United States Department of Agriculture | **Natural Resources Conservation Service** | **11 Campus Boulevard Suite 200 Newtown Square, PA 19073**

Subject: Soils – Electromagnetic Induction (EMI) training

Date: 8 March 2007

To: Mike Risinger
MO9 Leader / State Soil Scientist
USDA-NRCS
101 South Main Street
Temple, Texas

Purpose:
The purpose of this field trip was to provide training on the use and operation of the EM38 meter, Allegro field computer and related software programs; and to demonstrate the potential of using EC_a data as an additional layer of soil information to improve the efficacy of soil surveys and the quality and quantity of soil data collection.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Shanna Dunn, Resource Soil Scientist, USDA-NRCS, Corpus Christi, TX
Dwight Head, Zone Engineer, USDA-NRCS, Corpus Christi, TX
Bruce Henderson, Zone Agronomist, USDA-NRCS, Corpus Christi, TX
Juan Pena, District Conservationists, USDA-NRCS, Raymondville, TX
John Lloyd Reilley, Natural Resource Specialist, USDA-NRCS, E Kika De La Garza Plant Material Center, Kingsville, TX
Dean Santistevan, Engineer, USDA-NRCS, San Benito, TX

Activities:
All activities were completed during the period of February 26 to March 2, 2007.

Summary:

1. Field training was provided on the operation of the EM38 meter, DAS70 Data Acquisition System, and supporting software. For each field site, an EMI survey was completed and the resulting apparent conductivity (EC_a) data transferred, processed, and displayed as two-dimensional plots using different software programs. Participants interpreted the spatial EC_a patterns that appeared on these plots. At the sites selected for this field visit, spatial EC_a patterns were related principally to differences in the soluble salt contents.

2. In-depth instructions were provided to Shana Dunn. Shana is commended for her attention to instructions, quick mastery of subject matters, and enthusiasm in tackling this technology. However, the information overload was acute during this brief one week period. A training DVD covering the fundamentals of this system has been provided by the National Soil Survey Center, to help Shana refresh her memory on the procedures covered this week.

3. Field studies demonstrated the potential of using EMI for monitoring and assessing salt-affected soils in the Rio Grande Plain and Gulf Coast Prairie of south Texas. Dwight Head and Dean Santistevan noted the effectiveness of EMI for detecting older drainage tiles. They felt that EMI may be used to assess the adequacy of designs and tile line spacings for lowering the water table and reducing the ascent of saline ground water and the concentration of salts in soil profiles.

4. Surveys results have been shown in this report using both Surfer and ESAP software. The ESAP software has been made available to the Zone 3 Office. This software consists of several programs, three of which were used during this investigation. The ESAP-RSSD program can generate three different optimal sampling designs (6, 12, and 20 points) for the collection of soil samples and the development of predictive models. The ESAP-SaltMapper program is a plotting program design to generate, display and plot 2-D raster maps of the EC_a data. The ESAP-Calibrate program is a data analysis program, which is used to covert measured EC_a into soil salinity based on either stochastic or deterministic models. The stochastic modeling program requires soil data; the deterministic modeling program uses Rhoades dual-pathway conductance model and does not require field data.

5. To be effective in south Texas, a mobile EMI platform is needed. This will require the fabrication of a sled or cart and the purchase of a 7.5 m cable from Geonics Limited. Mobile field vehicles (ATVs) with EMI and GPS permit the rapid surveying of large tracts of land. In open fields, mobile surveys results in larger amounts of data collected, more comprehensive coverage of sites, greater acquisition efficiency, and less operator fatigue. Cannon et al. (1994) reported that mobile EMI surveys increased productivity by a factor of five over traditional pedestrian surveys. Freeland et al. (2002) recommend the use of mobile EMI surveys over pedestrian EMI surveys for larger survey areas and whenever the total number of observations exceeds 1600 data points. However, in some terrains, mobile EMI surveys are impractical and pedestrian surveys must be carried out.

6. Results contained in this trip report are interpretative and based on the methods and procedures used. As no sampling was carried out during the EMI surveys, interpretations are constrained.

It was my pleasure to work in Texas and to be of assistance to your staff, and especially Shana Dunn. I wish to assure you of the continued assistance of the National Soil Survey Center in helping you to explore and develop the use of EMI among soil scientists in Texas.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
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Background:
Soil surveys are expensive, time-consuming, and labor-intensive endeavors. In order to reduce the expenditure of resources, alternative methods are needed to ease and expedite fieldwork, provide more information, and improve the assessment of soils and soil properties. Electromagnetic induction (EMI) has demonstrated potential for identifying differences in soils and soil properties and inclusions in soil delineations (Fenton and Lauterbach, 1999). Because of its speed and ease of use, EMI has immense advantages over traditional survey techniques. Because of the larger number of measurements, maps prepared from EMI data provide higher levels of resolution than soil maps prepared with conventional tools or survey methods (Jaynes, 1995).

Electromagnetic induction measures the apparent conductivity (EC_a) of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in EC_a are produced by differences in the electrical conductivity of earthen materials. Electrical conductivity is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). The EMI response represents a single, depth-weighted estimate that reflects all of these factors over the depth of influence of the electromagnetic field. The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). In soils, EC_a is mainly affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston, et al., 1997).

Apparent conductivity provides an additional layer of soil information and is used to infer and map differences in soils and soil properties. In many areas, spatial EC_a patterns corresponded well with soil patterns shown on soil survey maps (Jaynes, 1995). Stafford (2000) observed that EC_a is often a good substitute for spatially varying soil properties that are not easily sensed or mapped such as clay or moisture contents. However, a weakness of this interpretative process is equivalence: simultaneous variations in more than one property may result in equivalent (or similar) EMI responses. In many landscapes, variations in more than one soil properties create interpretational ambiguities when attempting to relate EC_a to a specific soil property. Because of equivalence, a functional analysis of each soil-landscape or management units is often required to decipher the exact site-specific causes for variations in EC_a (Sommer et al., 2003).

Interpretations of EC_a data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in EC_a have been used to infer changes in soils and soil properties (Kravchenko et al., 2002; Doolittle et al., 1996 and 1994; Sudduth et al., 1995; Jaynes et al., 1993). Electromagnetic induction has been used to assess depths to claypans (Sudduth et al., 1995; Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993), soil drainage classes (Kravchenko et al., 2002) and soil salinity (Rhoades and Corwin, 1981). It has also been used to estimate soil water (Sheets and Hendrickx, 1995; Kachanoski et al., 1988), clay (Sommer et al., 2003; William and Hoey, 1987), exchangeable Ca and Mg (McBride et al., 1990), and soil organic carbon (Jaynes, 1996) contents, as well as field-scale leaching rates of solutes (Slavich and Yang, 1990) and herbicide partition coefficients (Jaynes et al., 1994). EMI has also been used as a soil-mapping tool to assist precision agriculture (Jaynes, 1995; Jaynes et al., 1995; Sudduth et al., 1995) and to evaluate soil properties that affect yields (Johnson et al., 2001). Jung et al. (2005) used EC_a to estimate several soil quality properties in the upper 30 cm of soil profiles. In each of these studies, EC_a was either directly related to the soil property under investigation or the soil property (e.g., soil organic carbon) was associated with changes in a property (e.g., moisture contents) that is sensed with EMI.

Electromagnetic induction surveys are commonly conducted with a field computer, which simultaneously records EC_a and global-positioning system (GPS) data. The speed and ease at which these data are recorded greatly reduces survey time and makes practical the surveying of large areas. Kitchen et al. (2005 and 2003) discuss the integration of these data sets to improve soil interpretations. A routine and convenient method of interpreting geo-referenced EC_a data is with graphic displays. Geographical information systems (GIS) are considered the most effective tool to organize, manipulate, and display both soil and EC_a data (Corwin and Lesch, 2005). However, the integration of EC_a data into GIS is presently not well documented or frequently undertaken.

Salt-Affected Soils:

All of the survey sites visited in south Texas were salt-affected. As a consequence, a discussion of the use of EMI for soil salinity assessments is essential. In order to optimize water management practices, conserve water, and minimize salinization, changes in soil salinity must be mapped and monitored. In the early 1980s, EMI gained quick acceptance by soil scientists and agronomists involved in salinity mapping. Presently, EMI is considered the most useful method for the rapid field identification and mapping of soil salinity (Johnston et al., 1997). In areas of saline soils, the concentration of dissolved salts is the main factor affecting EC_a (van der Lelij, 1983). William and Baker (1982) estimated that 65 to 70 percent of the variance in EC_a is the result of changes in the concentration of soluble salts alone. Studies have demonstrated that EMI can provide reasonably accurate estimates of soil salinity (William and Baker, 1982, van der Lelij, 1983, Diaz and Herrero, 1992). In these studies, moderate to high correlations have been found between EC_a and soil salinity.

A major challenge in using EMI for soil salinity mapping has been the conversion of apparent conductivity (EC_a) into a more commonly used measure of soil salinity (EC_e). A number of models have been developed that relate EC_a to EC_e (Johnston et al., 1996; Lesch et al., 1995a and 1995b; Cook et al., 1992; Corwin and Rhoades, 1990; Slavich, 1990; McKenzie et al., 1989; Rhoades et al., 1989a and 1989b; and Wollenhaupt et al., 1986). Most models require the collection of soil samples and the development of predictive equations. Statistical and deterministic approaches have been used to convert EC_a data into soil salinity (Lesch et al., 2005). These approaches are available in the ESAP Software Suite for Windows that has been developed by the USDA-ARS, Salinity Laboratory (Riverside, CA). The statistical approach requires the collection of soil samples and the development of regression calibration models. Data are commonly transformed to increase the precision of the standard error estimates. To assess prediction accuracy, the competing models are compared and the regression model with the smallest prediction sum of the squares is selected (Lesch et al., 2005). The deterministic approach uses a pre-specified soil conductivity model which can provide meaningful estimates of field salinity and minimizes the need for field calibration (Lesch et al., 2005). Rhoades et al. (1989a) developed the *dual-pathway parallel conductance* model based on extensive sampling in the arid southwestern United States. Data for this model were collected from 900 sites, 10 different soil types, and an area of 39 km^2. The model's intercept is closely related to field capacity water and clay contents (Rhoades et al., 1989b). Separate equations were developed for normal, uniform and inverted salinity profiles. The *dual-pathway parallel conductance* model has been shown to be generally reliable provided that the soil water content does not drop substantially below field capacity. Lesch and Corwin (2003) noted that the soil moisture content does not become an issue with this model unless the relative amount drops below 65 percent. The model is referenced to 25^o C for the specific depth zone sampled.

Most procedures used to convert EC_a into EC_e rely on measurements made in both the horizontal and vertical dipole orientations. Difference in measurements collected in the horizontal and vertical dipole orientations provide an indicator as whether water movement in the soil profile is typified by leaching or capillary rise (Hendrickx et al., 1992). However, Johnston et al. (1996), following the procedures of McKenzie et al. (1989) developed several regression equations relating EM38 measurements, taken in either the vertical or horizontal dipole orientations, to a depth-weighted EC_e value (weighted according to the response of the EM38 meter). They also developed equations for an average reading for the horizontal and vertical dipole measurements at each site and related this to a mean EC_e for the 0 to 1.2 m depth.

It must be remembered that models are not perfect and tend to be both time dependent and site specific (Lesch et al., 1998). Lesch et al. (1998) noted that errors in instrument calibration, instrument-to-instrument variations, variations in soils, moisture, temperature, and differences in the distribution of salts within soil profiles are factors that contribute to the time and field dependencies of models. Statistical models are often only valid for the geographic area and soil types from which the relationships were derived.

Equipment:

The EM38 meter is manufactured by Geonics limited (Mississauga, Ontario).[1] This meter weighs about 1.4 kg (3.1 lbs) and needs only one person to operate. No ground contact is required with this instrument. The EM38 meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998). An EM38DD meter (Geonics Limited) was used in a mobile survey at the Kerr Site in Willacy County. Geonics Limited (2000) describes the operating procedures for this meter. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal orientation with only the receiver switched on). The EM38DD meter weighs about 2.8 kg (6.2 lbs), is portable, and requires only one person to operate. It has the same effective penetration depths as the EM38 meter.

Geonics' DAS70 Data Acquisition System is used with the EMI meters to record and store both EC_a and position data.[1] The acquisition system consists of the EM38 meter, an Allegro CX field computer (Juniper Systems, North Logan, UT), and a Garmin GPS Map 76 receiver (with CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack)(Olathe, KS).[1] When attached to the acquisition system, the EMI meter is keypad operated and measurements can be automatically triggered. The NAV38, DAT38W, NAV38DD, Trackmaker38, and Trackmaker38DD software programs developed by Geomar Software Inc. (Mississauga, Ontario) were used to record, store, and process EC_a and GPS data.[1]

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct simulations of EC_a data.[1] Grids of EC_a data shown in this report that were created with SURFER used kriging methods with an octant search. Two-dimensional plots were also prepared using the ESAP Software Suite for Windows (Version 2.35R) that was developed by the USDA-ARS, Salinity Laboratory (Riverside, CA). A copy of the ESAP Software was left with Shana Dunn and the Zone 3 Office and available online through the web.

Field Methods:

The EM38 meter was generally operated in the deeper-sensing (0 to 1.5 m) vertical dipole orientation. Only quadrature phase (conductivity) data were collected. Data are expressed as values of EC_a in milliSiemens/meter (mS/m). The EM38 meter was operated in either the continuous (measurements recorded at 1-sec intervals) or station-to station (measurements manually recorded in both dipole orientations at each station) modes with the DAS70 system. Using either the DAT38W or NAV38 programs, both GPS and EC_a data were simultaneously recorded on the Allegro CX field computer. While surveying, the EM38 meter was held about 5 cm (about 2 inch) above the ground surface and orientated with its long axis parallel to the direction of traverse (see Figure 1). Surveys were completed by walking at a uniform pace, in a random or back and forth pattern across each site.

A mobile (using an ATV) EMI survey was conducted at the Kerr site in Willacy County. A mobile EMI survey provides more comprehensive site coverage, in a shorter period of time, and with less effort than the pedestrian surveys. In this survey, an EM38DD meter was towed behind an ATV in a plastic toboggan at speeds of 1 to 3 m/sec. Using the NAV38DD program, both GPS and EC_a data were simultaneously recorded on an Allegro CX field computer.

The EC_a measurements discussed in this report were not temperature corrected.

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

Figure 1. Shanna Dunn completes an EMI survey at the Chapman Ranch Site in Nueces County. She is simultaneously operating an EM38 meter, Allegro field computer, and Garmin GPS receiver.

Study Sites:
Study sites are located in the Gulf Coast Saline Prairies (MLRA 150B) and the Lower Rio Grande Plain (MLRA 83D) (USDA-NRCS, 2006). EMI surveys were conducted in four counties (Hidalgo, Kleberg, Nueces, and Willacy). These surveys were conducted in some of the principal soils that typify these major land resource areas. The taxonomic classification of the soils named in the map units in which EMI surveys were conducted are listed in Table 1.

Table 1.
Taxonomic classifications of the soils identified in the names of the soil map units at the study sites.

Soil Series	Taxonomic Classification
Greenhill	Hyperthermic, uncoated Ustic Quartzipsamments
Hidalgo	Fine-loamy, mixed, hyperthermic Typic Calciustolls
Madre	Siliceous, hyperthermic Sodic Psammaquents
Malaquite	Sandy, siliceous, hyperthermic Typic Halaquepts
Mustang	Siliceous, hyperthermic Typic Psammaquents
Raymondville	Fine, mixed, superactive, hyperthermic Vertic Calciustolls
Victoria	Fine, smectitic, hyperthermic Sodic Haplusterts

Padre Island Site:
The Padre Island site is located within the Padre Island National Seashore in Kleberg County. The site is located at the western end of Bird Island Basin Road. The site is in native, salt-tolerant vegetation. Polygons of Madre-Malaquite complex, 0 to 1 % slopes, occasionally flooded (M.U. 282), and Greenhill-Mustang complex, 0 to 12 % slopes, occasionally flooded (M.U. 399), dominate this site. The very deep, poorly drained Madre, Malaquite and Mustang soils formed in sandy eolian and storm washover sediments on barrier islands. These soils are salt-

affected and subject to occasional flooding by high storm surges and are ponded after periods of heavy rainfall. The very deep, excessively drained Greenhill soils formed in deep sandy eolian sediments on dunes.

Doan Site:

The Doan site is located along County Road 3400 W in Willacy County. The survey site spans the boundary separating two irrigated fields. At the time of this survey, the eastern field was bedded and recently seeded to sorghum. The western field was in sugarcane. Both fields are drained by buried polyurethane tile lines. The Doan site is located within a polygon of Raymondville clay loam (M.U. Rd). The deep, moderately well drained Raymondville soil formed in calcareous, moderately-fine and fine textured sediments. Within depths of 40 inches, the salinity and SAR of Raymondville soils can range from 0 to 4 mmhos/cm and 0 to 2, respectively (http://soildatamart.nrcs.usda.gov/). A seasonal water table occurs at depths of 2.5 to 8 feet in some irrigated areas.

Kerr Site:

The Kerr site is located along Farm to Market Road 1761 in Willacy County. The survey site is located in a cultivated field that is irrigated, but lacks subsurface drainage lines. This 40-acre field is located within a single polygon of Hidalgo sandy clay loam (M.U. HoA). The very deep, well drained Hidalgo soil formed in calcareous, moderately-fine textured sediments. Within depths of 40 inches, the salinity and SAR of Hidalgo soils can range from 0 to 4 mmhos/cm and 0 to 10, respectively (http://soildatamart.nrcs.usda.gov/). When irrigated, water may accumulate at depths of 4 to 8 feet below the surface.

Leist Site:

The Leist site is located along Farm Road 1921 in Hidalgo County. The survey site is located in a non-irrigated cultivated field. Buried polyurethane tile lines were installed at this site in September 2005. The study site is located within polygons of Raymondville clay loam, 0 to 1 percent slopes (M.U. 52), and Hidalgo fine sandy loam, 0 to 1 percent slopes (M.U. 25). Within depths of 40 inches, the salinity of Hidalgo and Raymondville soils can range from 0 to 4 mmhos/cm (http://soildatamart.nrcs.usda.gov/). Figure 2 is a picture that was taken in the summer of 2005 from the southwest corner of the Leist Site.

Figure 2. This picture of the Leist Site was taken in the summer of 2005. The view is from the southwest corner of the survey site looking north.

Chapman Farm Site:
The Chapman Farm site is located along County Highway 43 in Nueces County. The survey site is in CRP. The study site is located within a polygon of Victoria clay, 0 to 1 percent slopes (M.U. VcA). The very deep, well drained Victoria soils formed in clayey deltaic and marine sediments of the Beaumont formation. Within depths of 40 inches, salinity ranges from 1 to 8 mmhos/cm and SAR ranges from 1 to 10 (http://soildatamart.nrcs.usda.gov/).

Results:

Padre Island Site:
Table 2 summarizes the results of this survey. Within the Padre Island site, EC_a was exceedingly variable and ranged from about 5.4 to 1024 mS/m. EC_a averaged 310.3 mS/m with a standard deviation of 297.1 mS/m. One-half of the EC_a measurements were between 111.8 and 360.6 mS/m. The high EC_a values and large range are attributed to the high salt contents of ground and surface waters and the topographic diversity of this site. These sandy soils are exceedingly resistive on higher-lying dunal areas (Greenhill soil) and conductive on lower-lying areas of washover sediments (Madre, Malaquite, and Mustang soils).

Table 2
Basic Statistics for the EC_a data that was collected with the EM38 meter at the Padre Island Study Site.
(EC_a measurements are expressed in mS/m)

Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
947	5.4	111.8	360.6	1023.9	310.3	297.1

The spatial EC_a patterns within the Padre Island site are shown in Figures 3 and 4. In Figure 3, the isoline interval is 50 mS/m. A tidal salt flat is evident by the exceptionally high EC_a in the northwest corner of the site. With the exception of some sparse stands of salt tolerant plants, this area was devoid of vegetation and had an EC_a greater than 700 mS/m. A drainageway crosses the north-central portion of the study site from east to west. Soils within this drainageway are saturated with saline ground waters and have an EC_a greater than 200 mS/m. Areas with anomalously high (> 200 mS/m) EC_a are believed to represent the Malaquite soil with its high salt content. The location of a low dune is identifiable in Figure 3 by the insular area of relative low EC_a (<50 mS/m) in the southeastern portion of the study site. The aeolian sands that compose this dune are electrically resistive and the depth to saline groundwater exceeds the effective penetration depth of the EM38 meter on this higher-lying feature. The dominant soil on the dune is Greenhill. The spatial EC_a patterns shown in Figure 3 appear to conform to distinct communities of plants and reflect differences in soil type and salinity.

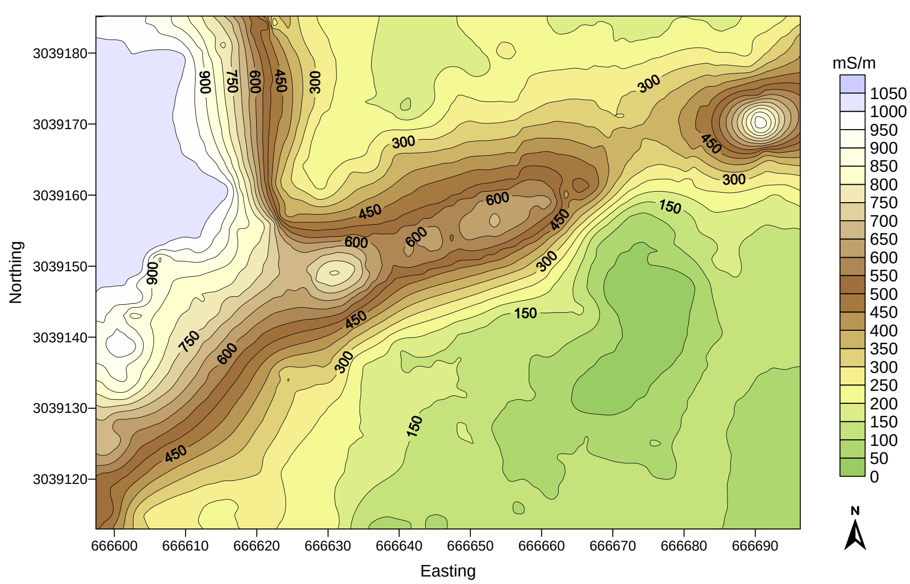

Figure 3. This plot of spatial EC_a *patterns within the Padre Island Site was prepared using Surfer software.*

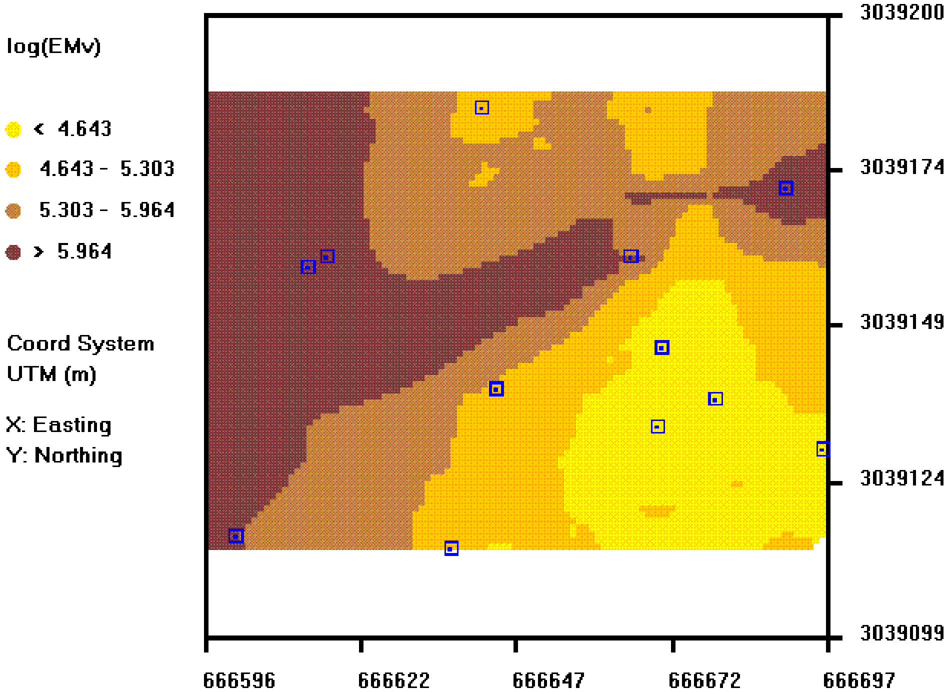

Figure 4. This plot of spatial EC_a *patterns within the Padre Island Site was prepared using ESAP Software Suite. Data has been log transformed and 12 optimal sampling sites are shown.*

Figure 4 is an alternate plot of spatial EC_a patterns with the Padre Island site. This plot was prepared with the ESAP Software Suite. This software has a less robust plotting package than Surfer Software, but does produce a suitable image with the same general trends that are shown in the plot prepared with Surfer (see Figure 3). One of the statistical programs available in ESAP is the Response Surface Sampling Design (RSSD). This program generates an optimal sampling design based on the EC_a data. The optimal sampling design provides the best possible information for generating predictive models of soil properties.

Because of the high salinity (extensive areas greater than 400 mS/m), a natural log transformation has been applied to the data shown in Figure 4. Based on the response surface sampling design, twelve optimal sampling sites have been selected for the collection of soil samples and the generation of predictive models of soil salinity. The locations of the optimal sampling sites are shown in Figure 4 as blue-colored squares.

Doan Site:

Table 3 summarizes the results of the Doan site survey. Within the Doan site, EC_a ranged from 83.5 to 294.8 mS/m. EC_a averaged 188.2 mS/m with a standard deviation of 45.40 mS/m. One-half of the EC_a measurements were between 147.4 and 226.8 mS/m. Areas of salt-affected soils were evident by bare spots and stunted sugar cane growth in the western field. These salts are derived from capillary rise and discharge from the groundwater.

Table 3
Basic Statistics for the EC_a data that was collected with the EM38 meter at the Doan Study Site.
(EC_a measurements are expressed in mS/m)

Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
4994	83.5	147.4	226.8	294.8	188.2	45.4

The spatial distribution of EC_a within the Doan site is shown in Figures 5 and 6. In Figure 5, the isoline interval is 10 mS/m. [On this and on all succeeding Surfer plots of the survey sites, the same color scale and intervals have been used for comparative purposes.] In Figure 5, the boundary line that separates the two cultivated fields is shown. Both fields have polyurethane tile lines buried at depths of 5 to 6 feet and spaced 150 feet apart. The tile lines were buried in the western field in 2000. Tile lines were buried last fall in the eastern field. These tile lines extend across each field in an east to west direction. An 8 inch collector line extends in a north to south direction along the field boundary line. Interceptor lines parallel the northern and southern boundaries of these fields. The locations of these features can be inferred from spatial EC_a patterns.

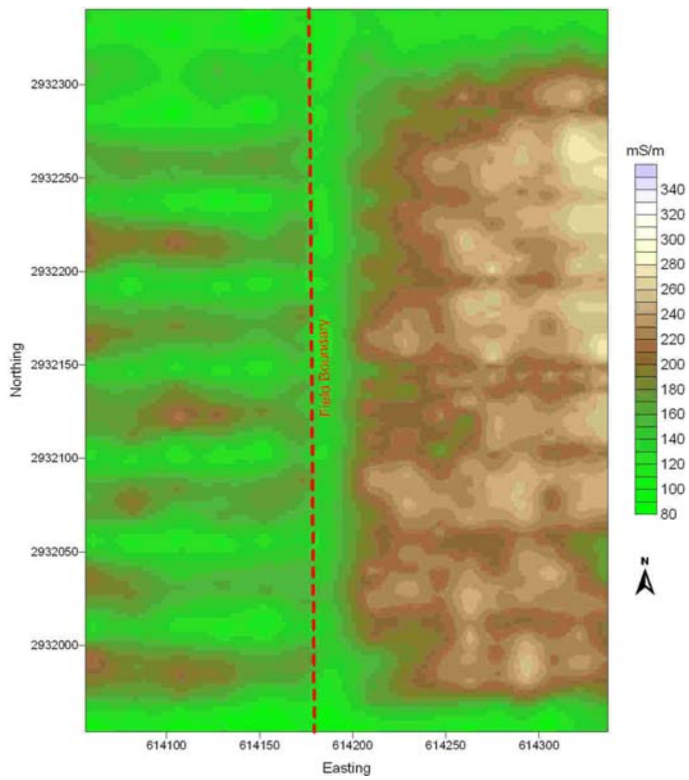

Figure 5. This plot of spatial EC_a *patterns within the Doan Site in Willacy County was prepared using Surfer software.*

The spatial EC_a patterns shown in Figure 5 are believed to principally reflect differences in the concentration of soluble salts and the effects of management. The study site is in a level area of Raymondville soil. Spatial differences in clay content are considered slight across the study area. Although the western field is in sugar cane and the eastern field has been recently planted, both fields are regard as having closely similar soil moisture contents. The difference between the two fields is most remarkable and reflects difference in soluble salt contents. In the western field, the older, more established, buried tile lines have effectively lowered the water table. As a consequence, salts (over the five year period since the tile lines were installed) have been leached to deeper depths resulting in lower concentrations in the soil profile and lower EC_a. This effect is most noticeable in areas that overlie or are nearest to the buried tile lines. The locations of the evenly-spaced tile lines are evident in the western field. Areas underlain by tiles form distinct linear patterns and have an EC_a of less than 140 mS/m. At greater distances from the buried tile lines, EC_a is higher and ranges from 140 to 240 mS/m. These areas are not as well drained by the buried tile lines and, as a consequence, the water table is higher and more salts occur in soil profiles. Low EC_a values are also recorded above the collector line that runs in a north-south direction along the field boundary line.

Tile lines in the eastern field were installed last fall and have not had sufficient time to lower the concentration of soluble salts in the soil profile. As a consequence, the eastern field has conspicuously higher EC_a. In this field, the buried tile lines are more indistinct, but some linear patterns with slightly lower EC_a are evident in Figure 5.

Figure 6 is an alternate plot of spatial EC_a patterns with the Doan site that was prepared with the ESAP Software Suite. Though constrained by a more limited number of isolines, this plot (Figure 6) effectively captures the relative difference in EC_a between the two fields, shows the same broad spatial EC_a patterns, and offers some indication of the older, more established, drainage tile system in the western field and the locations of the collector and interceptor lines.

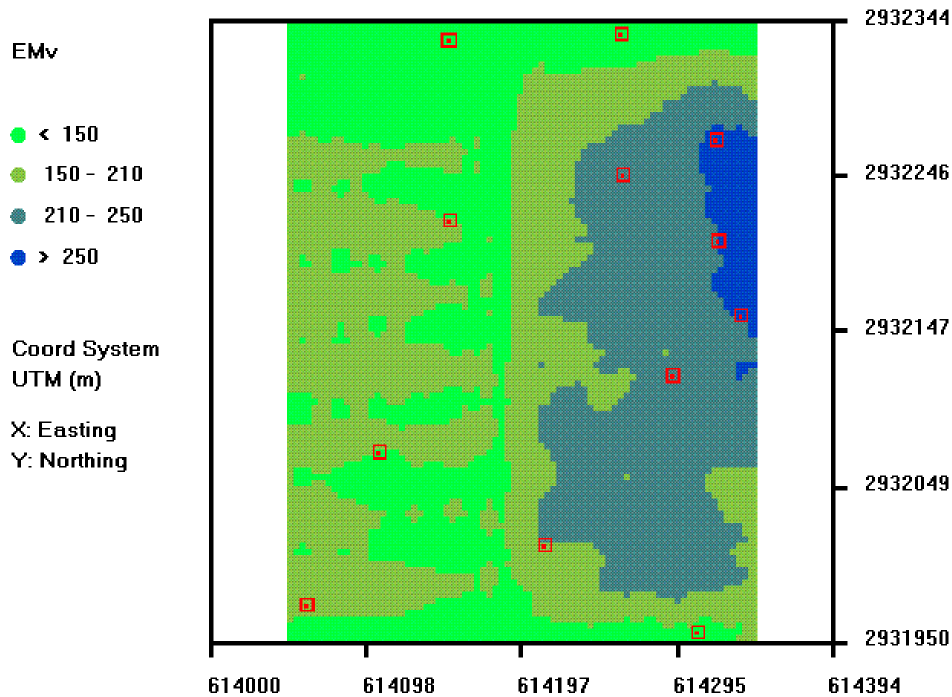

Figure 6. This plot of spatial EC_a *patterns within the Doan Site was prepared using ESAP Software Suite.*

The EC_a data used in the plot shown in Figure 6 have not been log transformed. Based on the response surface sampling design, twelve optimal sampling sites have been selected for the collection of soil samples and the development of predictive models. The locations of the optimal sampling sites are shown in Figure 6 as red-colored squares.

Kerr Site:
Table 4 summarizes the results of the survey conducted with the EM38DD meter at the Kerr site. In general, measurements obtained in the deeper-sensing vertical dipole orientation were higher than those obtained in the shallower-sensing horizontal dipole orientation. This relationship indicates that EC_a increases with increasing depth. This relationship is called a normal salt profile, and reflects increasing amounts of soluble salts with depth caused by capillary rise and discharge from the groundwater.

Within the Kerr site, in the deeper-sensing (0 to 1.5 m) vertical dipole orientation, EC_a ranged from 91.2 to 364.6 mS/m. In this dipole orientation, EC_a averaged 203.2 mS/m with a standard deviation of 40.5 mS/m. One-half of the EC_a measurements collected in the vertical dipole orientation were between 169.4 and 234.4 mS/m. Within the Kerr site, in the shallower-sensing (0 to 0.75 m) horizontal dipole orientation, EC_a ranged from 55.6 to 286.2 mS/m. In this dipole orientation, EC_a averaged 162.8 mS/m with a standard deviation of 41.7 mS/m. One-half of the EC_a measurements collected in this dipole orientation were between 129.1 and 196.8 mS/m.

Table 4
Basic Statistics for the EC_a data that was collected with the EM38DD meter at the Kerr Study Site.
(EC_a measurements are expressed in mS/m)

Dipole Orientation	Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
Vertical	2755	91.25	169.38	234.38	364.63	203.16	40.44
Horizontal	2755	55.63	129.13	196.75	286.25	162.80	41.74

The spatial distribution of EC_a within the Kerr site is shown in Figures 7 and 8. In Figure 7, the isoline interval is 10 mS/m. This field is irrigated but does not have buried drainage tiles. County Road 3400 W parallels the western (left-hand margin) margin of the site. In both plots, EC_a is lower along this boundary. This spatial pattern possibly reflects the influence of the road ditch. Two north-south orientated, linear patterns of higher conductivity are evident in the east and central portions of these plots. These patterns may represent an artifact caused by excessive ATV ground speeds and the jarring of the meter as it was propelled along the ground surface.

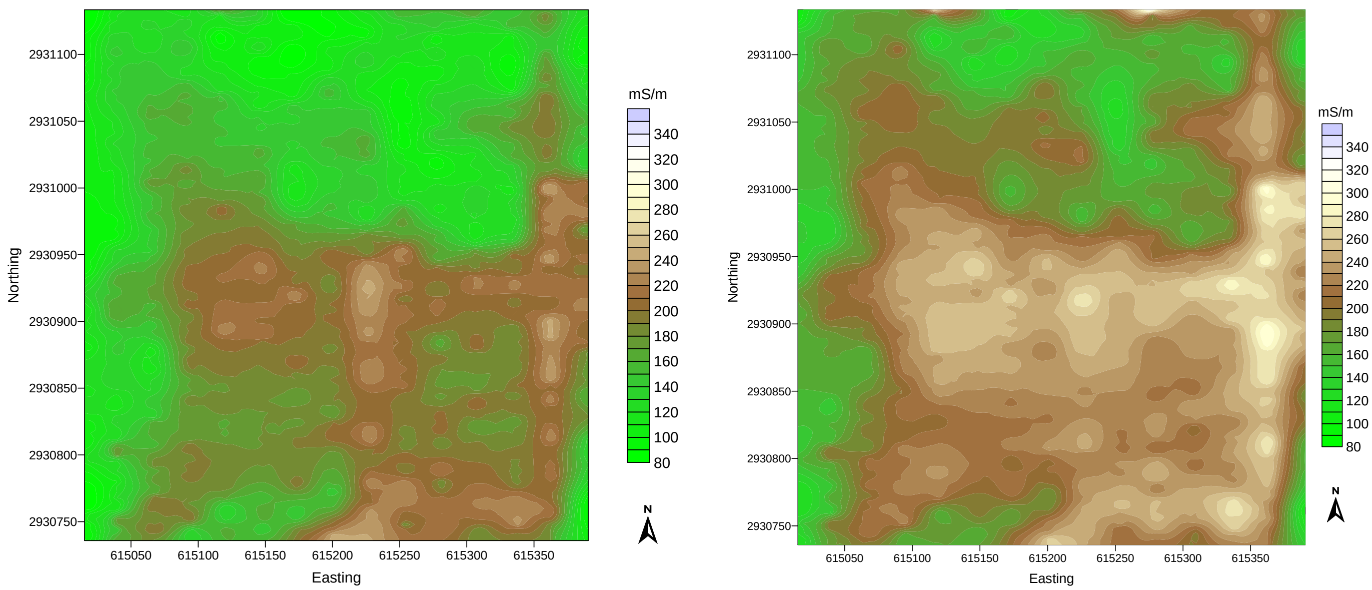

Figure 7. Data for these EC_a *plots of the Kerr Site were collected with an EM38DD meter operated in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations.*

Figure 8 is an alternate plot of spatial EC_a patterns within the Kerr site that was prepared with the ESAP Software Suite. This plot is base on data collected with the EM38DD meter in the vertical dipole orientation. Once again, the two-dimensional plots prepared using different software packages are similar. Based on the response surface sampling design, six optimal sampling sites have been selected for the collection of soil samples needed to develop predictive models. The locations of the optimal sampling sites are shown in Figure 8 as green-colored squares.

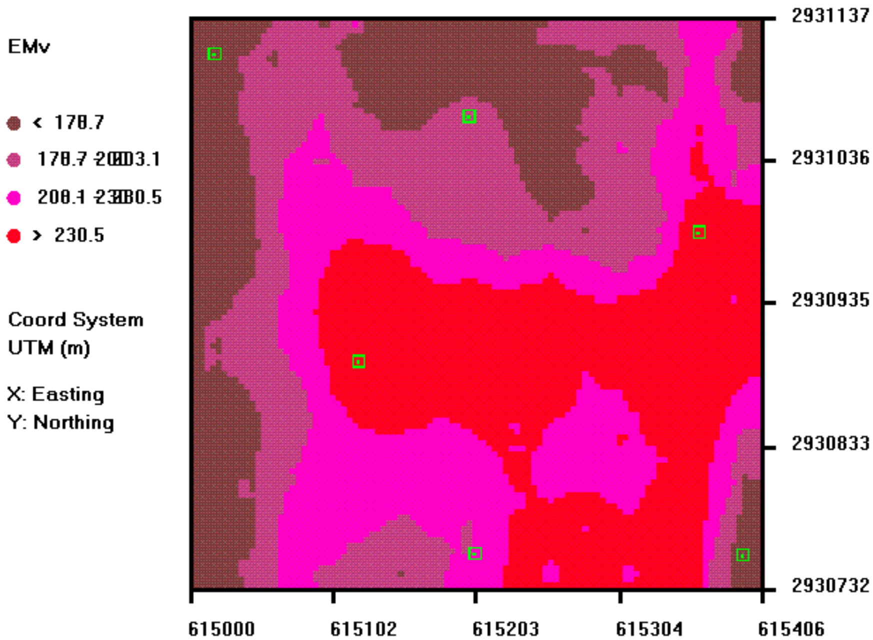

Figure 8. This plot of spatial EC$_a$ *patterns within the Kerr Site was prepared using ESAP Software Suite.*

<u>Leist Site:</u>
Table 5 summarizes the results of the Leist site survey. Within the Leist site, EC$_a$ ranged from 108.9 to 349.5 mS/m. With the EM38 meter operated in the vertical dipole orientation, EC$_a$ measurements averaged 238.0 mS/m with a standard deviation of 51.8 mS/m. One-half of the EC$_a$ measurements were between 206.1 and 277.9 mS/m. Of the three sites (Doan, Kerr, and Leist), the Leist site has the highest averaged and most variable EC$_a$. These statistical values are attributed to generally higher soluble salt contents in the soil profiles at the Leist site. The Leist site is not irrigated and the buried drainage tiles have only been recently installed (fall 2005).

Table 5
Basic Statistics for the EC$_a$ data that was collected with the EM38 meter at the Leist Study Site.
(EC$_a$ measurements are expressed in mS/m)

Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
1226	108.9	206.1	277.9	349.5	238.0	51.8

The spatial distribution of EC$_a$ within the Leist site is shown in Figures 9 and 10. In Figure 9, the isoline interval is 10 mS/m. The locations of the EMI traverse lines and observation points are shown in Figure 9. Within this site, EC$_a$ is high. A major portion of this site has been mapped as a consociation of the fine-textured Raymondville soils. In general, EC$_a$ decreases towards the northeast where a polygon of medium-textured Hidalgo soils has been mapped. In Figure 9, the locations of recently buried polyurethane tiles are not distinguishable in the spatial EC$_a$ patterns. It is believed that the time has been too short since the installation of these tiles and the ensuing period too dry, to have produced a noticeable leaching effect on the salts.

Figure 10 is a plot of spatial EC$_a$ patterns within the Leist site that was prepared with the ESAP Software Suite. The spatial patterns shown in Figures 9 and 10 are similar. Based on the response surface sampling design, a full (20 sampling points) optimal sampling design has been generated for sampling and the development of predictive soil models. The locations of the optimal sampling sites are shown in Figure 10 as blue-colored squares.

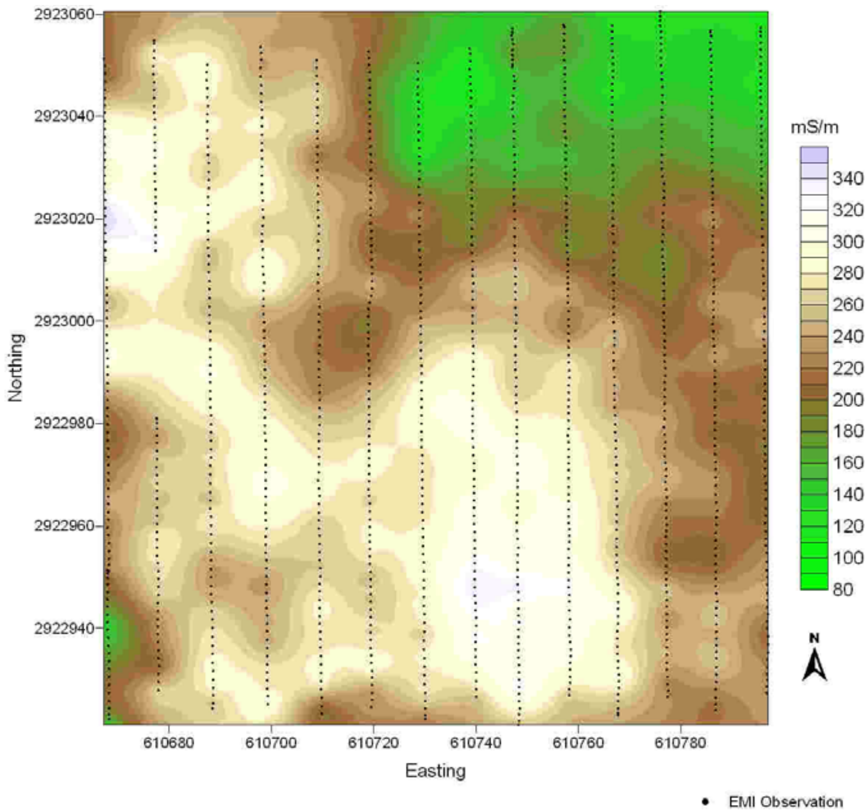

Figure 9. This plot of spatial EC_a *patterns within the Leist Site was prepared using Surfer software.*

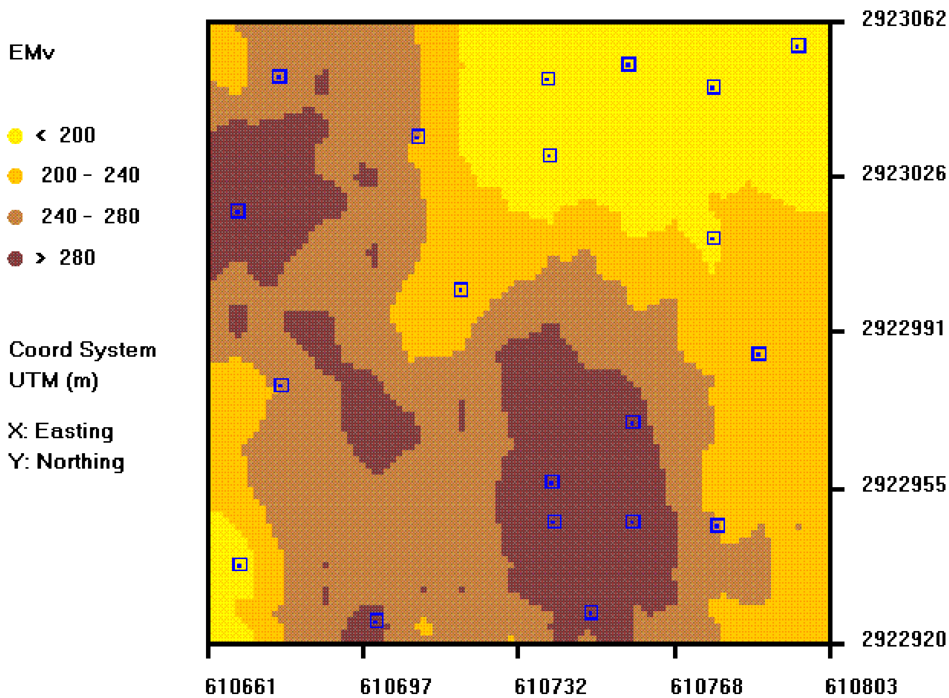

Figure 10. This plot of spatial EC_a *patterns within the Leist Site was prepared using ESAP Software Suite.*

Chapman Ranch Site:
Table 6 summarizes the results of this survey. Within the Chapman Ranch site, EC_a ranged from 130.5 to 378.1 mS/m. Within this study site, EC_a averaged 231.6 mS/m with a standard deviation of 30.8 mS/m. One-half of the measurements were between 210.1 and 247.6 mS/m. This site has been place in CRP because of its excess salts.

Table 6
Basic Statistics for the EC_a data that was collected with the EM38 meter at the Chapman Ranch Study Site.
(EC_a measurements are expressed in mS/m)

Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
3222	130.5	210.1	247.6	378.1	231.6	30.8

The spatial distribution of EC_a within the Chapman site is shown in Figures 11 and 12. In Figure 11, the isoline interval is 10 mS/m. A comparison of Figure 11 with the soil map of the Chapman Ranch site showed close similarities between soil polygons and general spatial EC_a patterns. However, areas with highest EC_a corresponded with areas of lower salinity map units. In addition, areas with higher EC_a were more densely vegetated with stands of brush willows.

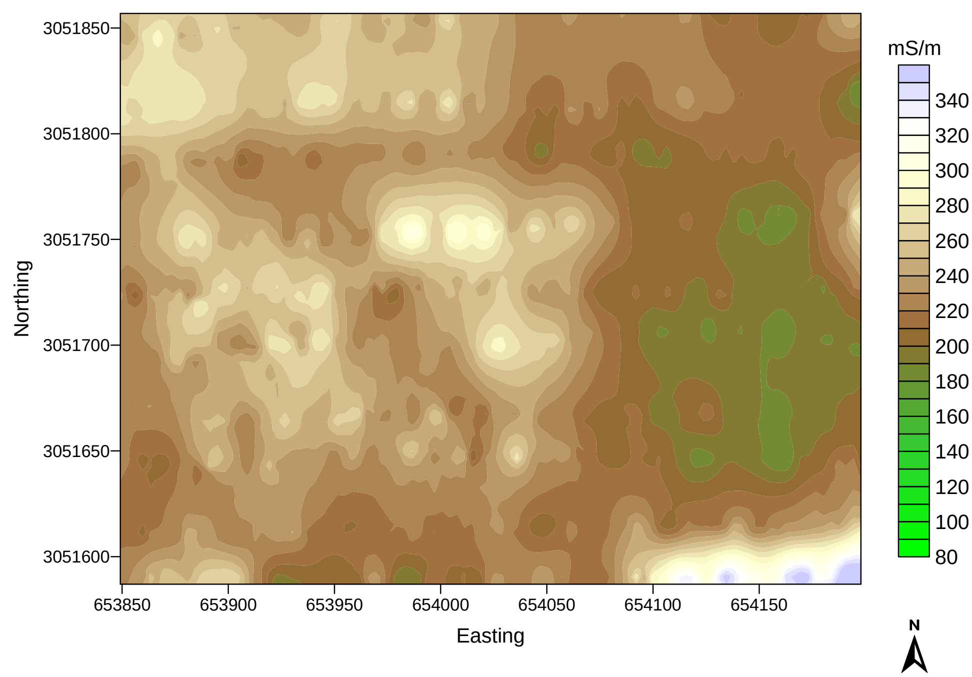

Figure 11. This plot of spatial EC_a *patterns within the Chapman Ranch Site was prepared using Surfer software.*

Figure 12 is a plot that was prepared with the ESAP Software Suite. As expected, spatial EC_a patterns of the plots that were prepared using different plotting software programs are similar. Based on the response surface sampling design, a 12 point optimal sampling design has been generated for sampling and the development of predictive soil models. The locations of the optimal sampling sites are shown in Figure 12 as blue-colored squares.

The results of the EMI surveys of the study sites have been shown using both Surfer and ESAP software. The ESAP software has been made available to the Zone 3 Office. This software consists of several programs (three of which were used during this investigation). The ESAP-RSSD program can generate three different optimal sampling designs (6, 12, and 20 points) based on the available resources to collect soil samples that are suitable to the intensity and intent of the survey. The ESAP-SaltMapper program is a plotting program design to generate, display and plot 2-D raster maps of the EC_a data. The ESAP-Calibrate program is a data analysis program, which is used to covert measured EC_a into soil salinity data by either using stochastic or deterministic models developed by the USDA-ARS Salinity Laboratory. The stochastic modeling program requires soil data; the deterministic modeling program uses Rhoades *dual-pathway conductance* model and does not require field data.

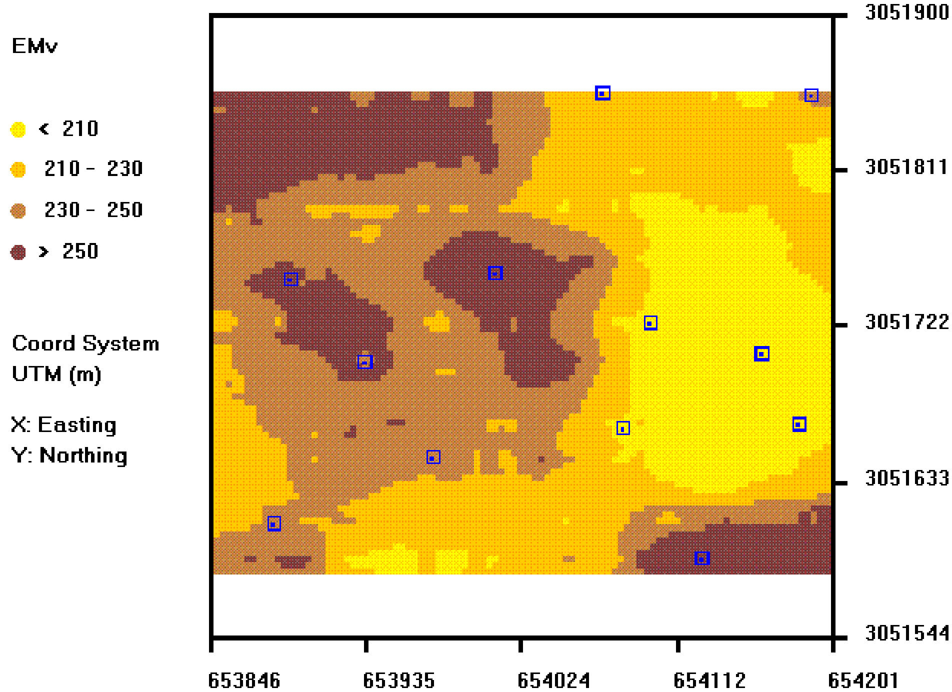

Figure 12. This plot of spatial EC_a *patterns within the Chapman Ranch Site was prepared using ESAP Software Suite.*

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