverse distance weighting, cubic spline, geostatistics)

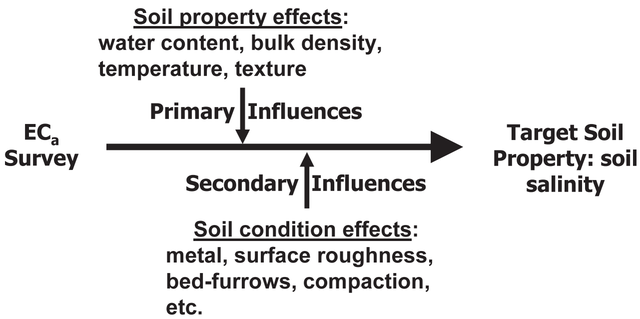

Figure 2. Conceptual path diagram of the primary and secondary factors influencing an EC_a survey targeted at measuring soil salinity.

edaphic factors influencing plants (or animals) are not representative of the field as a whole. As an example, runoff from roads surrounding a field can cause increased leaching of salts and higher water contents at the edges of fields. Salts used to de-ice roads at the edge of fields can accumulate. Higher temperatures and lower relative humidity at the edges of a field can cause increased evapotranspiration, which reduces leaching and lowers water contents, thereby increasing salinity. These and other processes can result in salinity and water content levels at the edges of fields that are not representative and do not reflect the processes occurring throughout the rest of the field; consequently, a buffer area around the field is recommended where no EC_a measurements are taken so that the sampling design is not influenced by unrepresentative edge effects.

The issue of edge effects influencing the sampling design is of particular concern for the response surface sampling design used in the ESAP software developed at the U.S. Salinity Laboratory by Lesch *et al.* (2000) because the software identifies sampling sites by minimizing clustering, which often results in the identification of sites near the edge. To combat the influence of edge effects, ESAP has a built-in means of creating a buffer area at the edge of a field where EC_a measurements can be omitted.

As a rule-of-thumb for a rectangular field, the first and last traverses and the start and end of each traverse using mobile geo-referenced EC_a equipment should be a distance of 0.5(w/n) and 0.5(d/n), respectively, from the edge of the field to avoid edge effects (the distance between traverses is d/n), where w is the width of the field, d is the length of the field and n is the number of desired EC_a traverses. For non-rectangular fields, the first and last traverses and the start and end of each traverse can be 0.5(w/n) from the edge of the field, where w is now the greatest width of the field. This rule-of-thumb is of greatest importance when a small number of soil sample sites are selected (*e.g.,* <10), whether by a model- or designed-based sampling strategy, from a

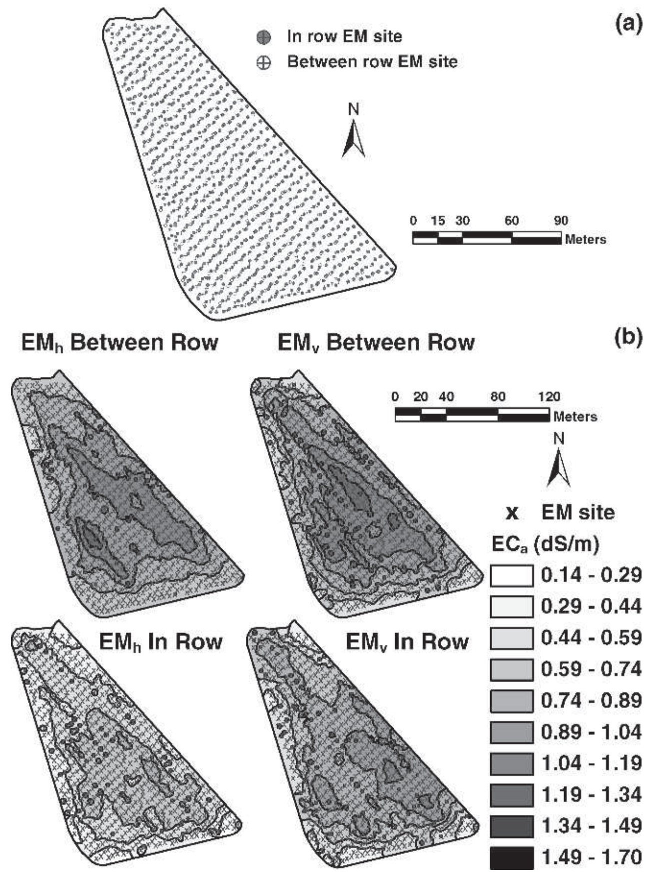

Figure 3. Napa Valley (Caneros Region) EC_a survey of a vineyard using electromagnetic induction: a) in-row and between row sites and b) EM_h and EM_v measurements between and in row.

minimal number of traverses (*e.g.,* <10). Concern for edge effects becomes less of an issue as the number of traverses and soil sample sites increases.

An example of an edge effect can be seen in the EC_a survey of a drip-irrigated vineyard in the Caneros region of California's Napa Valley (38° 15′ 53.00 lat., 122° 19′ 48.14 long.). An EC_a survey using a Geonics dual-dipole EM38 was conducted on a 1.8-ha block following the protocols presented in Table 2. Measurements were taken approximately 5 m apart and were taken both in the vine row and between vine rows (Fig. 3(a)). Metal trellises supporting the vines and drip lines were present in the vine row. In addition to EMI measurements, ER measurements of EC_a were taken at the same locations using a Biddle electrical resistivity meter with a Wenner array configuration and an inter-electrode spacing of 0.75 m for the four stainless-steel electrodes. Measurements of EC_a were taken with no consideration for a buffer zone around the edge of the field since a large number of traverses (29 traverses) were conducted (Fig. 3(a)). The EMI measurements of EC_a at the edges of the vineyard block are consistently lower (Fig. 3(b)). The lower EC_a measurements on the edges are a consequence of anthropogenic (use of a desiccant on the road surrounding the block to reduce road slickness), topographic (gentle downhill slope from west to east), and meteorological (lower relative humidity) influences, which influence the water content distribution at the edges of the block. The large number of traverses (*i.e.,* 29 traverses) clearly identifies these as edge effects. When large numbers of traverses are taken, edge effects do not disproportionately influence the sample design, but when few traverses are taken, the sampling design can be unduly influenced by less representative extreme EC_a values that are the result of processes confined mainly to the edge of the field. The average EM_h (EM_h is the measurement taken with the EM38 in the horizontal position) for the 29 in-row traverses is 0.78 dS m^{-1}, while for 5 in-row traverses with the traverses starting and ending at the edge of the block the average EM_h is 0.72 dS m^{-1}; for 5 traverses following the 0.5(w/n) rule-of-thumb the average EM_h is 0.80 dS m^{-1}. The drier edges of the vineyard block have a greater influence on lowering the field average for EM_h when a buffer area around the field is not used.

Another aspect of Step 1 that needs consideration specific to surveys of vineyards is the influence of metal, particularly metal trellises. Metal trellises in vineyards pose a challenge to EC_a surveys, both for EMI and for ER. Use of EMI for surveys of EC_a within vineyards with metal trellising have shown that the metal trellis distorts the EC_a values, causing increases as high as 0.50 dS m^{-1} or more (Lamb *et al.,* 2005). Close attention needs to be given to take EMI measurements of EC_a sufficiently far from any metal post and trellis wires to eliminate any magnetic influence on the EMI conductivity reading. The EC_a survey shown in Fig. 3(b) took the metal posts and wires of the trellises into account by positioning the EM38 midway between surrounding metal posts and keeping the EM38 at ground level away from the trellis. This was done for both in-row and between-row measurements. When the trellises were ignored and EMI measurements were taken without regard for the position of nearby metal posts, the average EM_h and EM_v (EM_v is the measurement taken with the EM38 in the vertical position) were roughly 0.10 dS m^{-1} higher, which are spurious elevated results resulting from the influence of metal. When trellises in a vineyard are comprised of steel posts, Lamb *et al.* (2005) recommended that EMI surveys should only be conducted where the row spacing is 3 m or more and traverses are made mid-row.

A relavent question arises, is the increase in the average EM_h and EM_v due strictly to the magnetic influence of the metal trellis? A correlation analysis between EC_a values obtained with an EM38 in the horizontal coil configuration (EM_h) and ER (*i.e.,* four-electrode Wenner array with a 0.75-m inter-electrode spacing) for in-row and for between-row EC_a surveys of the Napa Valley vineyard shows high correlations of R = 0.92 and 0.97, respectively. Similarly, the spatial patterns between EMI and ER instruments are virtually the same. This suggests that there is not only a magnetic influence but that there is a continuous conductance loop that extends from the soil up through the metal post, along the trellis, back down the adjacent metal post, and returning into the soil. This conductance loop is measured with both EMI and ER. The lower correlation for the in-row ER and EMI EC_a measurements (*i.e.,* R = 0.92) than for the between-row measurements (*i.e.,* R = 0.97) is presumably caused by the added magnetic influence on the EMI measurements.

Ostensibly, the influence of metal trellises is not solely a magnetic effect that only influences EMI and not ER. The fact that ER is not affected by magnetic influences caused by the presence of metal does not cause it to be the instrument of choice for vineyards with metal trellises. The presence of metal trellises is problematic for both EMI and ER because the metal posts and trellis wires potentially serve as a continuous conductance loop. To remove this influence of metal on either ER or EMI, the conductance loop must be broken, which can be accomplished by inserting an insulator between the metal posts and trellis wires. For numerous geo-referenced EC_a measurements, the insertion of an insulator between all trellis wires and supporting posts is likely impractical. However, as long as the trellis system configuration (*i.e.,* spacing of posts, dripper guide-wire, and cordon, gripper, and foliage wires) remains the same and measurements are taken in the same position relative to the trellis, the metal influences the absolute EC_a values similar to "background noise."

The presence of beds and furrows and drip irrigation requires special EC_a survey considerations because of the abrupt changes that occur in water content and salt accumulation. Flood irrigation down furrows causes the lateral and upward flow of salts into beds. To get a comprehensive understanding of the salinity distribution, separate EC_a surveys are needed for the furrow and for the bed. Similarly, abrupt changes in water content and salinity distribution occur under drip irrigation. To get a more realistic understanding of soil salinity distribution in fields under drip irrigation, field-scale EC_a surveys should be conducted so that traverses are made within and between drip lines. Figure 3(b) shows the dramatic difference in the spatial patterns and magnitude of EC_a as measured with EM_h for in-row and

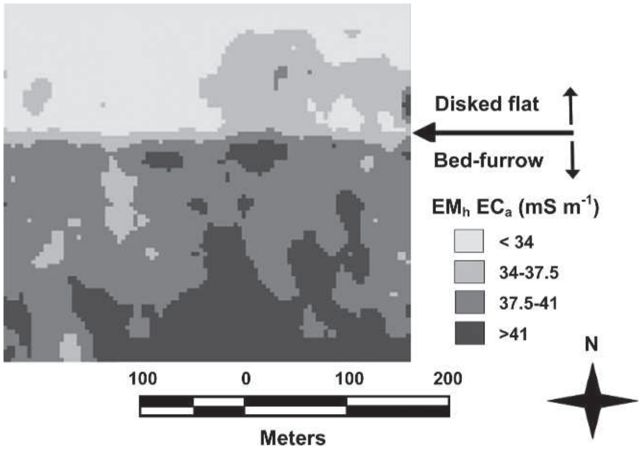

Figure 4. Effect of the presence and absence of beds and furrows on EC_a measurements when using electromagnetic induction.

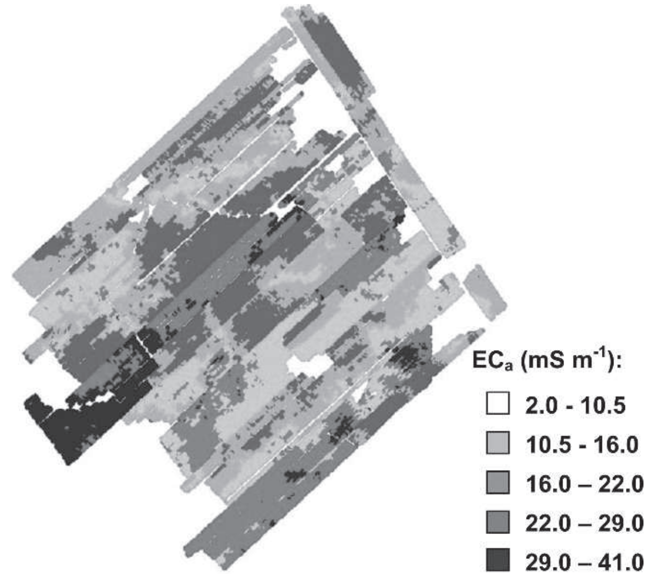

Figure 5. Banding effect characteristic of a failed EC_a survey of soil salinity resulting from the disregard for primary (*e.g.,* water content, bulk density, temperature, texture) and secondary influences (*e.g.,* surface roughness, presence of beds and furrows, compaction caused by heavy equipment) affecting EC_a.

between-row traverses of the drip-irrigated vineyard in Napa Valley. The in-row average EC_a (EM_h = 0.75 dS m^{-1}) is higher than between-row average EC_a (EM_h = 0.52 dS m^{-1}) because of the higher water content below the drip lines. The complex three-dimensional nature of salt and water distribution under drip irrigation cannot be understood without surveying both within and between drip lines to avoid misinterpretation of the spatial EC_a information concerning water content and soil salinity.

The EC_a survey design (Step 1) must also consider the surface roughness (*i.e.,* smooth or disked surface) and surface geometry (*i.e.,* presence and absence of beds and furrow). As an example, Fig. 4 shows an EMI survey of EC_a (*i.e.,* EM_h) of a field where the northern end was disked flat and the southern end was in beds and furrows. As can be seen, there is a sharp boundary between the flat disked area and bed-furrow area, showing the influence of the presence of beds and furrows, which is a result of salt accumulation in the beds caused by the lateral and upward flow of leached salts from the furrow into the bed. The roughness of the soil surface can also influence spatial EC_a measurements. Geospatial measurements taken on a smooth field surface will be higher than the same field with a rough surface from disking. This is because of the fact that the disturbed disked soil acts as an insulating layer to the conductance pathways, thereby reducing its conductance. The extent of the reduction in conductance depends upon the depth of the plow layer and the coarseness of the clods. When conducting a geospatial EC_a survey of a field, the entire field must have the same surface roughness and same surface geometry.

The above factors, if not taken into account when conducting an EC_a survey, will likely produce a "banding" effect. For example, if an EC_a survey is conducted on a field that has areal differences in water content, soil profile temperature, surface roughness, and surface geometry, then bands of EC_a such as those found in Fig. 5 will result. These bands reflect the secondary influences of soil moisture, temperature, roughness, and surface geometry that must be minimized to produce a reliable EC_a survey that can be used to direct soil sampling to spatially characterize the distribution of salinity.

Studies monitoring soil salinity have a temporal component, which causes concern with respect to temperature effects. Ideally, EC_a measurements should be referenced to 25°C using Eq. (A2) in the Appendix. However, even though soil temperature is a routine measurement, it is a measurement that can be disregarded if comparisons in a temporal study are made between data taken during the same time of day over a narrow time period (*e.g.,* a month) when soil temperatures are relatively stable or comparisons are made for the same day of the year for long-term studies that extend for years. The idea is to compare or use EC_a data that is at the same soil temperature. In this case, minimal soil temperature data is needed. The soil salinity monitoring studies by Lesch *et al.* (1998) and Corwin *et al.* (2006) are examples of how to handle EC_a-directed sampling with a temporal component.

The collection of geo-referenced EC_a data with mobile GPS-based equipment (Step 2 in Table 2) has associated concerns that were not identified in the protocols of Corwin and Lesch (2005b), including drift runs to determine the effect of ambient temperature on EMI instrumentation and the range of water contents over which the EC_a data must be collected to assure reliable data due to contiguous conductance pathways through the solution phase. A study by Robinson *et al.* (2004) indicated that drift commonly observed in the EM38 is likely caused by temperature effects on the EM38 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 throughout the day along the same transect to adjust for the drift in the post-processing of EC_a data. Drift runs are generally 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. As a rule-of-thumb, normalization of EC_a data using the drift runs should occur when successive drift runs are shifted by $\geq$5%.

The original general protocols by Corwin and Lesch (2005b) indicated that EC_a surveys should be conducted at or near field capacity, but did not specify the range of water contents. Original field data is presented in the following subsection entitled Importance of Water Content in EC_a-Directed Soil Sampling for Field-Scale Salinity Assessment, which identifies the range of water contents necessary to maintain contiguous conductance pathways for a reliable EC_a survey. Failure to conduct an EC_a survey within the identified range of water contents can result in spurious data that will render false conclusions about salinity distributions.

Once a geo-referenced EC_a survey is conducted, the data are used to establish the locations of the soil core sample sites for calibration of EC_a to the electrical conductivity of the extract from a saturated paste (EC_e) of the soil sample (Step 3). To establish the locations where soil cores are to be taken, either design-based or model-based sampling schemes can be used (Corwin and Lesch, 2005b). Design-based sampling schemes (*e.g.,* simple random sampling, stratified random sampling, unsupervised classification, etc.) have historically been the most commonly used and hence are more familiar to most research scientists. The validity and effectiveness of a sampling strategy is fundamental to the EC_a-directed soil sampling approach. Recent validation and comparison studies of model- and design-based sampling strategies for characterizing the spatial variability of soil salinity with EC_a-directed soil sampling have indicated that the model-based sampling approach resulted in better model discrimination, more precise parameter estimates, and smaller prediction variances than the design-based sampling strategy (Lesch and Corwin, 2008; Corwin *et al.,* 2010). Even though a model-based sampling design, such as a response surface sampling design, has been less prevalent in the literature, it is concluded from the comparison that there is no reason to refrain from its use and, in fact, warrants equal consideration. The clear advantage of the model-based sampling design, and more specifically the use of a response surface sampling design, is that there is a substantial reduction in the number of samples required to characterize the variation in soil salinity as compared to other approaches. A drawback is that the level of technical knowledge in the use of software such as ESAP (Lesch *et al.,* 2000), which uses the response surface sampling design approach, is greater than other statistical software.

A crucial aspect of Step 4 in Table 2, which has been largely overlooked in many past EC_a-directed soil sampling studies listed in Table 1 and deserving of attention, is that of establishing the local-scale variation through duplicate or replicate samples at 20% or more of the sample sites. Knowledge of the local-scale variation in comparison to global-scale variation is important since this helps to define sampling requirements (*i.e.,* number of replicates) and provide a perspective to the small- and large-scale variation in salinity that occurs within a field. If the local-scale variation in salinity approaches global-scale variation, then there is just as much variation within a small area (*e.g.,* 1 m^2) as over the entire field, which makes the EC_a-directed sampling approach untenable.

Steps 5–8 in Table 2 are the same as the original protocols by Corwin and Lesch (2005b).

Step 9 in Table 2 focuses on the methods of interpolation that are available to display the spatial distribution of soil salinity. Inverse distance weighting, cubic spline, and various geostatistical approaches are the prevalent choices. Previous studies comparing interpolation methods have met with mixed results; consequently, jackknifing is often used to establish the interpolation method that minimizes prediction error (Isaaks and Srivastava, 1989). Bourgault *et al.* (1997) provide a useful toolbox of geostatistical approaches used on a soil salinity data set and advise the use of cross-validation to decide the approach that is best. The advantage of using a geostatistical approach for interpolation over inverse distance weighting or cubic spline is an assessment of spatial uncertainty that can be obtained from geostatistical approaches.

Importance of Water Content in EC_a-Directed Soil Sampling for Field-scale Salinity Assessment

The EC_a survey protocols of Corwin and Lesch (2005b) emphasized the importance of conducting EC_a surveys in fields where the water content was at or near field capacity across the entire field. Field capacity refers to the water content at approximately 1/3 bar and in the field is taken to represent the water content at which free drainage no longer occurs, which generally occurs 2–4 days following a rainfall or irrigation (Peters, 1965). Presented herein is empirical data from two field studies illustrating over what range of water contents field-scale EC_a surveys must be conducted to provide reliable results.

Site locations of EC_a surveys. Surveys of EC_a were conducted at two field sites, one near Roswell, New Mexico (33° 23′ 14″ N, 104° 31′ 41″ W) and the other outside Sterling, Colorado (40° 35′ 02.795″ N, 103° 00′ 34.844″ W). The Roswell, NM site is a center-pivot irrigated field of approximately 95 ha. The circular field was subdivided into two fields, one in the north of 41 ha and one in the south of 54 ha. The Sterling, CO site consisted of four contiguous fields. The combined area of the four contiguous fields was 130 ha. The soil is predominantly Platner loam (fine, smectitic, mesic Aridic Paleustolls), Weld loam (fine, smectitic, mesic Aridic Argiustolls), and Rago loam (fine, smectitic, mesic Pachic Argiustolls).

EC_a surveys. The EC_a surveys for the Roswell, NM and Sterling, CO field sites were conducted using mobile EMI equipment following the protocols outlined by Corwin and Lesch (2005b), with the exception that close attention was not given to the water content of the soil at the time of the surveys, resulting in areas at both sites that were considerably less than field capacity.

Surveys of EC_a were confined to 7-ha sub-sections in the northern and southern sections of the Roswell, NM site. In each sub-section, seven (7) east-west traverses were made with geo-referenced EC_a measurements taken with the EM38 in the horizontal (EM_h) and vertical (EM_v) positions every 5 m. From the two EC_a surveys, six (6) sampling sites were selected in each sub-section (north and south) using ESAP software (Lesch *et al.,* 2000). Soil samples were taken at 0.3-m increments to a depth of 1.2 m. The soil samples were analyzed for salinity (EC_e, dS m^{-1}), gravimetric water content (θ_g, g g^{-1}), and saturation percentage (SP) following the methodologies provided by Rhoades (1996). Field capacity was estimated for each depth increment from field samples taken at each of the 6 sampling sites 2–3 days after irrigation according to the in situ field capacity method of Cassel and Nielson (1986).

The four contiguous fields in Sterling, CO were surveyed in April 2005 using mobile EMI equipment with traverses every 15 m and measurements of EM_h and EM_v taken with the EM38 every 5 m along each traverse. In addition, an EC_a survey using mobile ER equipment (*i.e.,* Veris 3,100[1]) was conducted so that each traverse with the Veris 3,100 went over the same traverse as the mobile EMI equipment. Measurements of EC_a were obtained with the Veris 3,100 at depths of 0–0.3 m and 0–0.9 m. Ten samples sites were selected in each field using a response surface sampling design (RSSD), and 9 sites were selected in each field using an unsupervised classification sampling design (UCSD) for a total of 76 sites over the four fields. Soil samples were obtained at depth increments of 0–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m. The soil samples were analyzed for EC_e (dS m^{-1}), bulk density (ρ_b, g cm^{-3}), θ_g (g g^{-1}), SP, and clay content (g kg^{-1}). The analytical procedure outlined by Rhoades (1996) was used for EC_e, θ_g, and SP. Clay content and ρ_b were obtained using the hydrometer method of Gee and Or (2002) and the core method of Grossman and Reinsch (2002), respectively. The field capacity for each of the five depth increments for each field was determined using the ceramic pressure plate method at 1/3 bar for disturbed soil samples.

Results and discussion. Table 3 presents EC_a-directed sampling data for the north and south sub-sections of the center-pivot irrigated field in Roswell, NM. The average EC_a measurements in the north are significantly higher than in the south for both EM_h and EM_v (Table 3a). The average EC_as in the north are above 1 dS m^{-1} (*i.e.,* 1.55 and 1.70 dS m^{-1} for EM_h and EM_v, respectively), which suggests that salinity is the soil property most likely responsible for the high EC_as. The low average EC_as in the south suggest that the south has a low salinity level. However, Table 3b shows that both north and south sub-sections have similar salinity levels at all depths; both north and south sub-sections are high in salinity (*i.e.,* 12–15 ds m^{-1}). The SP, which is reflective of the soil texture in low OM soils of the arid southwestern USA, does not explain the difference in average EC_as between north and south since both sub-sections have similar SPs at all depths. The discrepancy in average EC_a between north and south is caused by water content. When water content is expressed as the percent of field capacity, there is a distinct difference between the north and south sub-sections, where the north is wetter than the south. The data suggest that between 50–70% of field capacity the conductance pathways in the solution phase are broken, causing spurious EC_a measurements. The importance of being at or near field capacity when conducting an EC_a survey is substantiated by a comparison of the correlation of EC_a (for EM_v) to EC_e (for the composite

[1] Veris Technologies, Salina, KS, USA. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

Table 3. Apparent soil electrical conductivity (EC_a) directed sampling data for the north and south sub-sections of a 95-ha center-pivot irrigated field in Roswell, NM: a) average EC_a for the electromagnetic induction (EMI) measurements in the horizontal (EM_h) and vertical (EM_v) coil configurations and b) associated averages of the soil properties of salinity (EC_e), saturation percentage (SP), and water content (expressed as percent of field capacity) by depth increment for 6 sample sites in each sub-section.

	North	South
(a) Average EC_a (dS m^{-1})		
EM_h	1.55	0.06
EM_v	1.70	0.41

	EC_e (dS m^{-1})		SP		% of field capacity	
Depth increment (m)	North	South	North	South	North	South
(b) Associated averages of soil properties						
0–0.3	13.1	13.8	47.5	48.2	75.4	40.2
0.3–0.6	13.3	14.8	43.1	42.8	84.6	40.3
0.6–0.9	14.5	14.8	43.5	39.9	82.0	44.4
0.9–1.2	12.6	13.9	41.5	41.1	79.1	43.2

depth of 0–1.2 m) between the north and south sub-sections. The correlation coefficient is 0.93 for the north and 0.36 for the south, where the percent of field capacity is 80.3% for the north and 42.0% for the south for the 0–1.2 m composite depth. Consequently, the EC_a measurements (both EM_h and EM_v) are not reliable for the south sub-section because the water content is <50% of field capacity, which disrupts the liquid phase conductance pathway.

Table 4 presents corroborating data indicating that ≥70% of field capacity is needed down to the depth of penetration of the geophysical approach (*e.g.,* ER or EMI) used to measure EC_a to prevent spurious results from occurring caused by discontinuous conductance pathways in the soil solution phase. No correlation was found between EC_a as measured with EMI and any of the soil properties expected to influence EC_a at any composite depth. This was true for both EM_h, which measures down to a depth of roughly 0.75 m, and EM_v, which measures to a depth of about 1.5 m. Ostensibly, the lack of correlation is because of the fact that the water content was too low over the depths of penetration of the EMI measurements. The water content was 49% of field capacity for 0–0.6 m, 42% of field capacity for 0–0.9 m, and 39% of field capacity for 0–1.2 m. However, the measurement of EC_a with ER did correlate with salinity (EC_e) and θ_g over the 0–0.3 m increment, which was because of the fact that the water content was greater than 70% of field capacity (specifically measured to be 77% of field capacity) in the top 0.3 m of soil. The water content for 0–0.6 m dropped to 49% of field capacity and concomitantly the correlation coefficient between EC_a and EC_e dropped to 0.11 and between EC_a and θ_g dropped to 0.31. These results are compatible with the need for water contents ≥70% of field capacity for the conductance pathways in the solution phase to be open.

As a rule-of-thumb, geo-referenced EC_a data collection (Step 2) should be conducted only when the water content through the soil profile of interest is ≥70% of field capacity and preferably as close to field capacity as possible. A gray area exists in the range of 50–70% of field capacity. Surveys of EC_a are substantially affected at ≤50% of field capacity and should not be conducted on soils that are this dry. Sufficient water content is needed down to the depth of penetration of the geophysical approach that is used to prevent spurious and misleading measurements that would suggest that no salinity was present when actually there was. This has significant ramifications, particularly for EC_a surveys conducted on dryland farms, since EC_a surveys should only be conducted after sufficient rainfall has occurred (or sufficient irrigation water has been applied on irrigated crop land) to wet up the soil profile to the appropriate depth of penetration of the EC_a measurement instrumentation. If this precaution is not taken, the reliability of the EC_a survey is dubious.

Case Study of Field-scale Soil Salinity Assessment

Study Site Description

The on-farm research study site (lat. 33° 50′ 25.43″ N, long. 117° 00′ 14.93″ W) is located on Scott Brothers' Dairy Farm in San Jacinto in southern California's

Table 4. Correlation coefficients between EC_a (from electrical resistivity (ER) and electromagnetic induction (EMI)) and soil properties (salinity (EC_e), bulk density (ρ_b), gravimetric water content (θ_g), and saturation percentage (SP)) at composite depths for Sterling, CO. EM_v represents the EMI measurement in the vertical coil configuration and EM_h represents the EMI measurement in the horizontal coil configuration: a) response surface sampling design (RSSD) sites, b) unsupervised classification sampling design (UCSD) sites, and c) RSSD and UCSD sites.

	Depth increments (cm)																
	ER		EM_v					EM_h					Number of samples				
Soil property	0–30	0–90	0–15	0–30	0–60	0–90	0–120	0–15	0–30	0–60	0–90	0–120	0–15	0–30	0–60	0–90	0–120
(a) RSSD sites																	
EC_e	0.58	−0.05	−0.25	−0.21	−0.19	−0.18	−0.08	−0.21	−0.26	−0.23	−0.17	−0.11	40	40	40	36	26
ρ_b	0.43	0.16	−0.27	−0.18	−0.01	−0.21	0.004	−0.21	0.10	0.41	0.18	0.27	40	40	40	38	31
θ_g	0.64	0.02	0.27	0.23	0.21	0.32	0.07	0.55	0.60	0.34	0.46	0.46	40	40	40	38	31
SP	0.30	−0.38	−0.09	−0.05	−0.14	−0.37	−0.22	−0.41	−0.22	−0.17	−0.40	−0.40	40	40	40	36	26
Clay	0.29	−0.28	−0.06	0.09	−0.26	−0.42	−0.22	−0.05	0.11	−0.29	−0.47	−0.22	40	40	40	38	31
(b) UCSD sites																	
EC_e	0.85	0.33	−0.42	−0.49	−0.07	0.02	0.27	−0.17	−0.11	0.32	0.46	0.75	36	36	36	25	15
ρ_b	0.47	0.35	0.16	0.06	−0.01	−0.23	−0.14	0.49	0.41	0.20	0.08	0.04	36	36	36	31	20
θ_g	0.83	0.21	−0.45	−0.37	−0.24	−0.16	−0.15	−0.56	−0.42	−0.39	−0.40	−0.261	36	36	36	30	19
SP	0.47	−0.19	−0.44	−0.20	−0.17	−0.14	−0.06	−0.39	−0.02	−0.03	−0.08	−0.12	36	36	36	25	15
Clay	0.33	−0.22	−0.01	0.44	−0.15	−0.32	−0.25	0.07	0.27	−0.40	−0.1	−0.37	36	36	36	31	19
(c) RSSD and UCSD sites																	
EC_e	0.71	0.13	−0.21	−0.26	−0.14	−0.11	−0.07	−0.14	−0.21	0.01	0.05	0.24	76	76	76	61	41
ρ_b	0.45	0.25	0.09	0.13	0.08	0.07	−0.02	0.18	0.47	0.24	0.28	0.30	76	76	76	69	51
θ_g	0.73	0.11	−0.16	−0.27	−0.13	−0.17	−0.14	−0.01	−0.17	0.01	−0.05	0.00	76	76	76	68	49
SP	0.38	−0.29	−0.26	−0.10	−0.14	−0.26	−0.16	−0.18	−0.13	−0.11	−0.26	−0.32	76	76	76	61	41
Clay	0.31	−0.25	−0.25	0.20	−0.21	−0.36	−0.18	−0.26	0.15	−0.32	−0.49	−0.24	76	76	76	69	50

Riverside County. The 32-ha center-pivot irrigated field site provided an extensive range of spatial variability in EC_a needed to make a real-world evaluation of the salinity mapping capability outlined in EC_a-directed sampling protocols of Table 2. The field has received dairy lagoon water since 6 March 2008. The average EC_e, pH, NH_4^+, NO_3^-, PO_4^{-3} and sodium adsorption ratio of the dairy lagoon water from March 2008 to June 2009 were 1.63 dS m^{-1}, 7.8, 0.94 meq L^{-1}, 0.78 meq L^{-1}, 0.23 meq L^{-1}, and 4.3, respectively.

Intensive EMI Survey

Geospatial EC_a measurements were obtained with the Geonics EM38 dual-dipole electrical conductivity meter. The EC_a survey followed the detailed survey protocols outlined in Table 2. The EC_a survey was conducted 2–4 June 2009. The survey consisted of geospatial EC_a measurements taken with mobile EMI equipment where measurements were simultaneously taken both in the horizontal (EM_h) and vertical coil configurations (EM_v), with traverses roughly 7.5-m apart and measurement sites within each traverse roughly 5-m apart. Measurements were taken at 7,168 locations on transects running in a north-south direction. Figure 6 shows the interpolated EMI survey results for EM_h and EM measurements. Table 5a indicates the EC_a summary statistics for all 7,168 sites.

Sampling and Laboratory Analysis

Apparent soil electrical conductivity serves as a surrogate to characterize the spatial variation of those soil properties that are found to influence EC_a within a field. Based on the variation in EC_a, soil sample sites were selected that reflect the range and variation in EC_a using a model-based sampling strategy, specifically the response surface sample design (RSSD) used in the ESAP software (Lesch *et al.,* 2000). The RSSD specified 40 locations where soil samples were collected to map soil salinity, which are shown in Fig. 6. Soil samples were collected for the following depth increments: 0–0.15, 0.15–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20, 1.20–1.50, 1.50–1.80 m. Saturation extracts of the soil sample depth increments were prepared and the electrical conductivity of the saturation extracts (EC_e,

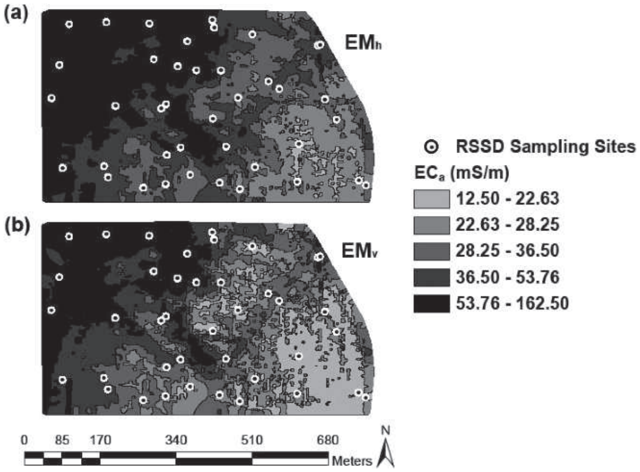

Figure 6. Interpolated map of the 2009 electromagnetic induction (EMI) EC_a survey for a field in San Jacinto, CA: a) EM_h and b) EM_v measurements. Figure shows the 40 response surface sampling design (RSSD) sites. EM_v represents the EMI measurement in the vertical coil configuration and EM_h represents the EMI measurement in the horizontal coil configuration.

dS m^{-1}) were measured using the method presented in Rhoades (1996), which also provides instructions for measuring θ_g and SP. Bulk density (ρ_b) was obtained using the core method of Grossman and Reinsch (2002). Table 5b provides the summary statistics for EC_e, ρ_b, θ_g, and SP.

Results and Discussion

The field mean EM_h of 0.48 dS m^{-1} exceeds the field mean EM_v of 0.38 dS m^{-1}, indicating the predominance of inverted profiles throughout the field (Table 5a). The magnitudes of the field mean EM_h and EM_v values are low to moderate. Both EM_h and EM_v are left skewed (skewness is 1.02 and 1.21, respectively), so the bulk of the values lie below the mean. A histogram of each indicates that EC_a values for both EM_h and EM_v are bi-modal, which is often the case in salt-affected soils. There is no 'peakedness' of the EM_h measurements as reflected by a kurtosis of 0, but the EM_v measurements are leptokurtic (kurtosis of 1.28), so more of the variance is the result of infrequent extreme deviations.

Table 5b shows the statistical summary of EC_e, ρ_b, θ_g, and SP. The mean EC_e values show a decrease in field mean EC_e with depth, going from 4.12 dS m^{-1} at the surface (0–0.15 m) to 2.24 dS m-1 at 0.6–0.9 m to 1.90 dS m^{-1} at the 1.5–1.8 m^{-1} depth increment, suggesting that the salinity profiles tend to be inverted, which is corroborated by the EM_h and EM_v values. The average θ_g increases slightly with depth and SP tends to decrease with depth. The decreasing SP with depth suggests that coarser textured sands tend to be deeper in the soil profile with finer textured soil at the upper depths. From the west side of the field to the east side, the SP decreases indicating a gradation from fine textured soil in the west to coarser textures in the east.

The correlation coefficients shown in Table 6 indicate that EC_a for both EM_h and EM_v correlates with EC_e (*i.e.,* soil salinity) best. For EM_h, the best correlation is for the composite depth of 0–0.9 m and for EM_h the best correlation is for 0–1.8 m, which roughly corresponds to the theoretical depths of penetration of the EM38 for the horizontal and vertical coil configurations, respectively.

The EC_e trends across the field for the 0–0.9 m and 0–1.8 m composite depths are similar (Fig. 7). The general trend is decreasing EC_e from the northwest to the southeast and an 'island' of high EC_e in the north-center of the field. The EC_e is slightly higher for the 0–0.9 m composite depth, which is caused by the application of saline dairy lagoon water that has not leached salts in significant amounts below 0.9 m, causing higher salinity in the upper portion of the soil profile.

The salinity maps in Fig. 7 provide an excellent spatial inventory of salinity in the San Jacinto field that is valuable for future site-specific irrigation management of the applied dairy lagoon water, site-specific remediation, and crop selection. From the data in Table 5 and spatial information in Fig. 7, it is apparent that the areas of salinity concern are the upper portion of the soil profile and the north-central portion of the field. In particular, additional leaching is needed in the middle of the field if crops with salinity thresholds below 4 dS m^{-1} are planted.

An interesting aspect of the San Jacinto study site, which made it difficult to obtain a reliable EC_a survey, is the wide range of textures that were found from east to west. The variation in texture from east to west made it difficult to establish when the field was at field capacity since the east side would drain more quickly than the west side, making it very difficult to adhere to the protocol of only conducting an EC_a survey at field capacity. Even though considerable care was taken in the timing of the EC_a survey so the field was near field capacity, there was a distinct contrast in the ability to reliably map EC_e because the east side of the field tended to drain and dry quickly. Correlation between EC_a and EC_e for the west and east sides of the field (where the 20 western most sites comprised the west side of the field and the 20 eastern sites comprised the east side of the field) using EM_v and EC_e (0–1.8 m) were 0.91 and 0.75, respectively. The east side contained 4 sites where the 0–1.8 m composite depth increment was $<70\%$ of field capacity and 6 sites very near 70% of field capacity. This no doubt resulted in the lower correlation between EM_v and EC_e for the east side.

Table 5. San Jacinto, CA: a) 2009 EC_a survey data summary statistics and b) associated soil property summary statistics where salinity is represented by EC_e (dS m^{-1}), bulk density is represented by ρ_b (g cm^{-3}), gravimetric water content is represented by θ_g (g g^{-1}), and saturation percentage is represented by SP. EM_v represents the EMI measurement in the vertical coil configuration and EM_h represents the EMI measurement in the horizontal coil configuration.

(a) EC_a survey summary statistics (N = 7,168 sites)		
Statistical parameter	EM_v (dS m^{-1})	EM_h (dS m^{-1})
Mean	0.38	0.48
Standard deviation	0.19	0.24
Skewness	1.21	1.02
Kurtosis	1.28	0.00

(b) Soil property summary statistics (N = 40 sites)														
	Depth increments (cm)													
	0–15	15–30	30–60	60–90	90–120	120–150	150–180	0–15	15–30	30–60	60–90	90–120	120–150	150–180
	Mean							Standard deviation						
EC_e	4.12	3.71	3.13	2.24	2.11	2.65	1.90	1.24	1.74	2.25	1.74	1.69	3.50	1.53
ρ_b	1.36	1.72	1.43	1.31	1.39	1.44	1.43	0.25	0.26	0.22	0.27	0.23	0.34	0.25
θ_g	0.22	0.21	0.16	0.16	0.24	0.24	0.24	0.04	0.05	0.07	0.08	0.10	0.11	0.11
SP	41.16	39.67	37.08	34.65	34.46	33.39	31.67	3.78	5.40	6.40	8.36	8.27	7.98	7.19
	Minimum							Maximum						
EC_e	1.99	1.14	0.76	0.42	0.22	0.23	0.22	6.77	9.39	13.03	7.58	6.87	20.50	5.83
ρ_b	0.70	1.01	0.71	0.77	0.95	0.79	0.81	2.08	2.56	1.79	1.87	1.85	2.15	2.17
θ_g	0.07	0.07	0.07	0.07	0.06	0.07	0.06	0.27	0.22	0.25	0.35	0.37	0.37	0.41
SP	34.66	30.23	24.89	19.36	22.09	20.90	20.84	50.96	58.27	53.83	53.70	57.53	56.15	49.73
	Skewness							Kurtosis						
EC_e	0.35	0.88	2.40	1.49	1.09	3.79	0.93	−0.53	1.62	8.90	2.01	0.28	18.01	−0.01
ρ_b	0.56	0.47	−1.38	−0.19	−0.05	0.25	0.37	2.39	2.73	2.96	−0.63	−0.83	−0.46	1.75
θ_g	0.05	0.18	0.71	1.14	0.59	0.17	0.40	−0.13	−1.17	−0.71	0.40	−0.68	−1.15	−0.83
SP	0.35	1.06	0.40	0.66	0.80	0.85	0.68	0.12	2.23	0.25	0.08	0.54	0.72	−0.43
	Coefficient of variation													
EC_e	30.03	47.03	72.08	77.51	79.91	131.94	80.51							
ρ_b	18.68	15.05	15.57	20.83	16.94	23.32	17.13							
θ_g	26.22	42.86	59.64	70.87	58.32	64.87	61.28							
SP	9.19	13.61	17.27	24.12	24.00	23.90	22.70							

Conclusion

Enhancements to the protocols of Corwin and Lesch (2005b) have been made that refine the methodology for mapping soil salinity at field scale. These enhancements focused on minimizing primary (*e.g.,* water content, temperature, texture) and secondary influences (*e.g.,* surface geometry and roughness, metal) that will affect the target soil property of soil salinity. Of greatest concern is conducting an EC_a survey at $\geq$70% of field capacity to assure that contiguous conductance pathways are present for either ER or EMI. Failure to do so will result in the breaking off of the solution phase conductance pathways, which are crucial to the measurement of soil salinity.

These protocol enhancements produce a more robust set of guidelines to assure reliable field-scale maps of soil salinity with the implication that future research on field-scale mapping of soil salinity with EC_a-directed sampling will be based on a standardized procedure suitable for a spectrum of applications related to salinity and broad range of conditions (*e.g.,* drip irrigation, vineyards with trellising, presence of beds and furrows, temporal studies).

Table 6. Correlation coefficients between EC_a (from electromagnetic induction (EMI)) and soil properties (salinity (EC_e), bulk density (ρ_b), gravimetric water content (θ_g), and saturation percentage (SP)) at composite depths for San Jacinto, CA. a) EM_v represents the EMI measurement in the vertical coil configuration and b) EM_h represents the EMI measurement in the horizontal coil configuration.

	Composite depth (cm)						
Property	**0–15**	**0–30**	**0–60**	**0–90**	**0–120**	**0–150**	**0–180**
(a) EM_h							
EC_e	0.4502	0.5586	0.7198	0.8843	0.8700	0.7747	0.7874
ρ_b	−0.1182	−0.1092	−0.4734	−0.5251	−0.5290	−0.5950	−0.5373
θ_g	0.1253	0.1999	0.4350	0.4882	0.6998	0.6374	0.6511
SP	−0.0211	0.0000	0.2398	0.4427	0.5054	0.5113	0.5028
(b) EM_v							
EC_e	0.4412	0.5096	0.6452	0.7035	0.8012	0.8174	0.8327
ρ_b	−0.1610	−0.0960	−0.5098	−0.5753	−0.5922	−0.6653	−0.6196
θ_g	0.1035	0.1916	0.4012	0.4628	0.6042	0.6517	0.6785
SP	0.0031	0.0107	0.2747	0.4809	0.5662	0.5789	0.5675

Even though EC_a-directed sampling is widely used for mapping field-scale salinity, there are definite advantages, disadvantages, and limitations that determine where and under what conditions it is best used and where there might be concerns for its use. There are three advantages of EC_a-directed sampling. First, it substantially reduces the number of soil samples compared to grid sampling since it uses geospatial EC_a measurements as a surrogate to establish the optimum number and location of sample sites to characterize the range and variability of soil salinity. The reduction in the number of samples greatly reduces labor and cost. Second, EC_a-directed sampling renders quick and reliable results that are statistically tied to ground-truth measurements of EC_e from soil samples, so there is a direct relationship with salinity. Third, EMI is a non-destructive measurement and ER results in minimal soil disturbance.

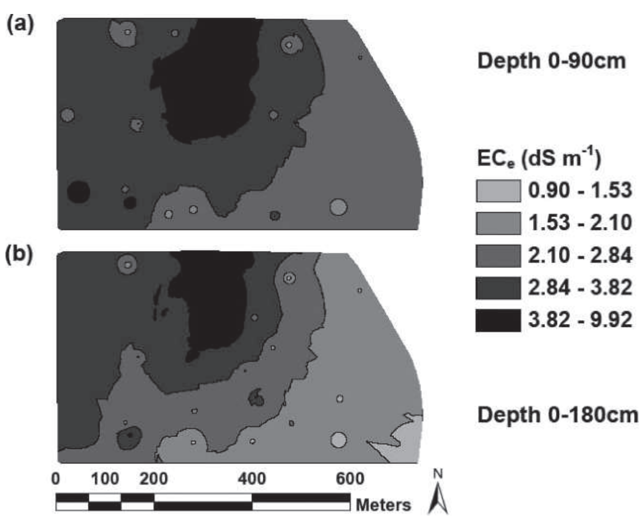

Figure 7. Interpolated map of soil salinity (EC_e, dS m^{-1}) for the field in San Jacinto, CA from the 40 EC_a-directed sampling sites for composite depths of a) 0–0.9 m and b) 0–1.8 m.

The disadvantages of EC_a-directed soil sampling do not overshadow the advantages, but are nonetheless worthy of careful consideration by laymen and untrained users. First, the complex interactions of various soil properties and their resulting influences on the EC_a measurement make it a complex measurement that is often difficult to interpret. Second, EC_a-directed sampling requires expensive and technologically sophisticated geophysical and GPS equipment and requires trained personnel to operate it.

There are three major limitations that determine the conditions under which EC_a-directed sampling must be used. First, there must be sufficient water content (*i.e.*, ≥70% of field capacity) so that continuous conductance pathways are maintained down to the depth of penetration of the geophysical approach used to measure EC_a (*i.e.*, ER or EMI). This may be of particular concern for soils with impermeable layers, dryland soils, or shallow soils above bedrock. Second, the ER approach requires good physical contact between the electrodes and soil surface and, as such, ER is not generally used in stoney soils or soils with dry surfaces. Third, fields with wide ranging soil textures present a challenge since it may become difficult for the entire field to be at or near field capacity.

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APPENDIX

Background Information Regarding Measurement of Soil Salinity with Electrical Conductivity

The most common technique for the measurement of soil salinity is laboratory analysis of aqueous extracts of soil samples. Soil salinity is quantified in terms of the concentration of total salts in the soil. The measurement of the total salt concentration of the aqueous extracts of soil samples can be done either directly through chemical analysis of the chemical constitutes that comprise soil salinity or indirectly through the measurement of electrical conductivity (EC). The chemical species of primary interest in salt-affected soils include: four major cations (*i.e.,* Na^{+}, K^{+}, Mg^{+2}, Ca^{+2}) and four major anions (*i.e.,* Cl^{-}, HCO_3^{-}, SO_4^{-2} and CO_3^{-2}) in the soil solution, exchangeable cations (*i.e.,* Na^{+}, K^{+}, Mg^{+2}, Ca^{+2}), and the precipitated salts calcium carbonate (lime) and calcium sulfate (gypsum). However, an analysis of the chemical constituents of soil salinity is too labor and cost intensive to be practical, particularly when large numbers of samples are involved such as field-scale assessments of salinity; consequently, the salinity of aqueous extracts of soil samples has been most often measured by EC.

It is well-known that the EC of water is a function of its chemical salt composition and total salt concentration (U.S. Salinity Laboratory Staff, 1954). In the laboratory, soil salinity is commonly determined from the measurement of the EC of soil solution extracts, where the current-carrying capacity of the soil solution is proportional to the concentration of ions in the solution. The total concentration of the soluble salts in soil is measured by EC of the soil solution in dS m^{-1}. Over a range of mixed salt concentrations commonly found in soils (*i.e.,* 1–50 meq L^{-1}), total salt concentration (C) in meq L^{-1} is linearly related to electrical conductance of the solution by Eq. (A1):

$$C \approx 10 \cdot EC_{w@25^{\circ}C} \tag{A1}$$

where $EC_{w@25^{\circ}C}$ is the electrical conductivity of the soil solution referenced to 25°C (dS m^{-1}). If C is measured in mg L^{-1} or ppm, then C is related to $EC_{w@25^{\circ}C}$ by a factor of 640 (*i.e.,* $C \approx 640 \cdot EC_{w@25^{\circ}C}$). Over a broader range of salt concentrations (*i.e.,* 1–500 meq L^{-1}), the relationship between C and $EC_{w@25^{\circ}C}$ is no longer linear and is best fit with a third-order polynomial (*i.e.,* $EC_{w@25^{\circ}C} = k_1 + k_2C + k_3C^2 + k_4C^3$) or an exponential equation (*i.e.,* $EC_{w@25^{\circ}C} = k_0C^b$). Another useful relationship is between osmotic potential (ψ_π) and EC, where ψ_π in bars is related to $EC_{w@25^{\circ}C}$ by a factor of -0.36 (*i.e.,* $\psi_\pi \approx -0.36 \cdot EC_{w@25^{\circ}C}$; for $3 \leq EC_{w@25^{\circ}C} \leq$ 30 dS m^{-1}).

Temperature influences EC; consequently, EC must be referenced to a specific temperature to permit comparison. Electrolytic conductivity increases at a rate of approximately 1.9% per degree centigrade increase in temperature. Customarily, EC is expressed at a reference temperature of 25°C. The EC measured at a particular temperature t (in °C), EC_t, can be adjusted to a reference EC at 25°C, $EC_{25^{\circ}C}$, using Eq. (2) from Handbook 60 (U.S. Salinity Laboratory Staff, 1954):

$$EC_{25^{\circ}C} = f_t \cdot EC_t \tag{A2}$$

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

To determine the EC of a soil solution extract, the solution is placed in a cell containing two electrodes of constant geometry and distance of separation. An electrical potential is imposed across the electrodes, and the resistance of the solution between the electrodes is measured. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. At constant potential the current is inversely proportional to the solution's resistance as shown in Eq. (A3):

$$EC_t = k/R_t \tag{A3}$$

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

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

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

Any dilution above field water contents introduces errors in the interpretation of data. The greater the dilution is, the greater the deviation between ionic ratios in the sample and the soil solution under field conditions. These errors are associated with mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. In particular, soil samples containing gypsum deviate most because the calcium and sulfate concentration remain nearly constant with sample dilution, while the concentrations of other ions decrease with dilution. The standardized relationship between the extract and the conditions of the soil solution in the field for different soils is lost with the use of soil-to-water above saturation. However, the recent development of software by Suarez and Taber (2007) allows for the accurate conversion from one extract ratio to another, provided sufficient chemical information is known (*i.e.,* knowledge of the major cations and anions and presence/absence of gypsum). The disadvantage of determining soil salinity using a soil sample is the time and labor required, which translates into high cost. However, there is no more accurate way of measuring soil salinity than with extracts from soil samples.

Prior to the 1950s, much of the data on soil salinity was obtained by using a 50-mL cylindrical conductivity cell, referred to as a Bureau of Soils Cup, filled with a saturated soil paste to estimate soluble-salt concentrations by measuring the EC_p. This approach was fast and easy; consequently, it was used to map and diagnose salt-affected soils. When Reitemeier and Wilcox (1946) determined that plant responses to soil salinity correlated more closely with the EC values of the saturation paste extract, the use of the paste was discontinued. The relationship between EC_p and EC_e is complex; consequently, the measurement of EC_p is not recommended except in instances where obtaining an extract of the saturation paste is not possible or is impractical. Figure A1 graphically illustrates the theoretical complexity of the relationship between EC_p and EC_e based on the dual parallel pathway conductance model of Rhoades *et al.* (1989a, 1989b).

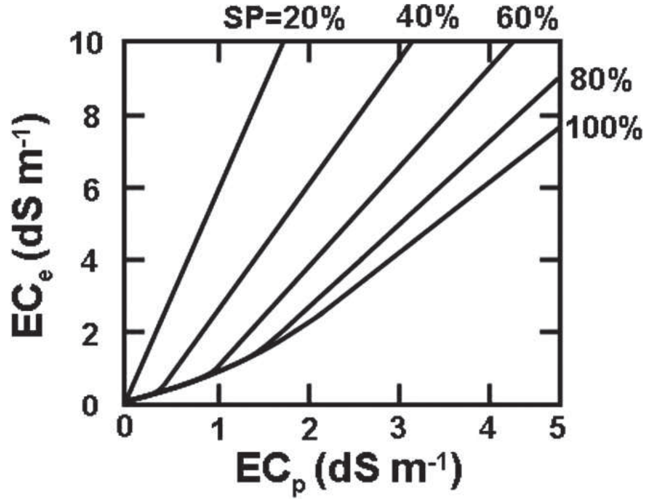

Figure A1. Theoretical relationship between EC_e and EC_p based on the dual parallel pathway conductance model of Rhoades *et al.* (1989a, 1989b).

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

There are various advantages and disadvantages to measuring EC using soil solution extractors or soil salinity sensors. The obvious advantage is that EC_w is being measured, but this is outweighed by the disadvantages. Even though the sample volume of a soil-solution extractor (*i.e.,* 10–100 cm^3) is roughly an order of magnitude larger than a salinity sensor (*i.e.,* 1–2 cm^3), both measure very limited sample volumes; consequently, there are serious doubts about the ability of soil solution extractors and porous-matrix salinity sensors to provide representative soil water samples, particularly at field scales (England, 1974; Raulund-Rasmussen, 1989; Smith *et al.,* 1990). Soil heterogeneity significantly affects chemical concentrations in the soil solution. Because of their small sphere of measurement, both solution extractors and salt sensors do not adequately integrate spatial variability (Amoozegar-Fard *et al.,* 1982; Haines *et al.,* 1982; Hart and Lowery, 1997). Biggar and Nielsen (1976) suggested that soil solution samples are "point samples" that can provide a good qualitative measurement of soil solutions, but not adequate quantitative measurements unless the field-scale variability is adequately 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 1) the thickness of the ceramic conductivity cell, 2) the diffusion coefficients in soil and ceramic, and 3) the fraction of the ceramic surface in contact with soil (Wesseling and Oster, 1976). 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). Soil solution extractors have the drawback of requiring considerable maintenance because of cracks in the vacuum lines and clogging of the ceramic cups with algae and fine soil particles. Both solution extractors and salt sensors are considered slow and labor intensive.

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

Because of the time and cost of obtaining soil solution extracts and the lag time associated with porous ceramic cups, developments in the measurement of soil EC shifted in the 1970s to the measurement of the soil electrical conductivity of the bulk soil, referred to as apparent soil electrical conductivity (EC_a). Apparent soil electrical conductivity provides an immediate, easy-to-take measurement of conductance with no lag time and no need to obtain a soil extract. Furthermore, EC_a can be related to EC_e. However, EC_a is a complex measurement that has been misinterpreted and misunderstood by users in the past because of the fact that it is a measure of the electrical conductance of the bulk soil and not just a measure of the conductance of the soil solution, which is the desired measurement since the soil solution is the soil phase that contains the salts affecting plant roots. The techniques of ER, EMI, and TDR measure EC_a. The most comprehensive body of research concerning the adaptation and application of geophysical techniques to the measurement of soil salinity within the root zone (top 1 to 1.5 m of soil) was compiled by scientists at the U.S. Salinity Laboratory. The most recent reviews of this body of research can be found in Rhoades *et al.* (1999a, 1999b), Corwin (2005), and Corwin and Lesch (2005a).

Electrical Resistivity

Electrical resistivity was originally used by geophysicists to measure the resistivity of the geological subsurface. Electrical resistivity methods involve the measurement of the resistance to current flow across four electrodes inserted in a straight line on the soil surface at a specified distance between the electrodes (Corwin and Hendrickx, 2002). The electrodes are connected to a resistance meter that measures the potential gradient between the current and potential electrodes (Fig. A2). These four-electrode methods were developed in the second decade of the 1900s by Conrad Schlumberger in France and Frank Wenner in the USA for the evaluation of near-surface ER (Rhoades and Halvorson, 1977; Burger, 1992).

Even though two electrodes (one current and one potential electrode) can be used, the stability of the reading is greatly improved with the use of four electrodes. With two electrodes, measurements are obscured or even masked by electrode polarization, which happens because of the interaction of the charged electrode surface with free charges in the electrolyte forming an electrical double layer on the electrode surface with a large capacitance. The factors affecting the double layer thickness are electrolyte concentration, valency, and electrode design. Four-electrode measurement techniques mitigated the problem of electrode polarization by providing a second pair of electrodes to measure the voltage across the soil.

The resistance is converted to EC using Eq. (A3), where the cell constant, k, in Eq. (A3) is determined by

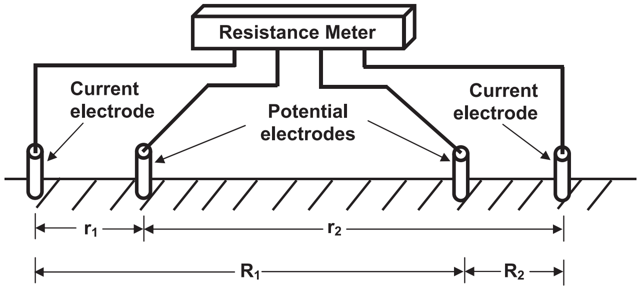

Figure A2. Schematic of four-electrode probe electrical resistivity used to measure apparent soil electrical conductivity (Corwin and Hendrickx, 2002).

the electrode configuration and distance. The depth of penetration of the electrical current and the volume of measurement depends on the electrode configuration and spacing between the electrodes. The two most common electrode configurations are the Wenner array and the Schluberger array. The four electrodes for the Wenner array are equidistantly spaced (inter-electrode spacing = a). For a homogeneous soil, the depth of penetration of the Wenner array is approximately equal to 1.5a and the soil volume measured is roughly equal to πa^3. Whereas, for the Schlumberger array the two inner potential electrodes are fixed and spaced closer together than the distance from inner to outer electrodes. The depth of penetration of the electrical current and the volume of measurement increases as the distance between the potential and current electrodes increases for both the Wenner and Schlumberger arrays.

There are additional four-electrode configurations that are frequently used, as discussed by Burger (1992), Telford *et al.* (1990), and Dobrin (1960). The influence of the inter-electrode configuration and distance on EC_a is reflected in Eq. (A4):

$$EC_{a,25^{\circ}C} = \left(\frac{1000}{2\pi R_t}\right)\left\{\frac{f_t}{\dfrac{1}{\left(\dfrac{1}{r_1}-\dfrac{1}{r_2}-\dfrac{1}{R_1}+\dfrac{1}{R_2}\right)}}\right\} \quad \text{(A4)}$$

where $EC_{a,25^{\circ}C}$ is the apparent soil electrical conductivity temperature corrected to a reference of 25°C (dS m^{-1}) and r_1, r_2, R_1, and R_2 are the distances in cm between the electrodes as shown in Fig. A2. For the Wenner array, where $a = r_1 = r_2 = R_1 = R_2$, Eq. (A4) reduces to $EC_a = 159.2\ f_t/aR_t$ and 159.2/a represents the cell constant (k).

Electrical resistivity is a 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 EMI, which does not require physical contact with the soil. 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. A distinct advantage of the ER approach is that the volume of measurement is determined by the spacing between the electrodes, which makes a large volume of measurement possible. For example, a 1-m inter-electrode spacing for a Wenner array results in a volume of measurement of more than 3 m^3. This large volume of measurement integrates the high level of local-scale variability often associated with EC_a measurements.

Because EC_e is regarded as the standard measure of salinity, a relation between EC_a and EC_e is needed to relate EC_a to salinity. The relationship between EC_a and EC_e is linear when EC_a is above 2 dS m^{-1} and is dependent on soil texture as shown in Fig. A3. Rough approximations of EC_e from EC_a in dS m^{-1} when $EC_a \geq 2$ dS m^{-1} are: $EC_e \approx 3.5 \cdot EC_a$ for fine-textured soils, $EC_e \approx 5.5 \cdot EC_a$ for medium-textured soils, and $EC_e \approx 7.5 \cdot EC_a$ for coarse-textured soils. For $EC_a < 2$ dS m^{-1} the relation between EC_a and EC_e is more complex. In general, at $EC_a \geq 2$ dS m^{-1} salinity is the dominant conductive constituent; consequently, the relationship between EC_a and EC_e is linear. However, when $EC_a <$ 2 dS m^{-1} other conductive properties (*e.g.,* water and clay content) and properties influencing conductance (*e.g.,* bulk density) have greater influence. For this reason, it is recommended that below an EC_a of 2 dS m^{-1} the relation between EC_a and EC_e is established by calibration. The calibration between EC_a and EC_e is established by measuring the EC_e of soil samples taken at a minimum of 3–4 locations within a study area where associated EC_a measurements have been taken. These samples should reflect a range of EC_as and should be collected over the volume of measurement for the EC_a technology used (*i.e.,* ER or EMI).

<u>Electromagnetic Induction</u>

Electromagnetic induction consists of a transmitter coil located at one end of the EMI instrument that 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 EC_a. The amplitude and phase of the secondary field will differ from those of the primary field as a result of soil properties (*e.g.,* clay content, water content, salinity), spacing of the coils and

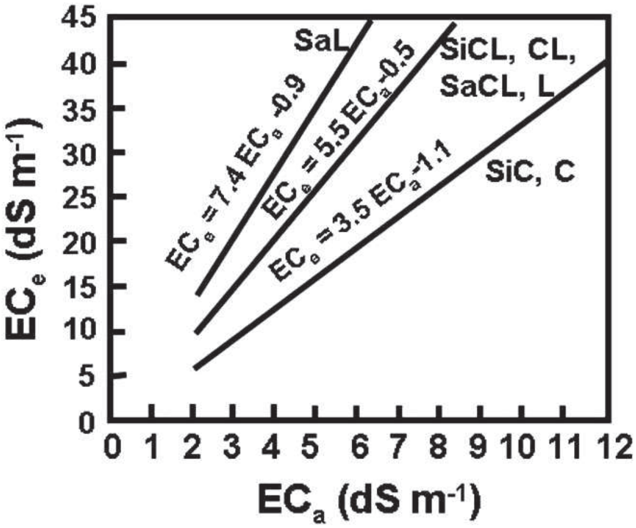

Figure A3. Relationships between EC_a and EC_e for representative soil types found in the northern Great Plains, USA. Modified from Rhoades and Halvorson (1977).

their orientation, frequency, and distance from the soil surface (Hendrickx and Kachanoski, 2002).

The most commonly used EMI conductivity meters in soil science and in vadose zone hydrology are the Geonics[2] EM31 and EM38 and the DUALEM-2[3]. The EM38 has had considerably greater application for agricultural purposes because the depth of measurement corresponds roughly to the root zone (*i.e.*, generally 1 to 1.5 m.). When the instrument is placed in the vertical coil configuration (EM_v, *i.e.*, coils are perpendicular to the soil surface) the depth of measurement is about 1.5 m and in the horizontal coil configuration (EM_h, *i.e.*, coils are parallel to the soil surface), the depth of the measurement is 0.75–1.0 m. The EM31 has an inter-coil spacing of 3.66 m, which corresponds to a penetration depth of 3 and 6 m in the horizontal and vertical dipole orientations, respectively, which extends well beyond the root zone of agricultural crops. However, the EM38 has one major pitfall, which is the need for calibration, which the DUALEM-2 does not require. Further details about and operation of the EM31 and EM38 equipment are discussed in Hendrickx and Kachanoski (2002). Documents concerning the DUALEM-2 can be found online at http://www.dualem.com/documents.html (verified 27 Sept. 2012).

Apparent soil electrical conductivity measured by EMI at $EC_a < 1.0$ dS m^{-1} is given by Eq. (A5) from McNeill (1980),

$$EC_a - \frac{4}{2\pi\mu_0 f s^2}\left(\frac{H_s}{H_p}\right) \quad (A5)$$

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

Both ER and EMI are rapid and reliable technologies for the measurement of EC_a, each with its advantage and disadvantage. The primary advantage of EMI over ER is that EMI does not require physical contact with the soil, so it can be used on dry and stony soils that would not be amenable to ER equipment. The primary advantage of ER over EMI is the ease of instrument calibration. Calibrating the EM31 and EM38 is more involved than for ER equipment. However, as previously mentioned there is no need to calibrate the DUALEM-2.

Profiling of soil EC_a at various depth increments using ER is a straightforward calculation and process. For example, discrete depth intervals of soil EC_a can be determined with the Wenner array by measuring the EC_a of successive layers by increasing the inter-electrode spacing from a_{i-1} to a_i and using Eq. (A6) from Barnes (1952) for resistors in parallel:

$$EC_x = EC_{a_i - a_{i-1}} - \frac{(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} - a_{i-1})}{(a_i - a_{i-1})} \quad (A6)$$

where a_i is the inter-electrode spacing, which equals the depth of sampling and a_{i-1} is the previous inter-electrode spacing, which equals the depth of previous sampling. Unlike ER, profiling of EC_a using EMI, though theoretically possible, is complex (Rhoades and Corwin 1981; Corwin and Rhoades, 1982; Rhoades *et al.,* 1990; Borchers *et al.,* 1997; Hendrickx *et al.,* 2002; Morris, 2009) and has resulted in limited application for this purpose.

Because of the different response functions of ER and EMI instruments with depth, a comparison of EC_a measurements taken for the same volume of soil will not be the same except by coincidence.

Time Domain Reflectometry

Time domain reflectometry (TDR) was initially adapted for use in measuring water content, 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

[2] 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.

[3] DUALEM Inc., Milton, Ontario, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

measured. Later, Dalton *et al.* (1984) demonstrated the utility of TDR to also measure EC_a. The measurement of EC_a with TDR is based on the attenuation of the applied signal voltage as it traverses the medium of interest with the relative magnitude of energy loss related to EC_a (Wraith, 2002).

By measuring ε, θ can be determined through calibration (Dalton, 1992). The ε is calculated with Eq. (A7) from Topp *et al.* (1980),

$$\varepsilon = \left(\frac{ct}{2l}\right)^2 = \left(\frac{l_a}{lv_p}\right)^2 \tag{A7}$$

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

By measuring the resistive load impedance across the probe (Z_L), EC_a can be calculated with Eq. (A8) from Giese and Tiemann (1975),

$$EC_a = \frac{\varepsilon_0 c}{l} \cdot \frac{Z_0}{Z_L} \tag{A8}$$

where ε_0 is the permittivity of free space (8.854×10^{-12} F m^{-1}), Z_0 is the probe impedance (Ω), and $Z_L = Z_u[(2V_0/V_f)-1]^{-1}$ where Z_u is the characteristic impedance of the cable tester, V_0 is the voltage of the pulse generator or zero-reference voltage, and V_f is the final reflected voltage at a very long time. To reference EC_a to 25°C, Eq. (A9) is used:

$$EC_a = K_c f_t Z_L^{-1} \tag{A9}$$

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

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

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