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

Subject: Soil - Geophysical Assistance **Date:** 11 June 2009

To: Serapio Flores Jr.
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USDA-NRCS,
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P.O. Box 1458
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Purpose:
The purpose of this visit was to explore the use of electromagnetic induction (EMI) and ground-penetrating radar (GPR) on sodium-affected soils (SAS). Some of the data collected during this visit will be used at the *Dryland Saline and Sodic Soil Workshop*, which is scheduled for late September 2009, in Carrington, North Dakota.

Participants:
Eric Brevik, Associate Professor of Geology and Soils, Dickinson State University, Dickinson, ND
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Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
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Kyle Thomson, Soil Scientist, USDA-NRCS, Devils Lake, ND
Mike Ulmer, Senior MO Soil Scientists, MO7, USDA-NRCS, Bismarck, ND

Activities:
All field activities were completed during the period of 10 to 13 May 2009.

Summary:

1. The color display for the RTmap38 program (see Figure 1) allows soil scientists to immediately track, observe, and interpret the results of EMI surveys. Following each EMI survey, soil scientists used the color-scaled, pseudo-grid image displayed on the screen of an Allegro CX field computer to guide them to four sampling sites based on relative EC_a values. At all sites, EC_a data helped soil scientists to identify distinct soils and characterize their general spatial patterns with units of management. Variations in the soluble salt contents of the soils are suspected to have caused the EC_a patterns.

2. In general, at all SAS study sites, EC_a increased with increasing soil depth (measurements for the shallower-sensing, 50-cm intercoil spacing were typically lower than measurements for the deeper-sensing, 100-cm intercoil spacing). This trend suggests that soluble salts increase with increasing soil depth, which is a reflection of the prevailing hydropedologic processes (e.g. depth to the water table, seepage, leaching, and evaporative discharge).

3. The ESAP software was used to locate sampling sites within each study site. Samples were collected at these sites for laboratory analysis. Results from these analyses will be used to calibrate a suitable regression equation for the prediction of soil sodicity.

4. The GPR soil suitability interpretations for Aastad and Ferney soils were confirmed. However, additional surveys on sodic, saline-sodic, and saline soils in North Dakota are desired to confirm interpretations and further evaluate the affects of excess sodium and other soluble salts on the effectiveness of GPR.

It was my pleasure to work in North Dakota and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist
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cc:
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Background:
Sodium-affected soils [SAS] extend well over 10 million acres in the Northern Great Plains. Concerns have risen over the interpretation, classification, and mapping of these areas, especially after tillage and applications of newer management systems (no-till) (Mike Ulmer, personal communication). Ground-penetrating radar (GPR) and electromagnetic induction (EMI) are two geophysical instruments that can quickly and non-invasively evaluate some soil properties. However, the effectiveness of these geophysical tools on SAS in the Northern Great Plains has not been fully ascertained. The purpose of this study is to determine the effectiveness of these geophysical instruments for the characterization of SAS.

Soil sodicity varies considerably across landscapes and within soil delineations. As a consequence, soil sodicity is difficult to measure, characterize, and manage. Soil sodicity is quantified by laboratory measurements of exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), and by field pH measurements and observations on the physical appearance of soils. Laboratory measurements are relatively time-consuming and costly, and are therefore limited in number. Surrogate field measures such as EMI have the potential to improve the mapping and management of SAS. This approach is more expedient and economical than conventional laboratory determinations of ESP, SAR, pH, and electrical conductivity of the saturated paste (EC_e). With EMI, comprehensive and detailed surveys of management units can be conducted. However, in order to establish relationships between EC_e and apparent conductivity (EC_a) and develop predictive equations, EMI requires the collection of a small number of soil samples for laboratory analysis.

Over the years, EMI has been limitedly used to study sodic soils (Amezketa, 2007; Corwin et al., 2003; Nelson et al., 2002; Nettleton et al., 1994, Ammons et al., 1989). Ammons et al. (1989) used EMI to distinguish Natraqualfs in Tennessee. Nettleton et al. (1994) observed relatively strong relationships between EC_a and ESP and EC_e. These researchers concluded that EMI provides a rapid and accurate method for describing the composition of SAS map units in south-central Illinois. Sodium-affected soils in Illinois are typically non-saline and lack significant concentrations of soluble salts. In California, a study conducted by Corwin et al. (2003) on saline-sodic soils resulted in correlation coefficients that ranged from 0.70 to 0.82 between EC_a and EC_e, SAR, SO_4, Na and Mg. However, correlation coefficients were noticeably lower (0.31 to 0.32) between EC_a and ESP. In Spain, in a study conducted by Amezketa (2007), a strong and significant correlation ($r = 0.91$) was observed between SAR and EC_a. However, the strength of this correlation was attributed to the significant auto-correlation between SAR and EC_e. The large auto-correlation between EC_e and SAR was attributed to "evapo-concentration processes that occur in saline-sodic soils" (Amezketa, 2007). Significant auto-correlations between EC_e and SAR were also reported in studies conducted by Corwin et al. (2003) and Nelson et al. (2002). In studies conducted by Nelson et al. (2002) on saline-sodic soils in Australia, EC_a measurements were reasonably correlated with ESP. However, on nonsaline-sodic soils, no relationships were observed between EC_a and ESP. Opposite to the findings of Nelson et al. (2002), Nettleton et al. (1994) observed significant correlations between EC_a and ESP on nonsaline-sodic soils.

Equipment:
An EM38MK2-2 meter (Geonics Limited; Mississauga, Ontario), was used in this investigation.[1] The EM38MK2-2 meter requires no ground contact and only one person to operate. The EM38-MK2-2 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. The receiver coils are separated from the transmitter coil at distances of 1.0 and 0.5 m. This configuration provides nominal depth ranges of about 1.5 and 0.75 m in the vertical dipole orientation and about 0.75 and 0.40 m in the horizontal dipole orientation. The EM38-MK2-2 meter, in either dipole orientation, provides measurements of both the quadrature-phase (EC_a) and the in-phase (susceptibility) components within two depth ranges. Apparent conductivity is typically expressed in milliSiemens/meter (mS/m). Susceptibility is expressed parts per thousand (ppt). Operating procedures for the EM38-MK2-2 meter are described by Geonics Limited (2007).

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced the EMI data.[1] Using the recently marketed RTmap38 program (Geomar Software, Inc.,

Mississauga, Ontario), both GPS and EC_a data were simultaneously recorded and displayed on an Allegro CX field computer (Juniper Systems, North Logan, UT).[1] The color display for the RTmap38 program (see Figure 1) allows soil scientists to immediately track, observe, and interpret the results of EMI surveys. With this software program, soil scientists can visually correlate EMI data with soil and landscape patterns, and move directly to sites of different EC_a for sampling and verifications of the factors influencing the EC_a. In Figure 1, the left-hand plot shows the display as data are being recorded; the right-hand plot shows the screen when data collection is paused and the *hidden menu* appears.

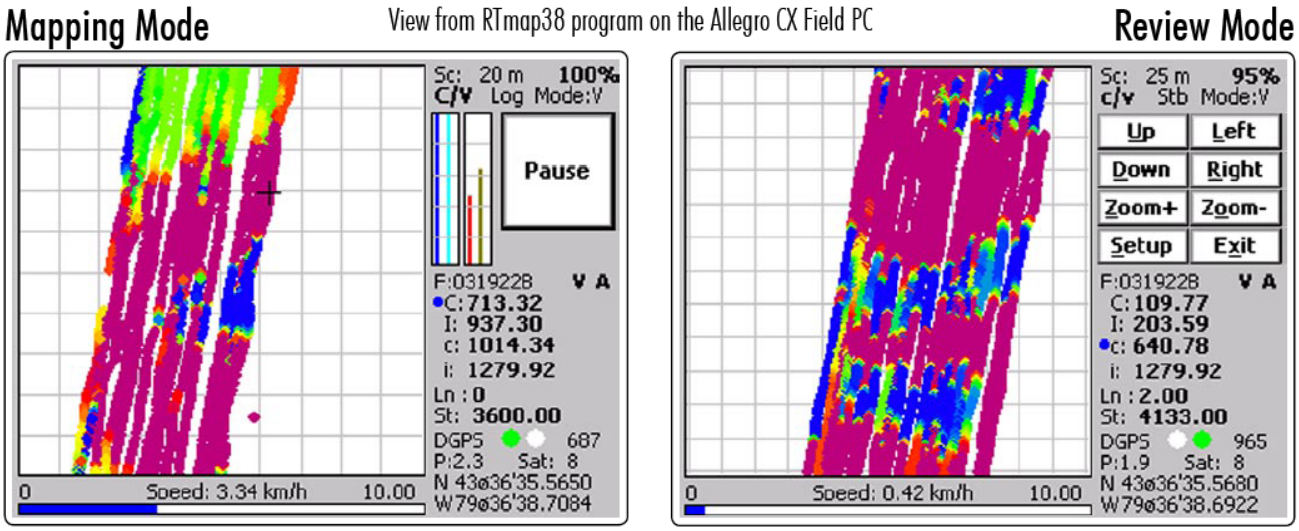

Figure 1. The RTmap38 program provides an instaneous track of each traverse and EC_a measurements displayed as a colored image on the Allegro field computer (courtesy of Geomar Software, Inc.).

To help summarize the results of the EMI surveys, the SURFER for Windows (version 8.0) 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. The ESAP Software Suite for Windows (Version 2.35R) developed by the USDA-ARS, Salinity Laboratory (Riverside, CA) was used to create optimal soil sampling schemes based on EC_a data (Lesch et al., 2000). The *Response Surface Sampling Design* (RSSD) of ESAP was used to generate these optimal sampling schemes and to identify the locations of sampling sites. The *ESAP-Salt Mapper* software was used to prepare raster maps showing the locations of the sampling sites.

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI, Salem, NH).[1] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the SIR-3000 requires two people to operate. Daniels (2004) and Jol (2008) discuss the use and operation of GPR. A 200 MHz antenna was used in this study.

The RADAN for Windows (version 6.6) software program (GSSI) was used to process the radar records.[1] Basic processing steps, which were applied to all radar records, included: header editing, setting the initial pulse to time zero, color table and transformation selection, and display range gain adjustments (see Daniels (2004) and Jol (2008) for discussions of these techniques).

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

Study Sites:

Billings County:

The two study sites located in Billings County are in rangeland. Site 1 is located in the southern ½ of Section 20, T. 139 N., R. 100 W. Within this site, soils are mapped as Janesburg-Dogtooth silt loams, 0 to 6 % slopes (51B). The moderately deep, well drained Janesburg and Dogtooth soils formed in residuum weathered from alkaline, soft shale, siltstone and/or mudstone on uplands. Site 2 is located in the eastern ½ of Section 21, T. 139 N., R. 100 W. Within Site 2, soils are mapped as Dogtooth-Janesburg silt loams, 0 to 6 percent slopes (13B), and Daglum-Rhoades complex, 0 to 6 % slopes (15B). The deep and very deep, moderately well drained and well drained Daglum soils formed in clayey alluvium or residuum on upland swales. The deep and very deep, well drained and moderately well drained Rhoades soils formed in stratified loamy and clayey materials derived from soft shale, siltstone or mudstone on uplands. Also observed on these sites were areas of Belfield and Farnuf soils. The deep and very deep, well drained or moderately well drained Belfield soils formed in alkaline, calcareous residuum or alluvium on uplands. The very deep, well drained Farnuf soils formed in alluvium on alluvial fans, stream terraces, hills, and sedimentary plains. The taxonomic classifications of these soils are listed in Table 1.

Table 1. Taxonomic classifications of the soils recognized at the Billings County study sites.

Soil Series	Taxonomic Classification
Belfield	Fine, smectitic, frigid Glossic Natrustolls
Farnuf	Fine-loamy, mixed, superactive, frigid Typic Argiustolls
Daglum	Fine, smectitic, frigid Vertic Natrustolls
Dogtooth	Fine, smectitic, frigid Leptic Natrustolls
Janesburg	Fine, smectitic, frigid Typic Natrustolls
Rhoades	Fine, smectitic, frigid Leptic Vertic Natrustolls

Table 2. Taxonomic classifications of the soils recognized at the Griggs County study sites.

Soil Series	Taxonomic Classification
Aastad	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
Cathay	Fine-loamy, mixed, superactive, frigid Glossic Natrudolls
Cresbard	Fine, smectitic, frigid Glossic Natrudolls
Emrick	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
Ferney	Fine, smectitic, frigid Leptic Natrudolls
Larson	Fine-loamy, mixed, superactive, frigid Calcic Natrudolls
Svea	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls
Wyard	Fine-loamy, mixed, superactive, frigid Typic Endoaquolls

Griggs County:

The two study sites located in Griggs County were both in cultivation. Site 1 is located in the northwest ¼ of Section 30, T. 148 N., R. 59 W. Within this site, soils are mapped as Larson-Cathay loams, 0 to 3 % slopes (G225A). The very deep, moderately well drained and somewhat poorly drained Larson and the moderately well drained Cathay soils formed in calcareous till. Site 2 is located in the northeast ¼ of Section 25, T. 148 N., R. 60 W. Within this site, soils are mapped as Emrick-Cathy loams, 0 to 3 percent slopes (G221A). The very deep, well drained and moderately well drained Emrick and moderately well drained Cathay soils formed in calcareous till on ground moraines on till plains Additional soils observed during field work included Aastad, Cresbard, Ferney, Svea and Wyard. All of these soils are very deep and form in calcareous till or local alluvium (Wyard). Wyard soils are somewhat poorly drained. Ferney soils are somewhat poorly drained and moderately well drained. Aastad soils are

moderately well drained. Cresbard and Svea soils are moderately well drained and well drained. Barnes soils are well drained. The taxonomic classifications of these soils are listed in Table 2.

Survey Procedures:
Most EMI surveys were completed by towing the EM38-MK2-2 meter behind an ATV in a plastic sled at speeds of 2 to 4 m/sec (see Figure 2). For the smaller, more detailed surveys within the Griggs County sites, pedestrian surveys were completed. Pedestrian surveys were completed by walking with the EM38-MK2-2 suspended above the ground surface (see Figure 3). Mobile surveys were completed by driving the ATV at a uniform speed in a back and forth manner across each site. The EC_a data discussed in this report were not temperature corrected to a standard temperature. At the time of this investigation soil temperature was about 7 ^{o} C at a depth of 30 inches.

All EC_a data were entered into an Excel spreadsheet and processed thru the ESAP (version 2.35) software program (Lesch, 2000). The Response Surface Sampling Design (RSSD) program of ESAP was used to generate an optimal sampling design within each field based on the EC_a data. Based on the response surface sampling design, six optimal sampling sites were selected in each study site. For each EMI survey, plots of EC_a data were prepared using the SURFER for Windows program. Plots of EC_a data showing the locations of the optimal sampling points for each site were compiled and copies used by soil scientists involved in soil sampling.

Figure 2. Most EMI surveys were completed by towing the EM38-MK2-2 meter in a plastic sled behind an ATV.

Figure 3. Kyle Thomson conducts a pedestrian EMI survey with the EM38-MK2-2 meter, an Allegro CX field computer, and a Trimble AG114 GPS.

Results:

EMI Surveys:

Billings County:

At both SAS study sites in Billings County, EC_a increased with increasing soil depth (measurements for the shallower-sensing, 50-cm intercoil spacing were typically lower than measurements for the deeper-sensing, 100-cm intercoil spacing). This trend suggests that the soluble salts increase with increasing soil depth, which is a reflection of the prevailing hydropedologic processes (e.g. depth to the water table, seepage, leaching, and evaporative discharge). While EC_a measurements were lower for the near surface layers, they were relatively more variable than measurements for the deeper layers (at Sites 1 and 2, coefficients of variation were 0.336 and 0.456 for the shallower measurements and 0.262 and 0.324 for the deeper measurements, respectively). Within each study site the range in EC_a at both depth intervals was rather large. At Sites 1 and 2 standard deviations were, respectively, 18.61 and 20.95 for the shallow measurements and 22.87 and 22.48 for the deeper measurements. These characteristics presumably reflect the presence and distribution of sodium and soluble salts within soil profiles and across each site. As Daglum, Dogtooth, Janesburg, and Rhoades soils have an EC_e greater than 4 mmhos/cm and SAR greater than 13 (http://soildatamart.nrcs.usda.gov) in some horizon within depths of 100 cm, they are all considered to be saline-alkaline soils (U.S. Salinity Laboratory Staff, 1954).

Table 3. Basic statistics for EMI grid sites located in Billings County.

	Site 1 - 0 to 150 cm	Site 1 - 0 to 75 cm	Site 2 - 0 to 150 cm2	Site 2 - 0 to 75 cm
Observations	1682	1682	2627	2627
Minimum	30.39	12.54	25.20	11.33
25 % tile	73.83	43.55	52.34	31.17
75 % tile	104.30	68.13	82.81	55.90
Maximum	136.05	103.59	172.15	146.76
Average	87.19	55.32	69.29	45.95
Standard Deviation	22.87	18.61	22.48	20.95

Table 3 provides the basic statistics for the two high-intensity EMI surveys, which were conducted in Billings County. At Site 1, EC_a averaged 87 mS/m and ranged from about 30 to 136 mS/m for the deeper-sensing, 100-cm intercoil spacing. One-half the EC_a measurements acquired with the 100-cm intercoil spacing were between about 74 and 104 mS/m. For the shallower-sensing, 50-cm intercoil spacing, EC_a averaged about 55 mS/m and ranged from about 13 to 104 mS/m. One-half the measurements obtained with the 50-cm intercoil spacing were between about 44 and 68 mS/m.

Figure 4 contains plots of the EC_a data collected with EM38-MK2-2 meter at Site 1. Following the EMI survey, soil scientists used the color-scaled, pseudo-grid image displayed on the screen of the Allegro CX field computer to guide them to four sampling sites based on relative EC_a values. The names and locations of the soils identified at these four core sites are shown in Figure 4. The core extracted in an area of lower EC_a (23 mS/m in shallower-sensing, 50-cm intercoil spacing; and 47 mS/m in the deeper-sensing, 100-cm intercoil spacing) was identified as the fine-textured Belfield (Glossic Natrustolls) soil. The core extracted in an area of higher EC_a (95 mS/m for the 50-cm intercoil spacing; and 115 mS/m for the 100-cm intercoil spacing) was identified as the fine textured Rhoades (Leptic Vertic Natrustolls) soil. Cores extracted in areas of intermediate EC_a values were identified as the fine-textured Daglum (Vertic Natrustolls) and an indeterminate Belfield/Daglum soils. As sodicity and salinity form a continuum, and transitional forms are often evident in the field, it is often difficult to correctly identify and distinguish some Daglum and Belfield soils. At this study site, EC_a data helped soil scientists to identify three distinct soils and characterize their general spatial patterns with a unit of management. Variations in the soluble salt contents are suspected to have caused these patterns.

At Site 2, EC_a averaged about 69 mS/m and ranged from about 25 to 172 mS/m for the deeper-sensing, 100-cm intercoil spacing. One-half the measurements obtained with the 100-cm intercoil spacing were between about 52 and 172 mS/m. For the shallower-sensing, 50-cm intercoil spacing, EC_a averaged about 46 mS/m and ranged from about 11 to 147 mS/m. One-half the measurements obtained with the 50-cm intercoil spacing were between about 31 and 56 mS/m. Compared to Billings County Site 1, the averaged EC_a was slightly lower and the range in EC_a was greater at Site 2.

Figure 5 contains plots of the EC_a data collected with EM38-MK2-2 meter at Billings County Site 2. Once again, following the EMI survey, soil scientists used the color-scaled, pseudo-grid image displayed on the screen of the Allegro CX field computer to guide them to sampling sites based on spatial EC_a values. The names and locations of the soils identified at three core sites are shown in Figure 5. The core extracted in an area of lower EC_a (14 mS/m in shallower-sensing, 50-cm intercoil spacing; and 30 mS/m in the deeper-sensing, 100-cm intercoil spacing) was identified as the medium-textured Farnuf (Typic Argiustolls) soil. The core extracted in an area of higher EC_a (75 mS/m for the 50-cm intercoil spacing; and 106 mS/m for the 100-cm intercoil spacing) was identified as the fine-textured Rhoades (Leptic Vertic Natrustolls) soil. A core extracted in an area of intermediate EC_a (50 mS/m

for the 50-cm intercoil spacing; and 70 mS/m for the 100-cm intercoil spacing) was identified as the fine-textured Belfield (Glossic Natrustolls) soil. Once again, spatial EC_a patterns helped soil scientists to identify distinct soil types and characterize their general distribution in a unit of management. At both SAS sites in Billings County, EMI successfully distinguished different soils and characterized relative levels of soil salinity and sodicity.

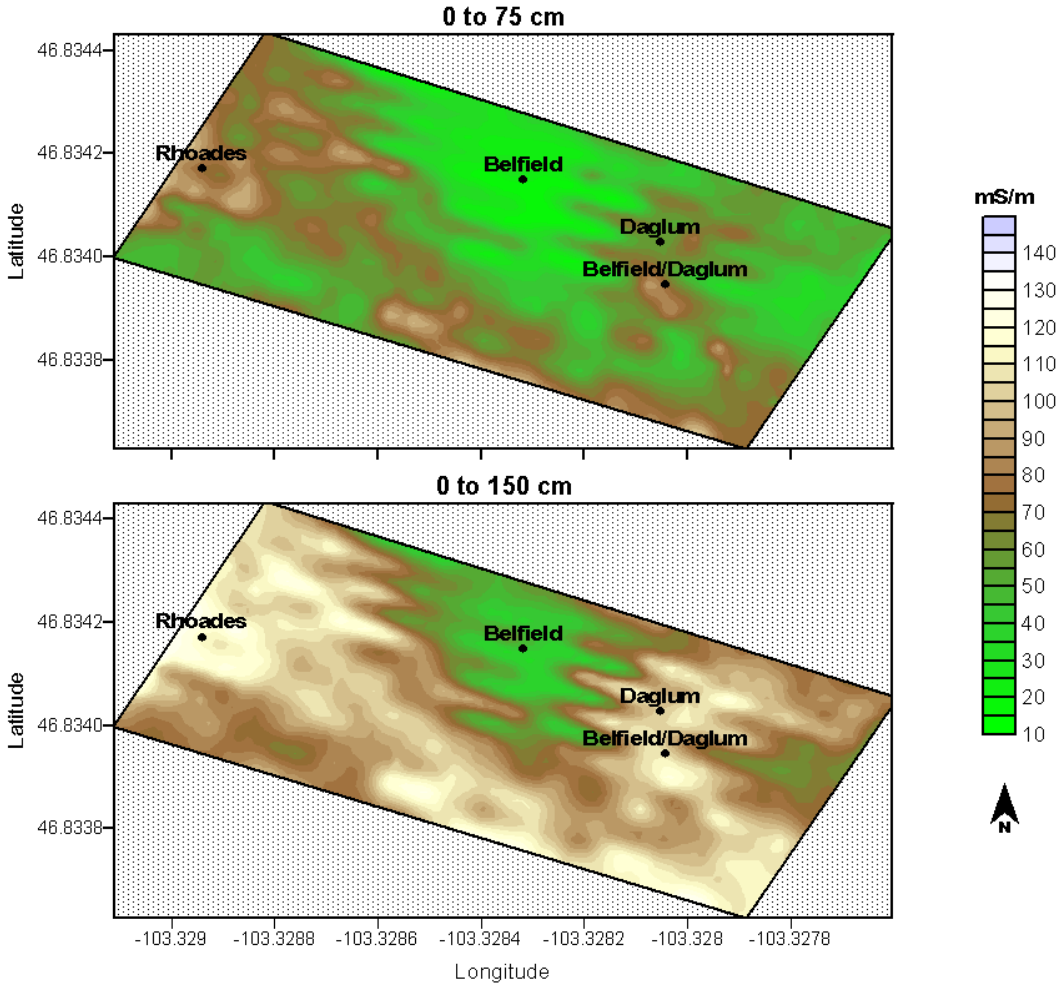

Figure 4. These plots of EC_a data were collected at Site 1 in Billings County. The upper and lower plots show the spatial distribution of EC_a recorded with the EM38-MK2-2 meter in the shallower-sensing 50-cm and the deeper-sensing 100-cm intercoil spacings, respectively. The locations and identities of four cored soil profiles are also shown.

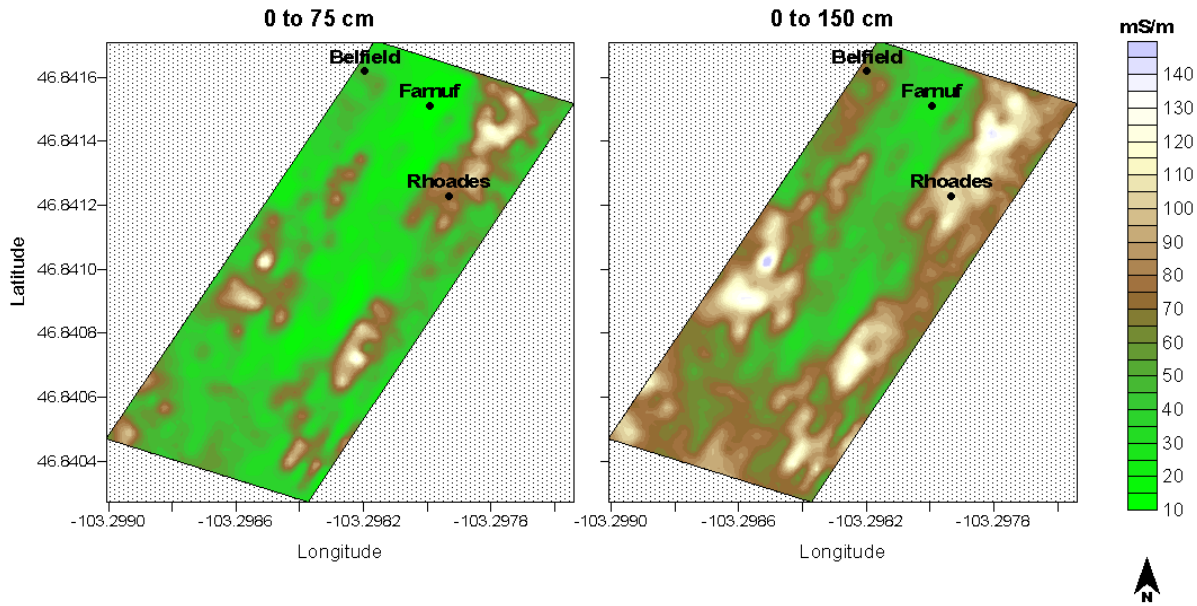

Figure 5. These plots of EC_a data were collected at Site 2 in Billings County. The left-hand and right-hand plots show the spatial distribution of EC_a recorded with the EM38-MK2-2 meter in the shallower-sensing 50 cm and deeper-sensing 100 cm intercoil spacings, respectively. The locations and identities of three cored soil profiles are also shown.

Griggs County:

At the two SAS study sites in Griggs County, EC_a was spatially variable with noticeable differences between the two adjoining sites. These characteristics are presumed to reflect variations in sodium and soluble salt contents and soil textures. Dominant soils at these sites included Ferney and Larson. Compared with the Billings County sites, soils were noticeably wetter in Griggs County. The higher moisture contents of the soils in Griggs County undoubtedly increased the EMI responses. However, the extent of this contribution is unknown at this time. As Ferney (Leptic Natrudolls) and Larson (Calcic Natrudolls) soils have an EC_e greater than 4 mmhos/cm and a SAR greater than 13 in some horizons within depths of 100 cm (http://soildatamart.nrcs.usda.gov), they are considered to be saline-alkaline soils (U.S. Salinity Laboratory Staff, 1954). Cathay soils (Glossic Natrudolls) have an EC_e greater than 4 mmhos/cm and a SAR, which ranges from 5 to 15, in some horizon within depths of 100 cm, and are also considered saline-alkaline soils.

As was the case in Billings County, EC_a increased with increasing soil depth (measurements for the shallower-sensing, 50-cm intercoil spacing were typically lower than measurements for the deeper-sensing, 100-cm intercoil spacing) at both sites in Griggs County. This trend suggests that the amounts of soluble salts increase with increasing soil depths and is assumed to reflect prevailing hydropedologic processes (e.g. depth to the water table, seepage, leaching, and evaporative discharge). In general, EC_a measurements were lower and more variable for near surface layers than for deeper layers (at Sites 1 and 2, coefficients of variation were 0.436 and 0.409 for the upper 50-cm, and 0.368 and 0.256 for the upper 150-cm, respectively). Site 1 had the highest averaged and most variable EC_a for both depth intervals. At Griggs County Site 1, the range in EC_a for both depth intervals was the largest of all the study sites (both Billings and Griggs Counties) with standard deviations of 31.44 for the upper 50-cm and 36.57 for the upper 150-cm. In contrast, nearby Griggs County Site 2 had the lowest averaged and least variable EC_a for both depth intervals. At Griggs County Site 2, the range in EC_a at both depth intervals was the smallest of all the study sites (both Billings and Griggs Counties) with standard deviations of only 6.80 for the upper 50-cm, and 5.60 for the upper 150-cm. At Griggs County Site 2, the low and invariable EC_a is presumed to reflect the absence of high concentrations of soluble salts and relatively similar soils and/or soil properties. Site 2 is

mapped as Emrick-Cathy loams, 0 to 3 percent slopes (G221A). As Cathy soils have an EC_e greater than 4 mmhos/cm and a SAR ranging from 5 to 15 (http://soildatamart.nrcs.usda.gov) in some horizon within depths of 100-cm, they are considered to be saline-alkaline soils (U.S. Salinity Laboratory Staff, 1954).

Table 3 provides the basic statistics for the two EMI surveys that were conducted in Griggs County. At Site 1, EC_a averaged about 99 mS/m and ranged from about 44 to 237 mS/m for the deeper-sensing, 100-cm intercoil spacing. One-half the measurements obtained with the 100-cm intercoil spacing were between about 71 and 115 mS/m. For the shallower-sensing, 50-cm intercoil spacing, EC_a averaged about 72 mS/m and ranged from about 28 and 191 mS/m. One-half the measurements obtained with the 50-cm intercoil spacing were between about 49 and 86 mS/m.

Table 4. Basic statistics for EMI grid sites located in Griggs County.

	Site 1 - 0 to 150 cm	**Site 1 – 0 to 75 cm**	**Site 2 - 0 to 150 cm**	**Site 2 - 0 to 75 cm**
Observations	1458	1458	2198	2198
Minimum	44.18	28.52	-37.70	-245.39
25 % tile	71.41	49.41	17.93	14.22
75 % tile	114.73	85.98	24.49	18.67
Maximum	237.46	191.33	41.21	29.88
Average	99.28	72.13	21.86	16.62
Standard Deviation	36.57	31.44	5.60	6.80

Figure 6 contains plots of the EC_a data collected with EM38-MK2-2 meter at Site 1. Once again, following the EMI survey, soil scientists used the color-scaled, pseudo-grid image displayed on the screen of the Allegro field computer to guide them to sampling sites based on relative EC_a values. The names and locations of the soils identified at four core sites are shown in Figure 4. A core extracted in an area of higher EC_a (155 mS/m in shallower-sensing, 50-cm intercoil spacing; and 196 mS/m in the deeper-sensing, 100-cm intercoil spacing) was identified as the fine-textured Ferney (Leptic Natrudolls) soil. A core extracted in an area of lower EC_a (32 mS/m for the 50-cm intercoil spacing, and 54 mS/m for the 100-cm intercoil spacing) was identified as the fine-textured Cresbard (Glossic Natrudolls) soil. Cores extracted in areas of intermediate EC_a values were identified as the medium-textured Svea (Pachic Hapludolls) and Wyard (Typic Endoaquolls) soils. All four soils identified at this site are considered to be affected by sodium and other soluble salts to varying extents. Areas of higher sodicity and salinity are associated with areas of higher EC_a and are readily distinguishable on these plots (Figure 6). However, not all soils are distinguishable with EMI. At the time of this investigation, Svea and Wyard soils were impossible to differentiate with EMI. It is surprising that the core identified as Cresbard soil had a lower EC_a than cores identified as Svea and Wyard soils. As Cresbard, Svea and Wyard soils occur in the same landscape, share common limits, and are often not as easily differentiated in the field as one would expect from their taxonomic classification, the result is not entirely unanticipated.

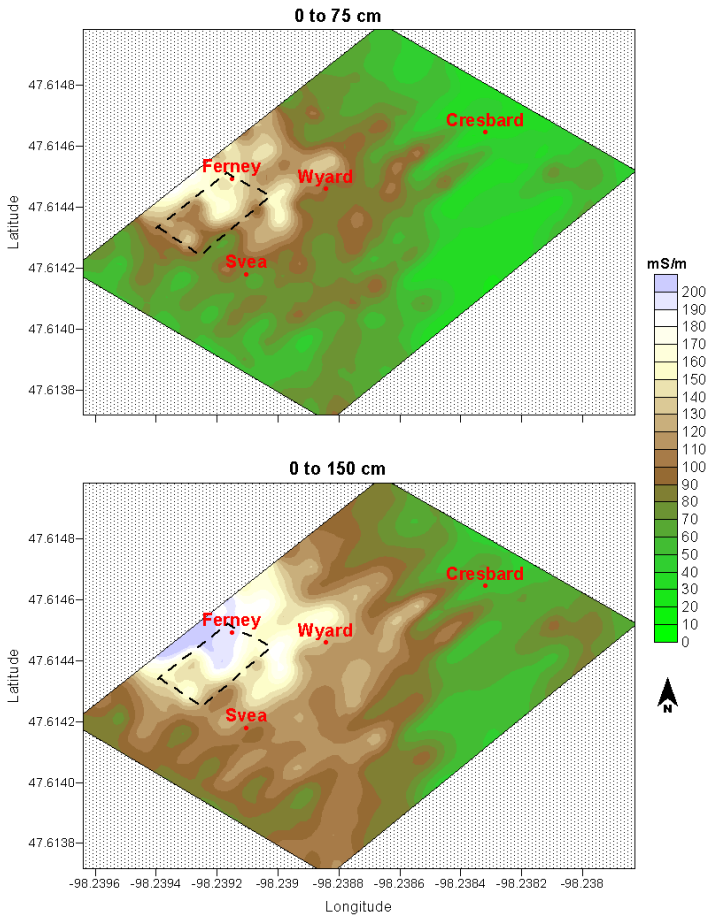

Figure 6. These plots of EC_a data were collected at Site 1 in Griggs County. The upper and lower plots show the spatial distribution of EC_a recorded with the EM38-MK2-2 meter in the shallower-sensing 50 cm and deeper-sensing 100 cm intercoil spacings, respectively. The locations and identities of the four cored soil profiles and the detailed grid site are also shown.

Figure 7 contains plots of the EC_a data, which were collected with EM38-MK2-2 meter at a smaller grid site within Site 1. The location of this smaller grid within Site 1 is shown in Figure 6. The smaller grid was located in an area of higher EC_a and presumably Ferney soils. This grid site was more intensely covered by a pedestrian EMI survey. This more intensive survey revealed similar, but more intricate spatial EC_a patterns than the mobile survey conducted across the larger, encompassing grid area of Site 1. However, in terms of relative site variability, coefficients of variations were less within the smaller grid than the larger grid area (0.1786 versus 0.3683 for 100-cm intercoil spacing and 0.3683 versus 1.005 for the 50-cm intercoil spacing). Considering the variations in sodicity and salinity that can occur within soil polygons, these results are not unexpected.

At Griggs County Site 2, EC_a averaged 22mS/m and ranged from about -38 to 41 mS/m for the deeper-sensing, 100-cm intercoil spacing. One-half the measurements obtained with the 100-cm intercoil spacing were between about 18 and 24 mS/m. For the shallower-sensing 50-cm intercoil spacing, EC_a averaged about 17 mS/m and ranged from about -245 to 30 mS/m. One-half the measurements obtained with the 50-cm intercoil spacing were between about 14 and 19 mS/m. Negative EC_a values are attributed to metallic artifacts buried within the site. In general, the lower and less variable EC_a at Site 2 is attributed to lower clay and soluble salt contents and the dominance of coarser-textured Emrick (Pachic Hapludolls) soils.

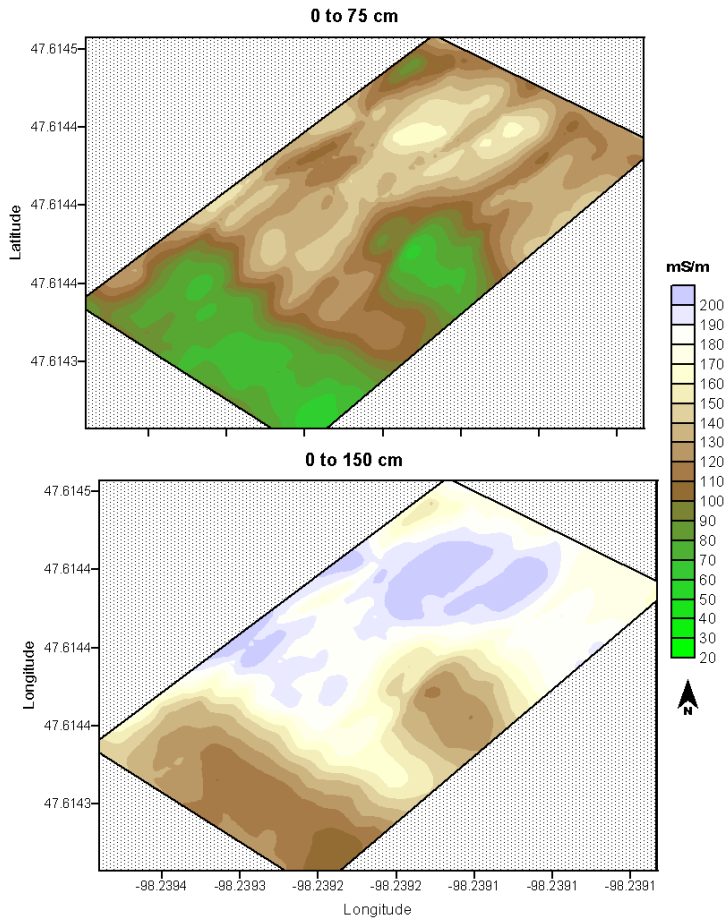

Figure 7. These plots of EC_a data were collected within a smaller grid located at Site 1 in Griggs County. The location of this detailed grid site is shown in the plots of Figure 6. The upper and lower plots show the spatial distribution of EC_a recorded with the EM38-MK2-2 meter in the shallower-sensing 50 cm and deeper-sensing 100 cm intercoil spacings, respectively.

Figure 8 contains plots of the EC_a data collected with EM38-MK2-2 meter at Site 2. In comparison to the previous plots of EC_a data, the scale in Figure 8 has been reduced to accommodate the lower and less variable EC_a measurements. The site is mapped as Emrick-Cathy loams, 0 to 3 percent slopes (G221A). The comparatively low and invariable EC_a at this site suggest that the soils in this polygon are closely similar and have lower soluble salt and clay contents than those at Site 1. Following the EMI survey, soil scientists used the color-scaled, pseudo-grid image displayed on the screen of the Allegro field computer to guide them to three sampling sites based on relative EC_a values. The names and locations of the soils identified at the three core sites are shown in Figure 8. Soils identified in these cores were identified as Barnes, Svea and Aastad/Cresbard. At these core sites, EC_a ranged from only 12 to 23 mS/m in shallower-sensing, 50-cm intercoil spacing and from 17 to 32 mS/m in the deeper-sensing, 100-cm intercoil spacing. The lowest EC_a was recorded at the Svea core site (12 mS/m for the 50-cm intercoil spacing and 17 mS/m for the 100-cm intercoil spacing). The Aastad/Cresbard and the Barnes cores had closely similar EC_a (22 and 23 mS/m for the 50-cm intercoil spacing, and from 30 to 32 mS/m for the 100-cm intercoil spacing, respectively).

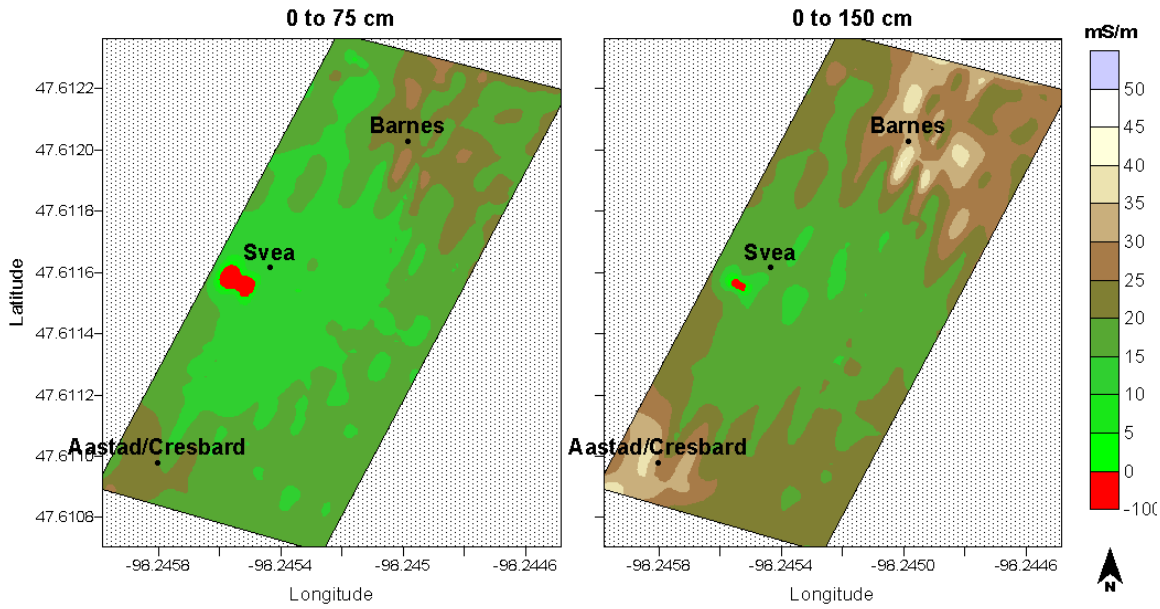

Figure 8. These plots of EC_a data were collected at Site 2 in Billings County. The left-hand and right-hand plots show the spatial distribution of EC_a recorded with the EM38-MK2-2 meter in the shallower-sensing 50 cm and deeper-sensing 100 cm intercoil spacings, respectively. The locations and identities of three cored soil profiles are shown.

Directed Sampling:

As a tool for precision agriculture and high intensity soil surveys, EC_a data can be used as an ancillary measure for a spatially varying soil property that is not easily sensed or mapped, to direct soil sampling, and to refine maps (Jaynes, 1995; Stafford, 2000). With EMI, EC_a data are quickly and effortlessly collected at field-scales. In precision agriculture, with EMI, units of management are partitioned into zones based on spatial EC_a patterns and sparse sampling is conducted in each zone. Zone sampling reduces the costs of sampling while maintaining information on soil variability (Shaner et al., 2008). In this study, zone sampling was conducted by soil scientists immediately following each EMI survey using the colored plots of EC_a data on an Allegro field computer. With the RTmap38 program, soil scientists moved directly to sites of different EC_a to identify the soils and verify the factors influencing EC_a.

Recently, the United States Salinity Laboratory (Riverside, California) has developed software to select optimal soil sampling points based on EC_a data (Lesch, 2005; Lesch et al., 2000, 1995a, 1995b). The USDA-ARS's ESAP (Sampling, Assessment, and Prediction) software was designed to predict soil salinity (EC_e) from EC_a data. This software, however, can be used to predict other soil properties as well. Amezketa (2007) used ESAP to determine levels of sodicity in saline-sodic soils. Prediction-based sampling and modeling approaches are embraced in this program as a cost-effective alternative to geostatistical modeling techniques, which are often more sample-intensive (Eigenberg et al., 2008). The ESAP software is designed to combine high-intensity EC_a data with sparse, low-density soil sampling in order to calibrate a suitable predictive equation. A goal of this prediction-based sampling approach is to reduce the number and optimize the collection of sampling data.

The ESAP-*Response Surface Sampling Design* (RSSD) program can generate three different directed-sampling plans (6, 12, and 20 sample sites). The selection of the most suitable sampling design will depend on the availability of resources and the intensity and use of the survey. The RSSD program determines sampling sites based on the magnitude and spatial locations of the collected EC_a data. In this directed-sampling approach, a minimum number of calibration samples sites are selected based on the observed magnitudes and spatial location of

EC_a data (Eigenberg et al., 2008). The sampling sites are selected to optimize the estimation of a regression model and to simultaneously maximize the average separation distance among sampling sites. Sample locations are representative of the total variation of EC_a and, hopefully, the targeted soil property (Corwin et al., 2006). The directed-sampling approach has been described as a hybrid blend of a response surface sampling design with a space-filling algorithm (Eigenberg et al., 2008; Lesch, 2005).

Raster maps (Figure 9) of depth-weighted EC_a obtained with the EM38-MK2-2 meter (for the 100-cm intercoil spacing) were prepared using the ESAP-*SaltMapper* program, which employs an inverse distance-squared interpolation (Lesch et al., 2000). These maps show the spatial EC_a distributions and the locations of the optimal sample points in Site 1 of both Griggs and Billings Counties. Tables 7 and 8 provide relevant data for the six optimal sampling points in Griggs and Billings Counties, respectively.

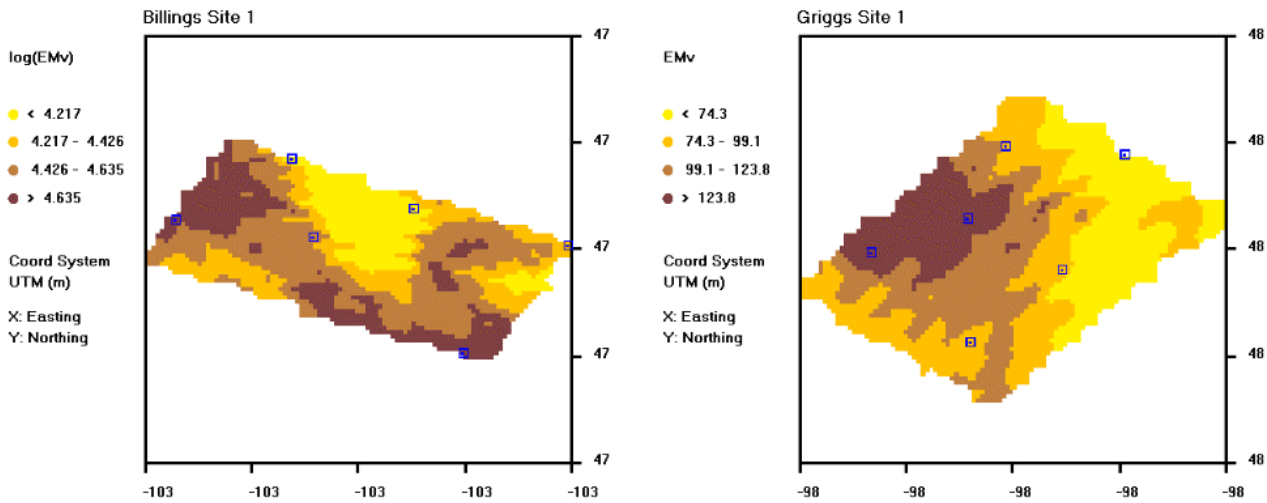

Figure 9. These raster maps of EC_a data collected at Site 1 in Billings (left-hand plot) and Griggs (right-hand map) Counties were prepared using ESAP-SaltMapper Program. The locations of the six optimal sampling points, which were determined using ESAP- Response Surface Sampling Design, are shown in each map.

Table 5. These optimal sampling sites in Billings County were selected using the ESAP-RSSD Program.

Site 1

Observation #	**Longitude**	**Latitude**	**EC_a 0 to 175 cm**	**EC_a 0 to 75 cm**
35	-103.32902	46.83414	136.0	98.1
147	-103.32798	46.83366	132.9	100.6
209	-103.3276	46.83405	86.8	55.3
295	-103.3286	46.83436	39.0	16.6
377	-103.32816	46.83418	52.8	37.5
1028	-103.32852	46.83408	83.6	49.1

Site 2

Observation #	Longitude	Latitude	EC_a 0 to 175 cm	EC_a 0 to 75 cm
192	103.29878	46.84039	65.7	37.15
264	-103.2982	46.84054	66.6	35.9
687	-103.29851	46.84101	151.8	121.0
1040	-103.29826	46.84126	68.0	46.1
2060	-103.29793	46.84126	108.32	84.5
2614	-103.29795	46.8415	28.32	11.3

Table 6. These optimal sampling sites in Griggs County were selected using the ESAP-RSSD Program.

Site 1

Observation #	Longitude	Latitude	EC_a 0 to 175 cm	EC_a 0 to 75 cm
130	-98.2382	47.6148	45.20	30.47
353	-98.2394	47.6143	154.92	127.54
419	-98.2388	47.6148	98.59	71.29
584	-98.2389	47.6145	163.28	120.08
1163	-98.2389	47.6140	74.61	43.71
1206	-98.2385	47.6143	90.66	65.23

Site 2

Observation #	Longitude	Latitude	EC_a 0 to 175 cm	EC_a 0 to 75 cm
128	-98.2452	47.6109	21.68	16.88
530	-98.2452	47.6128	21.99	16.84
607	-98.2455	47.6114	14.77	10.04
658	-98.2458	47.6109	33.36	22.42
1416	-98.2451	47.6116	16.21	14.73
1864	-98.2447	47.6119	30.12	24.10

Ground-penetrating radar (GPR) Tests:
The radar records from the Billings County sites were unfortunately lost. Though recorded and viewed in the field, they were not properly formatted on the storage card used in the SIR3000. As a consequence, the records from Billings County were not retrievable. In Griggs County, a small metallic reflector was buried in areas of both Aastad and Ferney soils at a depth of 50 cm. A short traverse line was extended across the position of the buried reflector. The 200 MHz was pulled along the traverse line to calibrate the GPR and depth scale the radar records.

Ground-penetrating radar is a time scaled system. The system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, bedrock) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in equation [1] (after Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to equation [2] (after Daniels, 2004):

$$E_r = (C/v)^2 \qquad [2]$$

Where C is the velocity of propagation in a vacuum (0.298 m/ns). Velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and *v*.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (a 25-cm diameter, metal plate), the velocity of propagation and the relative dielectric permittivity through the upper part of soil profiles were estimated using equations [1] and [2]. In Griggs County, in an area of Aastad and Ferney soils, based on the plate being buried at a depth of 50 cm, the estimated E_r was 7.1 and the estimated *v* was 0.1126 m/ns.

Because of their high electrical conductivity, saline (saturated extract electrical conductivity ≥ 4 mmhos cm $^{-1}$) and sodic (sodium absorption ratio ≥13) soils are considered unsuited to ground-penetrating radar (Doolittle et al., 2003). In saline and sodic soils, penetration depths are generally assumed to be less than 25 cm (Daniels, 2004). To verify these interpretations, radar traverses were conducted across two soils in Griggs County. The sites are located in an area mapped as Larson-Cathay loams, 0 to 3 % slopes (G225A). Soils identified at the two GPR calibration sites were classified as Aastad and Ferney. Aastad soils are considered to have low potential for GPR. The sodic Ferney soils are considered to be unsuited to GPR. The taxonomic classifications of these soils are listed in Table 2. Though classified as an Argiudolls, the Aastad soil is considered to be slightly affected by excess sodium.

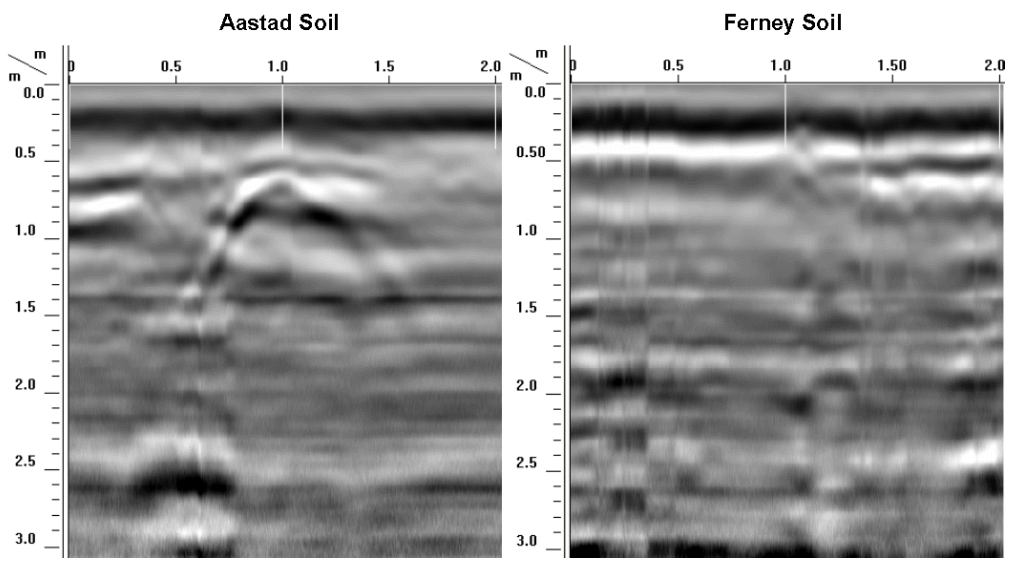

Figure 10. These radar records were obtained with a 200 MHz antenna in areas of Aastad (left-hand), and Ferney (right-hand) soils. In each soil, a metallic reflector was buried at a depth of 50 cm.

A both site, 3 survey flags were placed in the soil at 1 m intervals. This created a 2 m traverse line. At the middle flag, a 25 cm diameter metal plate was buried at a depth of 50 cm. The radar records from the Aastad and Ferney sites are shown in Figure 10. In both plots, depth and distance measurements are expressed in meters. On each radar record, the metal plate should appear at a depth of 50 cm beneath the 2-m distance mark. On both radar

records, radar signals were rapidly attenuated and penetration was severely depth restricted. On the Aastad radar record (left), the metal plate is not clearly imaged, but diffraction tails from this reflector form an identifying hyperbolic pattern beneath the 1-m distance mark. On the Ferney radar record (right), the metal plate is not imaged and no diffraction tails from this reflector are identifiable beneath the 1-m distance mark.

No subsurface reflectors are readily apparent on either radar record. The broad horizontal bands in the lower parts of the radar records represent low-frequency background noise. On each radar record, jarring of the antenna, caused by vegetation and surface roughness, resulted in several short, segmented, vertical patterns of noise. In the left-hand portion (0 to 1.5 m) of the Aastad radar record, the upper boundary of the Bt horizon is apparent between depths of 40 to 60 cm. This interface appears to partially obscure the hyperbolic (^) reflections from the metal plate. No meaningful subsurface information can be obtained with a 200 MHz antenna in the area of Ferney soils. The GPR soil suitability interpretations for Aastad and Firney soils have been confirmed. However, additional surveys on sodic, saline-sodic, and saline soils in North Dakota are desired to confirm interpretations and to further evaluate the effects of excess sodium and other soluble salts on GPR.

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