United States Department of Agriculture

NRCS

Natural Resources Conservation Service
National Soil Survey Center
Federal Building, Room 152
100 Centennial Mall North
Lincoln, NE 68508-3866

Phone: (402) 437-5499
FAX: (402) 437-5336

Subject: Soils – Geophysical **Date:** 21 October 2010

To: Steve Chick
State Conservationist
USDA-Natural Resources Conservation Service
Federal Building, Room 152
100 Centennial Mall North
Lincoln, NE 68508-3866

Purpose:
The purpose of this assignment was to provide refresher training on the use of electromagnetic induction (EMI) and introduce MLRA soil scientists to the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) software, which can be used to generate optimal soil sampling schemes and to estimate soil salinity based on apparent conductivity (EC_a) data collected with EMI meters.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Bruce Evans, MLRA Project Leader, USDA-NRCS, Lincoln, NE
Dave Kohake, Soil Scientist, USDA-NRCS, Lincoln, NE
Casey Latta, Soil Scientist, USDA-NRCS, Lincoln, NE
Nathan Roth, Soil Scientist, USDA-NRCS, Scottsbluff, NE
David Vyain, Soil Scientist, USDA-NRCS, Scottsbluff, NE
Tim White, MLRA Project Leader, USDA-NRCS, Scottsbluff, NE

Activities:
All activities were completed during the period of on 27 September to 6 October 2010.

Summary:

1. Training exercises provided soil scientists with a refresher on EMI meter calibration, field procedures, and data processing and interpretation. Soil scientists viewed and operated the newly developed EM38-MK2 meter, and the RTmap38 and RTmap38MK2 software programs. Also, soil scientists were provided with an overview and an introduction into the various programs within the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) software suite, which is designed for use with EC_a data.

2. The *Response Surface Sampling Design* (RSSD) Program of the *ESAP* software suite was discussed and training on its use provided to soil scientists. This program can be used with dense EC_a survey data to generate optimal soil sampling schemes with a limited number of soil sampling locations identified within surveyed areas based on EC_a data.

3. Using the *ESAP-Calibrate* deterministic conversion modeling methods, different field-scale salinity estimates were produced using data collected with both the EM38 and EM38MK2 meters, and different conversion formula types. Unlike the stochastic models of the *ESAP-Calibrate* program, no expression of correlation strengths between the calculated EC_a and the salinity

estimates were possible using deterministic models. Results, however, seemed reasonable.

4. Although deterministic methods in the *ESAP-Calibrate* program were used to convert EC_a into salinity, equations were not developed for use with an EMI meter operated in only one dipole orientation (Scott Lesch, personal communication 5 October 2010). However, a specific equation (using coefficients of a0=0, a1=1) was recommended for use with the EM38 meter, operated in the vertical dipole orientation. This equation produced fairly reasonable estimates of soil salinity, but for only a profile average (0-150 cm depth interval).

5. Using deterministic models, estimated soil salinity level were lower using the single-depth EC_a measurements recorded with the EM38 meter than the two-depth EC_a measurements recorded with the EM38-MK2 meter.

6. The EM38-MK2 meter has replaced the EM38 meter. The deterministic, *dual pathway parallel conductance* (DPPC) *model* was developed for data collected with an EM38 meter. Comparative studies using the EM38 and EM38-MK2 meters resulted in closely similar, deeper-sensing (0 to 150 cm) EC_a data and spatial patterns. It is known that Geonics Limited has changed the electronics of the EM38-MK2 meter to achieve increased signal stability (especially in the shallower-sensing (0 to 75 cm), 50-cm intercoil spacing). While results for the two meters appear closely similar, more field test are necessary to determine the suitability of the newly developed EM38-MK2 meter, especially with the shallower-sensing 50-cm intercoil spacing, for salinity appraisals and use with the *ESAP* program.

7. At the Minatare site in Scotts Bluff County, collected soil sample data were analyzed and regressed with EC_a data using a stochastic model. Surprisingly, no correlation was found between the data sets. The Center has never experienced this before when using the *ESAP* program. Unidentified processing errors or differences in the types of salts are suspected.

It was the pleasure of Jim Doolittle and the National Soil Survey Center to work with and be of assistance to your fine staff.

JONATHAN W. HEMPEL
Director
National Soil Survey Center

cc:
Shandy Bittle, Acting State Soil Scientist, USDA-NRCS, 100 Centennial Mall North, Room 152, Lincoln, NE 68508-3866
James Doolittle, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, USDA-NRCS, Newtown Square, PA
Bruce Evans, MLRA Project Leader, USDA-NRCS, Lincoln Service Center, 8000 South 15th, Suite C Lincoln, NE 68512
Micheal Golden, Director, Soils Survey Division, USDA-NRCS, Washington, DC
J. Cameron Loerch, National Leader, Soil Standards, USDA-NRCS, 100 Centennial Mall North, Room 152, Lincoln, NE 68508-3866
Philip Schoeneberger, Research Soil Scientist/Liaison MO-5, Soil Survey Research & Laboratory, NSSC, MS 41, USDA-NRCS, 100 Centennial Mall North, Room 152, Lincoln, NE 68508-3866

John Tuttle, Soil Scientist, Soil Survey Research & Laboratory, NSSC, P.O. Box 60,207 West Main Street, Rm. G-08, Federal Building, Wilkesboro, NC 28697
John Warner, Soil Data Quality Specialist, MO5, USDA-NRCS, 760 S. Broadway, Salina, KS 67401-4642
Cleveland Watts, MLRA Office Leader (MO 5), USDA-NRCS, 760 S. Broadway, Salina, KS 67401-4642
Larry West, National Leader, Soil Survey Research & Laboratory, NSSC, MS 41, USDA-NRCS, 100 Centennial Mall North, Room 152, Lincoln, NE 68508-3866
Tim White, MLRA Project Leader **,** USDA-NRCS, Scottsbluff Service Center, 818 Ferdinand Plaza, Scottsbluff, NE 69361-4401

Technical Report on the introduction of ESAP software to soil scientists tasked with assessing soil salinity in Nebraska (27 September to 6 October 2010).

Jim Doolittle

Background:

Soil scientist in Kansas and Nebraska are using electromagnetic induction (EMI) as a quality control tool for high intensity soil surveys and saline and sodic soil assessments. They are in periodic need of refresher EMI training and introductions to newly developed and available software and technologies. This training experience provided soil scientists with a refresher on EMI meter calibration, field procedures, and data processing and interpretation. Soil scientists viewed and operated the newly-developed EM38-MK2 meter, and the RTmap38 and RTmap38MK2 software programs. Also provided was an overview and an introduction to the various programs within the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) Software Suite for Windows (Version 2.35R), developed by the USDA-ARS, Salinity Laboratory (Riverside, CA). The *ESAP-RSSD* (Response Surface Sampling Design) software was used to generate optimal soil sampling schemes and to identify soil sampling locations within surveyed areas. The *ESAP-Salt Mapper* software was used to prepare raster maps showing plots of apparent conductivity (EC_a) data. The *ESAP-Calibrate* software was used to estimate soil salinity (EC_e) from the collected apparent conductivity (EC_a) data.

Equipment:

The EM38 and EM38-MK2 meters (Geonics Limited; Mississauga, Ontario) were used in training[1]. The EM38 meter is used by soil scientist in Central Great Plains Soil Survey Region (MO 5). This meter is no longer being produced by Geonics Limited (but the meter is still supported). The EM38 meter has been replaced by the EM38-MK2 meter. The EM38-MK2 provides simultaneous measurement of both quadrature phase (apparent conductivity) and in-phase (apparent susceptibility) components, within two distinct depth ranges, to a maximum effective depth of 1.5 m. In addition, the EM38-MK2 meter has Bluetooth functionality for wireless data transmission and can be automatic calibrated. Both the EM38 and EM38-MK2 meters require no ground contact. These meters measure the EC_a and magnetic susceptibility of soils and earthen materials. Apparent conductivity is typically expressed in milliSiemens/meter (mS/m). Apparent magnetic susceptibility is the ratio of the secondary to the primary magnetic fields, which is expressed in parts per thousand (ppt).

The EM38 meter operates at a frequency of 14,600 Hz and weighs about 1.4 kg (3.1 lbs). This meter has one transmitter and one receiver coil that are spaced 1-m apart. When placed on the soil surface, the EM38 meter has effective penetration depths of about 0.75 m and 1.5 m in the horizontal (HDO) and vertical (VDO) dipole orientations, respectively (Geonics Limited, 1998).

The EM38-MK2 meter operates at a frequency of 14,500 Hz and weighs about 5.4 kg (11.9 lbs). The meter has one transmitter coil and two receiver coils, which are separated from the transmitter coil at distances of 1.0 and 0.5 m. This configuration provides nominal penetration depths of about 1.5 and 0.75 m in VDO, and about 0.75 and 0.40 m in the HDO. In either dipole orientation, the EM38-MK2 meter provides simultaneous measurements of both the quadrature phase (apparent conductivity) and in-phase (susceptibility) components for two depth ranges. Operating procedures for the EM38-MK2 meter are described by Geonics Limited (2007).

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced data collected with the EMI meters.[1] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both GPS and EMI data[1]. The newly developed RTM38

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

and RTM38MK2 programs (Geomar Software, Inc., Mississauga, Ontario) were used with the EM38 and EM38-MK2 meters, respectively, to display and record both GPS and EC_a on the Allegro CX field computer.[2] The RTM38 and RTmap38MK2 software provide immediate tracking and viewing capabilities, displayed as a spatial color image on the Allegro CX computer. With these capabilities, operators can visually correlate spatial EC_a with soil and landform patterns as surveys progress. In addition, with this software, surveys are carried out faster, and sites can be more uniformly covered (avoiding skipping areas), and unnecessary overlap of survey lines prevented.

To help summarize the results of the EMI surveys, the SURFER for Windows (version 9.0) software (Golden Software, Inc., Golden, CO) was used to construct the two-dimensional simulations shown in this report.[2] Grids were created using kriging methods with an octant search.

ESAP:
As a tool for precision agriculture, high intensity soil surveys, and assessments of saline and sodic soils, spatial-referenced EC_a data are used to direct soil sampling, refine maps, and provide ancillary measures for spatially varying soil properties that are not easily sensed or mapped (Stafford, 2000; Jaynes, 1995). The USDA-ARS Salinity Laboratory (Riverside, California) has developed the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) software for use with EC_a data (Lesch, 2005; Lesch et al., 2000, 1995a, 1995b). The *ESAP* software was originally designed to predict soil salinity (EC_e) from EC_a data. However, the *ESAP* software can be used to predict soil properties other than soil salinity. The *ESAP* software is designed to combine copious, high-intensity EC_a data with sparse, low-density soil sampling to calibrate suitable equations for the prediction of soil salinity or other soil properties. A goal of this prediction-based sampling approach is to statistically select a small number of sample locations from the EC_a survey data. In order to be effectively used, however, the spatially varying soil property must <u>strongly correlate</u> with EC_a. Amezketa (2007) used *ESAP* to determine levels of sodicity in saline-sodic soils. Hunsaker et al. (2009) used *ESAP* to infer the spatial variability of basal crop coefficients and crop water use from normalized difference vegetation indices (NDVI) obtain from aerial images. Fitzgerald et al. (2006) used *ESAP* to predict crop height and width attributes from aerial imagery. Eigenberg et al. (2008) used *ESAP* to assess and manage the flow of liquid cattle wastes within vegetative treatment areas.

Directed-Sampling:
The ESAP-*Response Surface Sampling Design* (RSSD) program can generate three different directed-sampling schemes (6, 12, and 20 sample locations). The selection of the most suitable sampling design will depend on site and soil conditions, availability of resources, and intended use of the survey information. In this directed-sampling approach, a minimum number of calibration sample locations are identified based on the observed magnitudes and spatial distribution of the EC_a data (Eigenberg et al., 2008). The sampling locations are selected to statistically optimize the estimation of a regression model and to simultaneously maximize the average separation distance among sample locations. Sample locations are representative of the total variation of EC_a and, hopefully, the targeted soil property (Corwin et al., 2006). This directed-sampling approach has been described as an amalgam of a response surface sampling design with a space-filling algorithm (Eigenberg et al., 2008; Lesch, 2005).

Deterministic Model:
Apparent soil electrical conductivity can be correlated with any soil property that <u>significantly</u> influences the EC_a measurements (Corwin and Lesch, 2005). The *ESAP-Calibrate* program estimates a calibration equation that can be used to predict soil properties from EC_a data. Two models are available in *ESAP-Calibrate*: a *deterministic* and a *stochastic model*. The deterministic model does not require (as does the stochastic model) the collection of soil sample characterization data, but can only be used to estimate soil salinity (EC_e) from EC_a survey data. When used with an EMI meter, the deterministic model is designed

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

for use with EC_a data that are collected in two dipole orientations or at two different depth intervals. However, the deterministic equation was also design for use with a four-electrode resistivity array (Rhoades et al., 1989a). This array measures the average EC_a within a 0 to 90 cm soil-depth-interval. Using this array and the deterministic model, the *ESAP* calculated salinity estimates should correspond on a one-to-one basis to the raw EC_a measurement (Lesch and Corwin, 2003a). With this method the conversion formula for calculating EC_a is:

$$EC_a = 0 + 1*(\text{raw } EC_a) \quad [1]$$

As the EM38 can only be operated in the continuous mode in one dipole orientation (for most surveys, the VDO) at a time, the collection of two simultaneous EC_a measurements is not possible and the deterministic model is considered improper. Estimates of soil salinity derived with the EM38 meter do not generally exhibit a one-to-one relationship with the measured EC_a data (Corwin and Lesch, 2003b). This is due to the non-linear, depth-weighted EC_a response of EMI meters; the partial breakdown of the assumptions of *low induction number* (linear relationship between true and apparent conductivity) at high EC_a values (> 100mS/m); and variations in soil and terrain conditions (Corwin and Lesch, 2003b). However, in these training exercises, Equation [1] was used with the EC_a measurements collected with the EM38 meter for comparative purposes and to evaluate the conversion of raw EC_a into estimates of soil salinity using the deterministic model. Scott Lesch believes that the deterministic model, though not developed for use with measurements obtained in only one dipole orientation, should provide a fairly reasonable estimate of salinity, but ONLY to estimate a profile average (0-150 cm depth) (Scott Lesch, personal communication 5 October 2010).

In the deterministic model, for EC_a data that were collected simultaneously in two dipole orientations or for two depth intervals, the *dual pathway parallel conductance* (DPPC) *model* (Rhoades et al., 1989a, 1989b, 1990; Corwin and Lesch, 2003a) is used to convert EC_a into EC_e based on knowledge of other soil properties. The DPPC model is based on the premise that soil electrical conductivity can be modeled by a multi-pathway, parallel, electrical conductance equation. In this model, soil electrical conductivity is reduced to a nonlinear function of five soil physiochemical properties: EC_e, saturation potential, volumetric soil water content, bulk density, and soil temperature (Corwin and Lesch, 2005). Although the use of stochastic models is generally preferred, the deterministic approach is favored when significant localized variations in soils and soil properties exist within the survey area (Corwin and Lesch, 2005). Deterministic models, however, also require accurate field estimates of the average (both vertically and spatially) soil temperature, clay content or saturation percentage, and average percent water content relative to field capacity. These secondary soil properties influence EC_a and are components of the DPPC model. Errors in the estimation of any one of these soil properties will produce inaccuracies in the predictive model.

The stochastic model requires the collection and analysis of soil sample data (from sample locations selected by RSSD program), but, unlike the deterministic model, can be used to predict soil attributes other than EC_e alone. In addition, the stochastic model is suitable for use with EC_a data collected in only one dipole orientation (an advantage for mobile EMI surveys conducted with an EM38 meter). As a training exercise, a six-point optimal sample scheme was developed for the sites in Lancaster and Scotts Bluff Counties and samples were collected at each of the calibration points in 30 cm depth intervals down to a depth of 90 cm (a total of 18 samples from each site). These samples will be analyzed for soil salinity using the instruments available in MLRA office. When this data becomes available, it will be processed through the stochastic model (the preferred method). Estimates of soil salinity derived from the deterministic and stochastic models can then be compared.

Survey procedures:

At the training sites, separate EMI surveys were completed with each meter. The meters were mounted in a plastic sled and towed behind a 4WD ATV (Fig. 1). Both meters were operated in the vertical dipole orientation. These mobile surveys were completed by driving the ATV at in a back and forth manner across each site. An attempt was made to replicate the traverse lines and speeds for the two surveys. However, traverse speeds and tracks were variable for each survey.

Figure 1. State-of-the art, integrated technologies and mobile platforms provide fast, efficient, cost-effective, and less-fatiguing means of surveying large areas of saline and sodic soils.

All collected EC_a data were entered into an Excel spreadsheet and processed thru the *ESAP* (version 2.35) software suite (Lesch et al., 2000). The *Response Surface Sampling Design* software program of *ESAP* software suite was used to generate an optimal sampling design for each field based on the EC_a data. Based on the results of the RSSD program, soils were sampled at six optimal soil sampling locations within each site.

Plots of EC_a data showing the locations of the optimal calibration locations for each site were compiled and copies supplied to soil scientists involved in soil sampling. These calibration locations were cored with the soils sampled at 30 cm intervals to a maximum depth of 90 cm. Samples will be analyzed for salinity using a DiST WP 4 conductivity/TDS meter from Hanna Instruments and a Hach conductivity meter[3]. At the Scottsbluff office pH was also measured using a Denver Instrument Model 220 pH-conductivity meter[3].

Auger observation made at these *calibration sites* were used to characterize the soil property (clay content, percent water content relative to field capacity, and temperature) data needed in the *ESAP*-

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Calibrate program. These soil properties were extended across both sites and used with the deterministic models of *ESAP-Calibrate*.

MLRA 106 – Nebraska and Kansas Loess-Drift Hills:

Study site:

The training site (41.0447 N Latitude, 96.6356 W. Longitude) is located in a wetland near the intersection of US 77 and Ashland Road in northern Lancaster County. The site is principally mapped as Saltillo silt loam, occasionally flooded (7067), with a small included area of Salmo silt loam, occasionally flooded (7015) on a low levee adjacent to Rock Creek. These very deep soils formed in silty alluvium on flood plains. The poorly drained Saltillo has a sodium absorption ratio greater than 13 throughout the control section. Saltillo is a member of the fine-silty, mixed, superactive, calcareous, mesic Typic Halaquepts family. Salmo soils are somewhat poorly drained and poorly drained. Salmo is a member of the fine-silty, mixed, superactive, calcareous, mesic Cumulic Endoaquolls family.

Results:

Table 1 provides the basic statistics for the two EMI surveys that were conducted at the training site with the EM38 and EM38-MK2 meters. For the EM38 meter, EC_a data were only collected in the VDO with a nominal penetration depth of 150 cm. For the EM38-MK2, EC_a data were collected in the VDO for both the 50 and 100 cm intercoil spacings, which provide nominal penetration depths of 75 and 150 cm, respectively. In Table 1, comparison between the two meters should only be made for the columns labeled *EM38-VDO* and *EM38-MK2-100 cm*, as these data sets have comparable penetration depths (0 to 150 cm). Data collected with the two meters over this depth interval were closely similar. For the two meters, however, both the number and locations of observations were slightly different. Apparent conductivity averaged about 195 mS/m and ranged from about 70 to 397 mS/m for measurements obtained with the EM38 meter. Apparent conductivity averaged about 204 mS/m and ranged from about 87 to 413 mS/m for measurements obtained with EM38-MK2 meter with the deeper-sensing, 100-cm intercoil spacing. The measurements recorded with both meters are considered high and indicative of excessive amounts of soluble salts in soil profiles.

Table 1. Basic statistics for the EMI surveys conducted with the EM38 and EM38-MK2 meters at the training site in Lancaster County.

	EM38-VDO	EM38-MK2-100cm	EM38-MK2-50cm
Number	816	759	759
Minimum	70.25	87.11	-26.45
25%-tile	143.00	148.24	122.85
75%-tile	244.50	255.12	215.43
Maximum	397.13	413.05	403.05
Mean	195.16	204.44	172.05
Std dev.	61.88	64.55	60.04

For 757 of the 759 measurements obtained for the EM38-MK2 meter, EC_a was greater with the deeper-sensing (0 to 150 cm) 100-cm intercoil spacing than with the shallower-sensing (0 to 75 cm) 50-cm intercoil spacing. In areas of saline soils, this relationship indicates a *normal salt profile* with salts (assumed to be the principal factor influencing EC_a) increasing with increasing depths (associated with the water table). Had the relationship been reversed (*inversed salt profile*), with higher values at shallower depths, salinization would be attributable to periodic inundation by flood waters containing soluble salts.

Figure 2 contains plots of the EC_a data collected with both the EM38 and EM38-MK2 meters at the training site. The effective penetration depth for both meters is 150 cm (measurements obtained in the VDO with the EM38 meter and with the 100 cm intercoil spacing for the EM38-MK2 meter). In both plots, similar color scales and ramps have been used. The soil boundary line separating units of Saltillo silt loam, occasionally flooded (7067) and Salmo silt loam occasionally flooded (7015) has been digitized from Web Soil Survey data[4]. The spatial patterns of EC_a are considered remarkably similar for both meters.

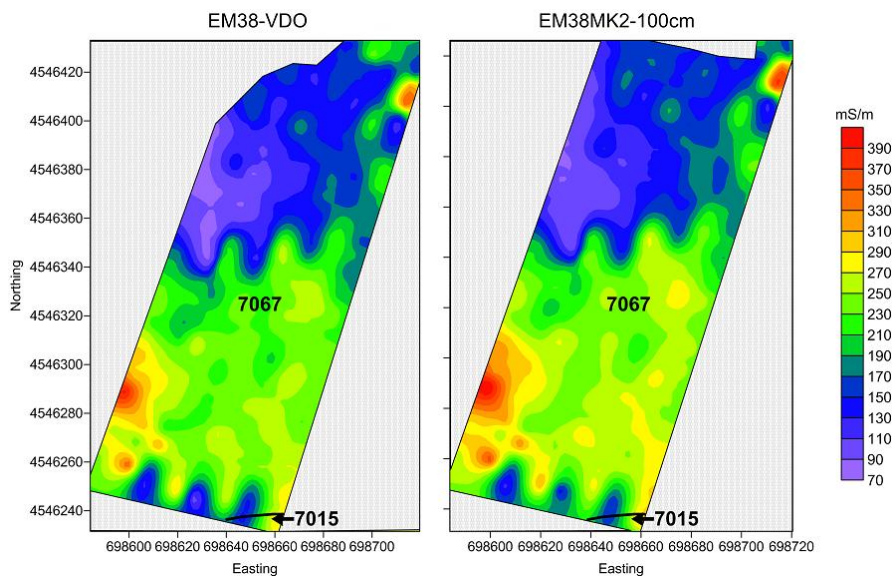

Figure 2. These plots compare EC_a data collected in the VDO with the EM38 meter (left-hand plot) and for the 100-cm intercoil spacing with the EM38-MK2 meter (right-hand plot) at the Lancaster County training site. The depth of effective penetration is 150 cm for the two meters.

The *Response Surface Sampling Design* software program of *ESAP* was used to generate a six-point optimal soil sampling design for the training site based on the EC_a data. Figure 3 is a plot of the six optimal sampling points, which were generated from EC_a data collected with the EM38 meter. In Figure 3, the observation number for each optimal sampling point is provided. Also, the locations of measurement points and traverse lines are also shown in this plot. Table 2 lists the coordinates and EC_a for these six optimal sampling points. At each of the six optimal sampling locations, soil samples were collected by the MLRA office.

Table 2. The six-point sampling scheme for the Lancaster County Site generated from the ESAP-RSSD program.

Observation	Longitude	Latitude	EC_a
10	-96.6357	41.0447	347.38
43	-96.6360	41.0441	196.63
100	-96.6365	41.0433	186.88
582	-96.6365	41.0444	70.25
664	-96.6367	41.0441	102.00
700	-96.6370	41.0435	299.75

[4] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [9/29/2010].

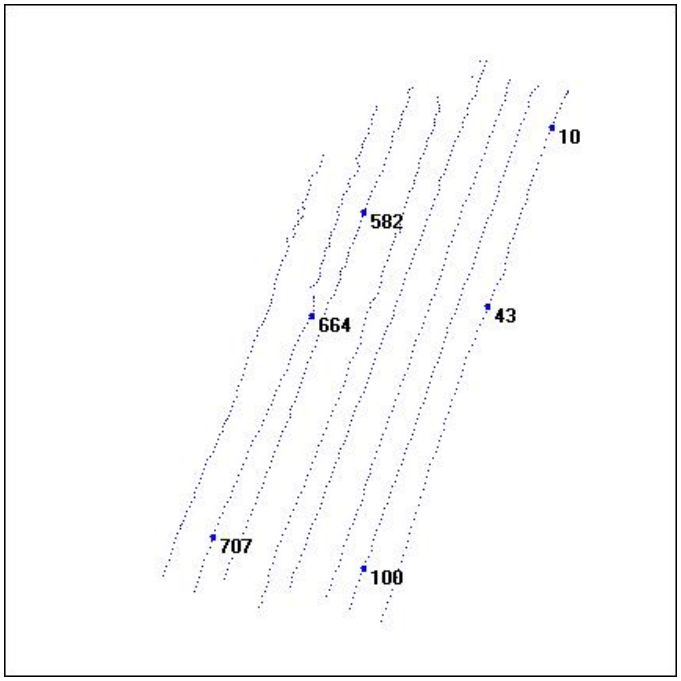

Figure 3. Plot of the six optimal soil sampling locations generated by the ESAP-RSSD program and based on EC_a data collected with an EM38 meter.

The *ESAP-Calibrate* program was used to estimate salinity based on the collected EC_a data. The raw EC_a data collected with the EM38 and EM38-MK2 meters were properly formatted and imported into the *ESAP-Calibrate* program. The first step in this program is to convert the raw EC_a data into depth-specific conductivity data. However, this was not possible for the single measurements (VDO) recorded with the EM38 meter. For this data, only bulk averaged conductivity for the 0 to 150 cm depth interval was possible. The deterministic model also requires estimates for several soil properties. Estimates of clay content and percent water content relative to field capacity were based on "feel" interpretations made for the different 30-cn depth intervals at one core site. Soil temperature was based on a single observation made at a depth of 50 cm (18° C).

The only options available within the *ESAP-Calibrate* program for the single EC_a measurements recorded with the EM38 meter are a *linear conversion* formula type and a *single equation* type ($EC_a = 0 + 1(EC_a)$). These options are recommended for use with a single, direct-contact four-electrode resistivity array. The deterministic conversion routine was then invoked to convert the bulk averaged EC_a into estimates of soil salinity. Based on this analysis, within the training site, the estimated salinity averaged 5.58 dS/m with a range of 0.05 to 14.53 dS/m.

Figure 4 is a plot of the estimated salinity generated from the deterministic modeling of the EC_a data collected with the EM38 meter operated in the VDO. At first glance, soil scientists believe that the spatial data in Figure 4 looked reasonable and corresponded with observed vegetative patterns. Based on deterministic modeling, using EC_a data collected with the EM38 meter, soils were estimated to be non- to slightly saline (> 4 dS/m) at 35 %, slightly saline (4 to 8 dS/m) at 45 % and moderately saline (8 to 16 dS/m) at 20 % of the observation points.

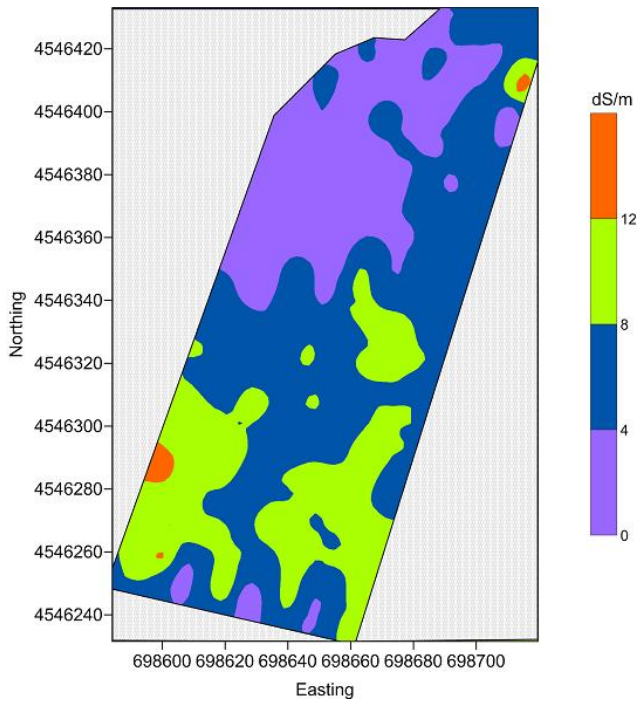

Figure 4. Plot of estimated soil salinity (dS/m) generated by deterministic modeling of the raw EC_a data collected with an EM38 meter operated in the vertical dipole orientation.

The data collected with the EM38-Mk2 meter were also processed through the *ESAP-Calibrate* program. Unlike the EC_a data collected with the EM38 meter, EC_a data were collected for two depth intervals with the EM38-MK2 meter. As a consequence, the deterministic model using the *DPPC* equation and a *log linear* formula type could be appropriately applied. The first step in the *ESAP-Calibrate* program is to convert the raw EC_a data into depth-specific soil conductivity. The same soil property (clay content, percent water content relative to field capacity, and temperature) that were used to process the EM38 data were used with the EM38-MK2 data. A conversion algorithm was next used to estimate soil salinity for three depth intervals (0 to 30, 30 to 60, and 60 to 90 cm). A bulk average estimate was also calculated for the 0 to 90 cm depth interval. Table 3 provides the basic statistics for these salinity (dS/m) estimates. The estimated soil salinity level is lowest and least variable in the surface layers (0 to 30 cm), and highest and most variable in the 30 to 60 cm depth interval.

Table 3. Basic salinity statistical data, by depth interval, for the EC_a data collected with the EM38-MK2 meter using the deterministic model of the *ESAP-Calibrate* program. With the exception of number, all data is expressed in dS/m.

	0-30 cm	30-60 cm	60-90 cm	0-90 cm
Number	756	756	756	756
Minimum	0.0	1.2	3.5	1.7
25%-tile	3.4	9.1	9.4	7.4
75%-tile	9.1	22.7	19.7	17.1
Maximum	37.9	54.0	37.3	38.3
Mean	6.5	16.4	14.9	12.6
Std. Dev.	4.3	9.0	6.4	6.5

Figure 5 contains plot of estimated salinity generated from the deterministic model for the EC_a data collected with the EM38-MK2 meter. Compared with the estimates made using data collected with the EM38 meter (Fig. 4), salinity is estimated for different depth intervals rather than a bulk profile averaged salinity, and salinity levels are higher for all estimates made using the EM38-MK2 data and the *DCCP* model. For the 0 to 90 cm depth interval (Figure 5, lower-right plot), soils were estimated to be non- to slightly saline at 1%, slightly saline at 16 % , moderately saline at 35 %, and strongly saline (>16 dS/m) at 48 % of the observation points.

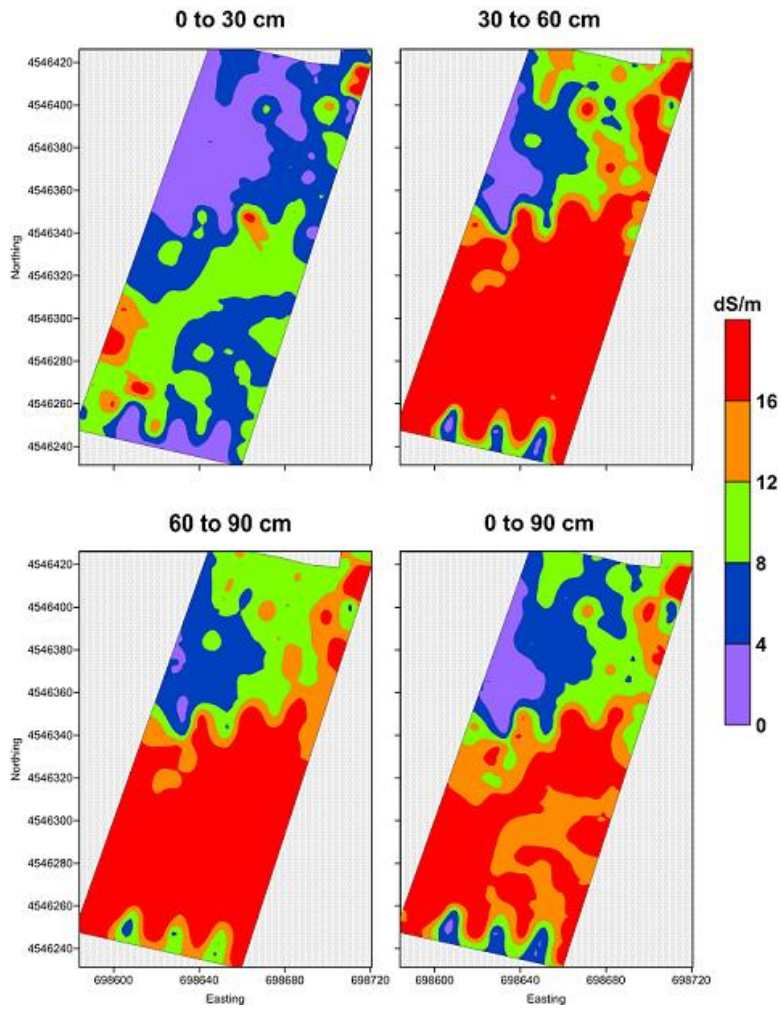

Figure 5. Plots of estimated soil salinity (dS/m) generated by deterministic modeling of the raw EC_a data collected with the EM38-MK2 meter for four different soil depth intervals.

Using the *ESAP-Calibrate* deterministic modeling, different salinity estimates were produced using data collected with the EM38 and EM38MK2 meters and different conversion formula types. Is either salinity estimate accurate? If so, which one provides the better estimates? In order to evaluate these two sets of estimates, each made with different meters and deterministic models, the collected soil samples will be analyzed for salinity. Once analyzed, the sampled soil profile data will be processed through stochastic models in the *ESAP-Calibrate* program. The stochastic models will provide correlations between the model's salinity estimates and the sampled profile data. At that point, the salinity estimates provided by the different meters and models will be compared and further evaluated for prediction accuracy.

MLRA 67A – Central High Plains, Northern Part:

Study site:

The training site (41.81338 N Latitude, 103.4875 W. Longitude) is located in an irrigated (center pivot) field along US 27 just east of Minatare, Nebraska, in Scotts Bluff County. Patches of stunted plants and visible salt efflorescence on the soil surface identified areas of moderately and strongly saline soils**.** The site is mapped as Minatare-Janise complex, rarely flooded (5665). The very deep, somewhat poorly drained Minatare and Janise soils formed in loamy or clayey alluvium on flood plains. The soil materials are strongly or very strongly affected by sodium and commonly by excess soluble salts. Minatare is a member of the fine, mixed, superactive, mesic Aquic Natrustalfs family. Janise is a member of the coarse-silty, mixed, superactive, calcareous, mesic Typic Halaquepts family. The anticipated spatial and vertical variations in clay contents of these alluvial soils were expected to lower the accuracy of soil salinity predictions made with the *ESAP-Calibrate* program.

Results:

Table 4 provides basic statistics for the EC_a data collected at the Minatare site with the EM38 and EM38-MK2 meters. For the EM38 meter, EC_a data were only collected in the VDO with a nominal penetration depth of 150 cm. For the EM38-MK2, EC_a data were collected in the VDO for both the 50 and 100 cm intercoil spacings, which provide nominal penetration depths of 75 and 150 cm, respectively. In Table 4, comparison between the two meters should only be made for the columns labeled *EM38-VDO* and *EM38-MK2-100 cm*, as these data sets have comparable nominal penetration depths. Data collected with the two meters over this depth interval are remarkably similar. Apparent conductivity averaged about 155 mS/m and ranged from about 76 to 335 mS/m for measurements obtained with the EM38 meter operated in the VDO. Apparent conductivity averaged about 153 mS/m and ranged from about 67 to 356 mS/m for measurements obtained with EM38-MK2 meter with the deeper-sensing, 100-cm intercoil spacing.

Table 4. Basic statistics for the EMI surveys conducted with the EM38 and EM38-MK2 meters at the training site in Scotts Bluff County.

	EM38-VDO	EM38-MK2-100 cm	EM38-MK2-50 cm
Number	1420	1626	1626
Minimum	76.25	66.63	47.62
25%-tile	122.13	119.10	102.62
75%-tile	176.38	175.35	176.48
Maximum	335.00	356.10	403.89
Mean	155.30	152.83	144.46
Std. Dev.	46.81	47.59	58.73

For 1626 measurements recorded with the EM38-MK2 meter, 1151 (79 %) were greater in the deeper-sensing (0 to 150 cm) 100-cm intercoil spacing than in the shallower-sensing (0 to 75 cm) 50-cm intercoil spacing. In areas of saline soils, this relationship indicates a *normal salt profile* with salts increasing with increasing soil depths (associated with the water table). Had the relationship been reversed (*inversed salt profile*), with higher EC_a measurements at shallower depths, salinization would be attributable to periodic inundation by flood waters containing soluble salts.

Figure 6 contains plots of the EC_a data collected with both the EM38 and EM38-MK2 meters at the Minatare site. The effective penetration depth for both meters is 150 cm. In both plots, similar color scales and ramps have been used. The curved, white-colored line represents the maximum extent of irrigation from a center pivot system. Similar areas were surveyed with each meter. As was the case in Lancaster County, spatial EC_a patterns are remarkably similar in the plots for each meter. Although the

electronic settings are slightly different, for the 0 to 150 cm depth interval, the EC_a data collected with the EM38-MK2 meter are essentially identical to the EC_a data collected with the EM38 meter.

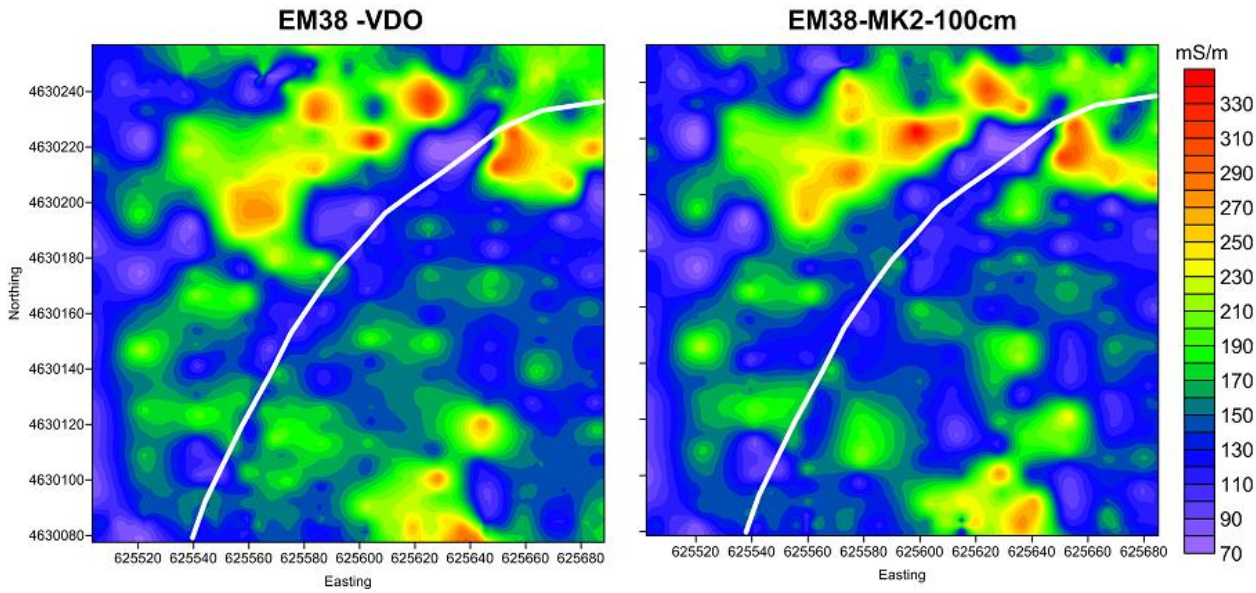

Figure 6. These plots compare EC_a data collected with the EM38 meter operated in the VDO (left) and the EM38-MK2 meter with a 100-cm intercoil spacing (right) at the Minatare site. The depth of effective penetration for the two meters is about 150 cm.

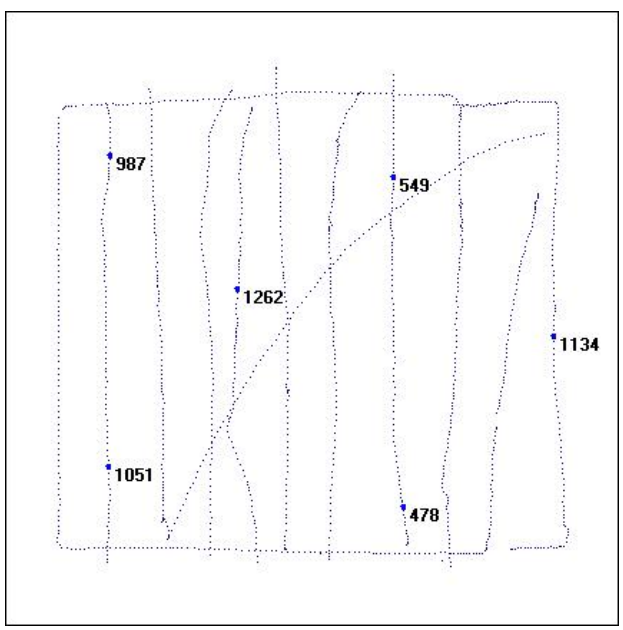

Figure 7. This plot shows the six optimal sampling locations generated by the ESAP-RSSD program. Locations are based on EC_a data collected with the EM38 meter.

The *Response Surface Sampling Design* software program of ESAP was used to generate a six-point optimal sampling design for the Minatare site based on the EC_a data. Figure 7 is a plot of the six optimal

sampling points, which was generated from EC_a data collected with the EM38 meter. In Figure 7, the observation number for each of the optimal sampling points is identified. The locations of measurement (measurement) points and traverse lines are also shown in this plot. Table 5 lists the coordinates and EC_a for these six optimal sampling points. At each of the six optimal sampling locations, soil scientists collected soil samples in 30-cm depth intervals to a maximum depth of 90 cm. These samples were analyzed for salinity in the MLRA office.

Table 5. The six-point sampling scheme for the Scotts Bluff County Site generated from the ESAP-RSSD program.

Obs. #	Longitude	Latitude	EM38V
478	-103.4875	41.81282	273.75
549	-103.4875	41.81388	77.13
987	-103.4888	41.81397	85.25
1051	-103.4888	41.81296	155.25
1134	-103.4868	41.81336	161.00
1262	-103.4882	41.81353	225.38

The *ESAP-Calibrate* program was used to predict soil salinity from the EC_a data collected at the Minatare site. The raw EC_a data collected with the EM38 and EM38-MK2 meters were properly formatted and imported into the *ESAP-Calibrate* program. The first step in this program is to convert the raw EC_a data into depth-specific conductivity. However, this is not possible with the single measurements (VDO) recorded with an EM38 meter. For this data, only estimates of the bulk average conductivity for the 0 to 150 cm depth interval are possible. The deterministic model required estimates of several soil properties. Estimates of clay content and percent water content relative to field capacity were based on "feel" interpretations made for different depth intervals at core sites. Soil temperature was based on a single observation made at a depth of 50 cm (18° C).

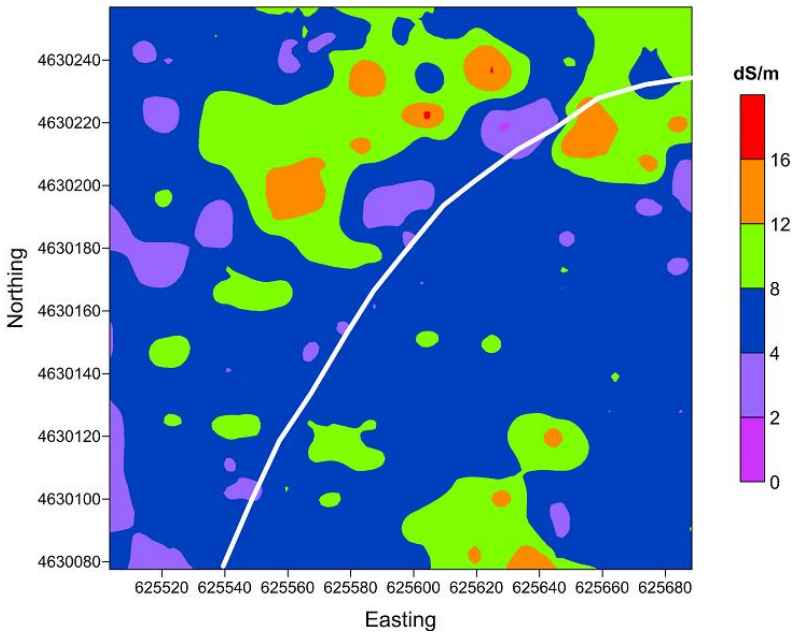

Figure 8 Plot of estimated soil salinity (dS/m) generated by deterministic modeling of the raw EC_a data collected with the EM38 meter operated in the vertical dipole orientation at the Minatare site.

Figure 8 is a plot of the estimated salinity within the Minatare site. The salinity estimates shown in this plot were generated from deterministic modeling of the EC_a data collected with the EM38 meter operated in the VDO. In general, within the Minatare site, areas of high soil salinity were easily identified by irregular plant growth patterns and visible surface salt efflorescence. Areas of high and low estimated soil salinity (Fig. 8) appear to correspond to the observed vegetative patterns and surface salts efflorescence. Using the deterministic model and the EC_a data collected with the EM38 meter, estimated salinity for the 0 to 150 cm depth interval averaged 6.76 dS/m and ranged from 2.24 to 17.05 dS/m. One half the observations fell between 4.87 to 7.97 dS/m. Based on deterministic modeling of the EC_a data, for the 0 to 90 cm depth interval, soils are estimated to be non- to slightly saline (> 4 dS/m) at 13 %, slightly saline (4 to 8 dS/m) at 62 % and moderately saline (8 to 16 dS/m) at 24 %and strongly saline (> 16 dS/m) at 1 % of the observation points.

The data collected with the EM38-MK2 meter were processed through the *ESAP-Calibrate* program. Unlike the data collected with the EM38 meter, the EM38-MK2 meter data were collected simultaneously for two different depth intervals. As a consequence, the deterministic model using the *DPPC* equation and a log *linear formula* type could be appropriately applied. The first step of this program is to convert the raw EC_a data into depth-specific conductivity. The same estimated soil property (clay content, percent water content relative to field capacity, and temperature) that were used with the EM38 data were used with the EM38-MK2 data in this model. A conversion algorithm was used to estimate soil salinity for three depth intervals (0 to 30, 30 to 60, and 60 to 90 cm). A bulk average estimate for the 0 to 90 cm depth interval was also made. Table 6 provides the basic statistics for these calculations. The estimated soil salinity levels are lowest in the surface layers (0 to 30 cm) and highest in the 30 to 60 cm depth interval. Compared with the 30 to 60 cm soil depth interval, estimated soil salinity levels decrease and becomes less variable in the 60 to 90 cm depth interval.

Table 6. Basic statistic for the conversion of the EC_a data collected with the EM38-MK2 meter using the deterministic model of the *ESAP-Calibrate* program. With the exception of number, all data is for salinity expressed in dS/m.

	0-30cm	30-60cm	60-90cm	0-90cm
Number	1626	1626	1626	1626
Minimum	0.00	0.32	2.87	1.13
25%-tile	2.68	7.04	8.24	6.19
75%-tile	12.18	17.85	13.92	14.87
Maximum	44.00	50.20	32.79	41.36
Mean	8.70	13.43	11.71	11.28
Std. Dev.	8.48	8.64	5.02	7.02

Figure 9 contains plot of estimated salinity generated from deterministic modeling of the EC_a data collected with the EM38-MK2 meter. Compared with the estimates made using data collected with the EM38 meter (Fig. 8), salinity estimates are higher for the EM38-MK2 data and the *DCCP* model. For the 0 to 90 cm depth interval (Figure 9, lower-right plot), soils were estimated to be non- to slightly saline at 11%, slightly saline at 28 % , moderately saline at 40 %, and strongly saline at 21 % of the observation points. These results, however, are inconclusive.

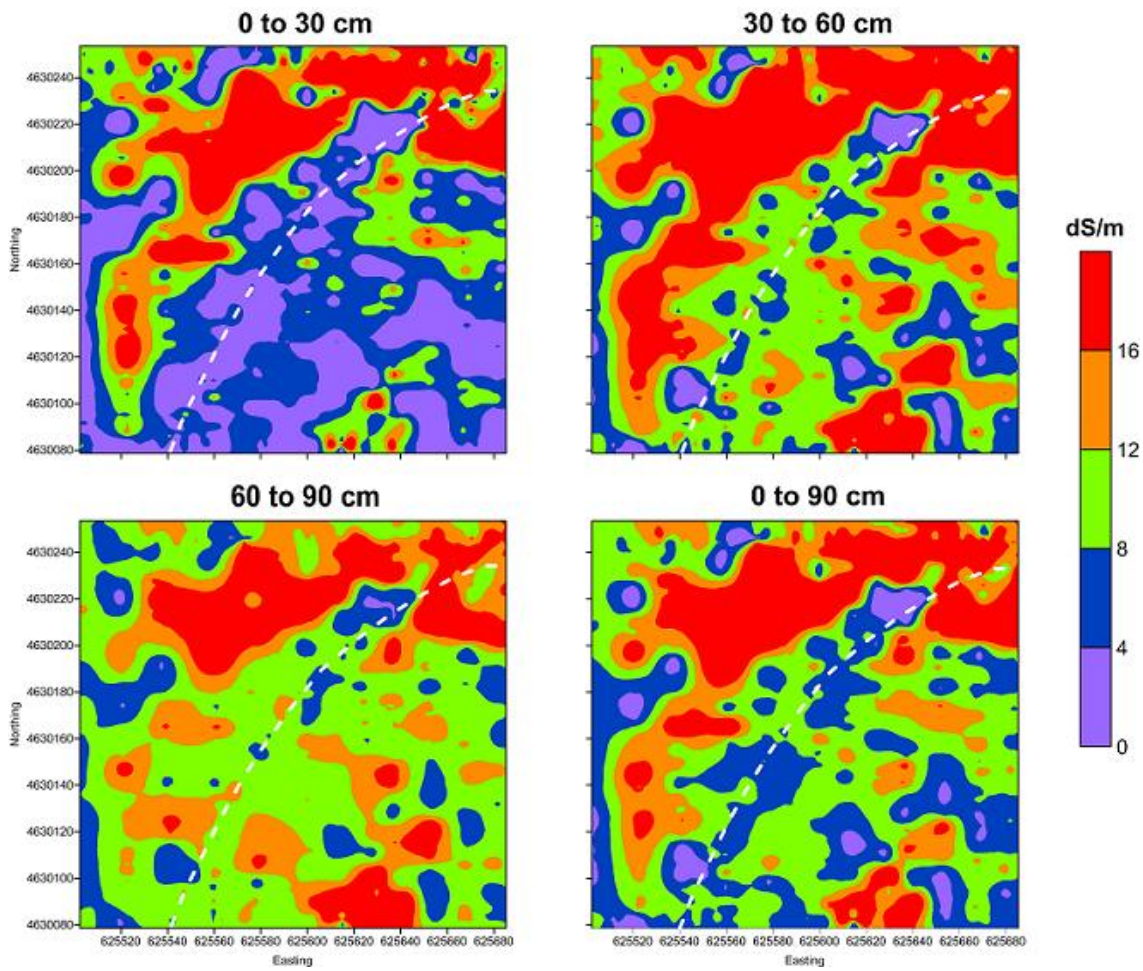

Figure 9. Plots of estimated soil salinity (dS/m) generated by deterministic modeling of the raw EC_a data collected with the EM38-MK2 meter for four different soil depth intervals at the Minatare Site.

Soil Analysis:

The soil samples that were collected at the Minatare site were analyzed in the Scottsbluff MLRA office using a soil conductivity (EC) and pH meter. The results of these analyses are listed in Table 7. The measured pHs (range of 8.6 to 10) imply that the soils are sodium-affected. Considering the delineated soil map unit, the readily apparent batches of barren ground and salt efflorescence, and the results of two separate EMI surveys, the salinity measured with the conductivity meter is surprisingly low (range of 1.16 to 5.34 dS/m) and relatively uniform at the six soil calibration sites, which varied greatly in EC_a (see Table 5). The low EC values (Table 7) and the mismatch with measured EC_a (Table 5) are befuddling and troubling to this investigator.

Following the analysis of the soil samples, the measured salinity and pH from each of the 6 soil calibration sites were format as a *Generic* profile data file and entered into *ESAP* program. Excluding the header row, Table 7 replicates the entered *Generic* data file format. Stochastic modeling was performed on the EC_a and soil profile characterization data from the site using the *ESAP-Calibrate* program. The *ESAP-Calibrate* program first converts the raw EC_a data into depth-specific soil EC_a data. Next, the program converts the depth-specific soil EC_a data into estimates of soil property data (e.g., salinity, pH) using a spatially-referenced, linear regression model.

Table 7. Data resulting from the analysis of samples collected at the six optimal sampling sites near Minatare, Scoots Bluff County, NE.

Observation #	Depth Interval mid-point	Easting	Northing	dS/m	pH
549	0.15	625625.21	4630217.89	2.04	9.4
549	0.45	625625.21	4630217.89	2.42	9.7
549	0.75	625625.21	4630217.89	1.95	9.7
478	0.15	625628.613	4630099.334	4.53	9.9
478	0.45	625628.613	4630099.334	4.32	10
478	0.75	625628.613	4630099.334	2.52	9.8
987	0.15	625522.504	4630225.236	4.42	8.6
987	0.45	625522.504	4630225.236	3.8	8.9
987	0.75	625522.504	4630225.236	3.72	8.9
1051	0.15	625522.176	4630113.566	2.92	9.1
1051	0.45	625522.176	4630113.566	3.32	9.1
1051	0.75	625522.176	4630113.566	1.63	8.8
1134	0.15	625683.133	4630160.409	5.34	9.1
1134	0.45	625683.133	4630160.409	3.15	9
1134	0.75	625683.133	4630160.409	1.16	9
1262	0.15	625568.823	4630177.744	1.56	9.2
1262	0.45	625568.823	4630177.744	1.77	8.9
1262	0.75	625568.823	4630177.744	1.66	8.7

ESAP-Calibrate:

Profile Shape /Magnitude Analysis:

The first process completed in the *stochastic data* analysis process of the *ESAP-Calibrate* program was to prepare one-dimensional (1D) profile plots of the sampled salinity and pH characterization data. The profile plots for salinity (upper plots) and pH (lower plots) are shown in Figure 10. In these plots, soil depth is plotted on the vertical axis; salinity or pH is plotted on the horizontal axis. In each set of plots (upper and lower), the left-hand plot contains the sampled soil data, while the right-hand plot contains the predicted profiles based on calculated averaged soil calibration data levels. These plots are useful in seeing the shape and variability of the salinity and pH within and among the six sampled soil profiles. The magnitude of both salinity and pH varies within individual soil profiles and among the six sampled soil profiles. A correlation (r) statistic is provided in the upper-right corner of the *smoothed* or predicted profile plots. As a general rule, the closer this coefficient is to 1, the more predictable is the profile shape from the averaged values, and the more accurate will be predictions made with stochastic models. In general, both salinity and pH decrease with increasing soil depth. Based on the correlation statistics, the profile shapes for salinity (r = 0.7566) should be moderately predictable across the surveyed site.

Stochastic Calibration Model:

Stochastic models were used to predict salinity and pH from the EC_a data. For the stochastic model, EC_a was not transformed, and the *ESAP-Calibrate* program was allowed to select the optimal parameters and the most appropriate model (suggested method). Salinity and pH were not correlated in the samples collected at this site. The bulk average (0 to 90 cm depth interval) correlation between pH and salinity was only 0.109.

Table 8 provides the stochastic models' coefficient of determination (R^2) for each analyzed depth interval at Minatare site using paired soil profile characterization and depth-weighted EC_a data. The *bulk average* represents the R^2 statistics for the 0 to 90 cm depth interval. The results are very disappointing. The

ESAP calibration model explained none of the variation in measured salinity at this site. This is most unexpected and perplexing. This is the only study that I have conducted in which relationships were not found between EC_a and salinity measurements. In previous studies, in areas of saline soils, EC_a is highly correlated with soil profile data. It is my belief therefore, that some errors have been committed.

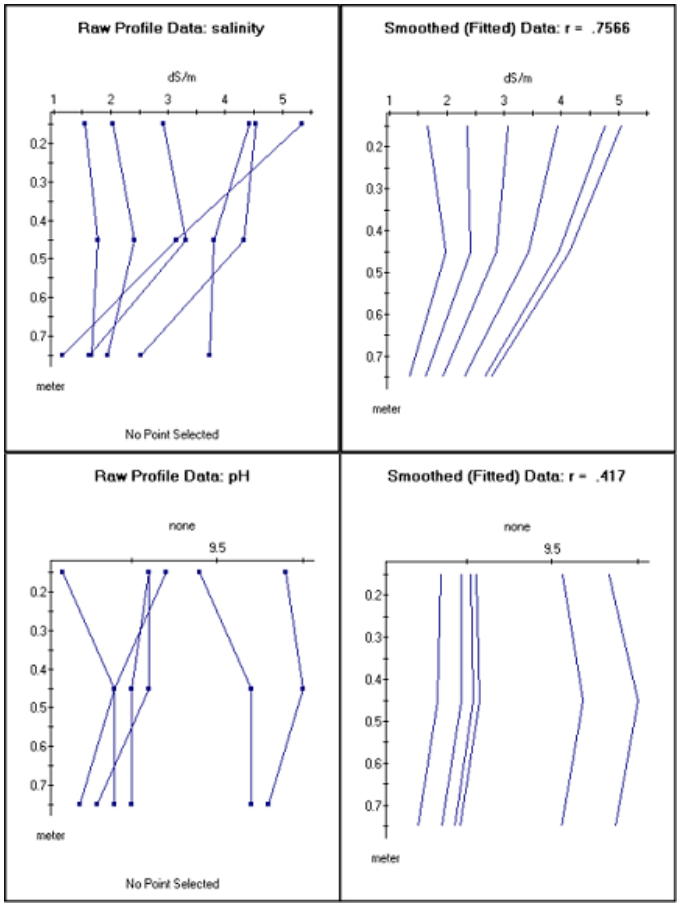

Figure 10. These 1D profile plots of the sampled soil calibration data for the Minatare site show the depth distribution of salinity (upper plots) and pH (lower plots) for each of the six sampled profiles.

Table 8. The coefficient of determinations for the salinity regression models at Minatare Site. Statistics are for individual and bulk-averaged sample depth intervals.

Depth Interval	R^2
0 to 30 cm	**0.0067**
30 to 60 cm	**0.0234**
60 to 90 cm	**0.0641**
Bulk Average	**0.0002**

References:

Amezketa, E. 2007. Use of electromagnetic induction to determine sodicity in saline-sodic soils. *Soil Use and Management* 23: 278-285.

Corwin, D.L., and S.M. Lesch, 2003a. Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agronomy Journal* 95:455-471.

Corwin, D.L., and S.M. Lesch, 2003b. Using the dual-pathway parallel conductance model to determine how different soil properties influence conductivity survey data. *Agronomy Journal* 95:365-379.

Corwin, D., S.M. Lesch, 2005. Characterizing soil spatial variability with apparent soil electrical conductivity. I. Survey protocols. *Computer and Electronics in Agriculture* 46: 103-133.

Corwin, D.L., S.M. Lesch, J.D. Oster and S.R. Kaffka. 2006. Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity. *Geoderma* 131: 369-387.

Eigenberg, R.A., S.M. Lesch, B. Woodbury and J.A. Nienaber, 2008. Geospatial methods for monitoring a vegetative treatment area receiving beef-feedlot runoff. *Journal of Environmental Quality* 35: S-68-S-77.

Fitzgerald, G.J., S.M. Lesch, E.M. Barnes, and W.E. Luckett, 2006. Directed sampling using remote sensing with a response surface sampling design for site-specific agriculture. *Computer and Electronics in Agriculture* 52: 98-112.

Geonics Limited, 1998. EM38 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario.

Geonics Limited, 2007. EM38-MK2 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario.

Hunsaker, D.J., D.M. El-Shikha, T.R. Clarke, A.N. French, and K.R. Thorp, 2009. Using ESAP software for predicting the spatial difference of NDVI and transpiration of cotton. *Agricultural Water Management* 96: 1293-1304.

Jaynes, D.B., 1995. Electromagnetic induction as a mapping aid for precision farming. 153-156 pp. In: Clean Water, Clean Environment, 21st Century: Team Agriculture. Working to Protect Water Resources. Kansas City, MO. 5 to 8 March 1995.

Lesch, S.M., 2005. Sensor-directed response surface sampling designs for characterizing spatial variation in soil properties. *Computers and Electronic in Agriculture* 46: 153-180.

Lesch, S.M., J.D. Rhoades and D.L. Corwin, 2000. ESAP-95 version 2.10R User Manual and Tutorial Guide. Research Report 146. USDA-ARS George E. Brown, Jr. Salinity Laboratory, Riverside, California.

Lesch, S.M., D.J. Strauss and J.D. Rhoades, 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques. 1. Statistical prediction models: A comparison of multiple linear regression and cokriging. *Water Resources Research*. 31:373-386.

Lesch, S.M., D.J. Strauss and J.D. Rhoades, 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques. 2. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. *Water Resources Research* 31:387-398.

Rhoades, J.D., S.M. Lesch, P.J. Shouse and W.J. Alves, 1989a. New calibrations for determining soil electrical conductivity depth relations from electromagnetic measurements. *Soil Science Society of America Journal* 53:74-79.

Rhoades, J.D., N.A. Manteghi, P.J. Shouse and W.J. Alves, 1989b. Soil salinity from soil electrical conductivity using different models and estimates. *Soil Science Society of America Journal* 54:46-54.

Rhoades, J.D., P.J. Shouse, W.J. Alves, N.A. Manteghi, and S.M. Lesch, 1990. Determining soil electrical conductivity depth relations from electromagnetic measurements. *Soil Science Society of America Journal* 53:74-79.

Stafford, J.V. 2000. Implementing precision agriculture in the 21st Century. *J. Agric. Engineering Research* 76: 267-275.