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**Subject:** Soil - Geophysical Assistance

**Date:** 1 June 2010

**To:** Paul J. Sweeney  
State Conservationist  
USDA-NRCS,  
220 East Rosser Avenue  
P.O. Box 1458  
Bismarck, ND 58502-1458

**Purpose:**

The purpose of this study was to use electromagnetic induction (EMI) to characterize sodium-affected soils (SAS) in different areas of North Dakota.

**Participants:**

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Mike Ulmer, Senior MO Soil Scientists, MO7, USDA-NRCS, Bismarck, ND

**Activities:**

All EMI activities were completed during the period of 10 to 14 May 2010.

**Summary:**

- During this field visits, EMI data were collected on seven sites located across North Dakota in Slope, Foster and Grand Forks Counties. Based on the results of these surveys, twenty-four soil pedons were described and sampled for laboratory characterization.
- Electromagnetic induction surveys have been completed and soil characterization data have been collected on multiple fields of saline (Walsh and Grand Forks Counties) and sodium-affected soils (SAS) (Billings, Slope, Foster, and Griggs Counties) in North Dakota. The characterization data have been processed and are now available from the National Soil Survey Laboratory. The data sets (EMI and characterization data) need to be analyzed and summarized. It is recommended that further fieldwork on saline soils and SAS be suspended until this task is completed and the results reviewed.



- By 1 January 2011, Jim Doolittle will create a data library of the geophysical projects that have been completed in North Dakota and Minnesota over the past ten years. This library will include trip reports, raw and processed data, worksheets, images, and interpretations. For each project, the type of assistance (whether GPR or EMI), objectives, and any associated laboratory data will be provided in this library.
- Using ESAP software, Jim Doolittle will evaluate the data collected in areas of saline soils in Walsh and Grand Forks Counties and sodium-affected soils (SAS) in Griggs, Foster, Billings, and Slope Counties. Results of these investigations will be summarized. A summary of the electromagnetic induction (EMI) surveys on saline and sodium-affected soils will be prepared for the State Soil Scientists by the end of December 2011.
- It is recommended that Jim Doolittle provide ESAP (EC<sub>e</sub> Sampling, Assessment, and Prediction) software training to several designated soil scientists in North Dakota in during the winter of 2010-2011. The ESAP software was developed USDA-ARS Salinity Laboratory (Riverside, California) to select sample sites, and assess and predict soil salinity and other soil properties within units of management based on EMI data. Training will allow North Dakota Soil Staff to independently process and analyze EMI data.

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

JONATHAN W. HEMPEL  
 Director  
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cc:

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# Technical Report on the use of Electromagnetic Induction (EMI) in areas of sodium-affected and saline soils in North Dakota on 10 to 14 May 2010.

Jim Doolittle

## **Background:**

### Sodium-affected soils:

North Dakota has millions of acres of sodium-affected soils (SAS). There are over 4.5 million acres of SAS in the *Rolling Soft Shale Plain* of western North Dakota (MLRA 54) alone. Millions of additional acres are present as named components or inclusions in other portions of the state. Concerns have recently arisen over inconsistent mapping, classification, and interpretation of these soils, especially with the use of modern management practices (e.g., no-till) (Mike Ulmer, personal communication). An area of increasing concern to management is productivity index interpretations as it affects crop insurance. In an example referenced by Jerry Schaar, no-till grain production on some western North Dakota SAS, which are interpreted as Class 6 land, exceeds the county average for wheat. Since Class 6 land is ineligible for crop insurance, producers are required to take on extra risks. Productivity index values range widely among Typic, Leptic, and Glossic taxa of SAS, but have never been systematically evaluated for soil properties that likely influence yield. Research and characterization of SAS has been spotty (Jerry Schaar, personal communication). As a case in point, only 19 pedons in the National Soil Characterization database (accessed 3/1/2010) represent SAS in MLRA 54, however, nearly 60 percent of these pedons were collected in a single county.

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 of the physical appearance of soils. Laboratory measurements are relatively time-consuming and costly, and are therefore limited in number. Surrogate field measures such as electromagnetic induction (EMI) have the potential to improve the mapping, interpretation, and management of SAS. In areas of SAS, the use of EMI is viewed as being more expedient and economical than conventional laboratory determinations alone. Because of the larger number of measurements that can be quickly obtained with EMI, more comprehensive and detailed surveys of SAS delineations and units of management can be completed than with traditional sampling methods. However, in order to establish relationships between SAR and apparent conductivity ( $EC_a$ ) and to develop predictive equations, the collection of a small number of soil samples for laboratory analysis is necessary with EMI. Presently, the effectiveness of EMI on SAS in the Northern Great Plains has not been fully established. The purpose of this study is to further evaluate the effectiveness of EMI for the characterization of SAS and to collect additional characterization data.

### Hydropedologic Functional Units:

The last two decades have witnessed the rapid growth of site-specific management (alternatively referred to as precision agriculture). Site-specific management adjusts farming practices to measured variations in soil properties by dividing farmlands into management zones that have different seeding and chemical requirements (Mulla, 1993). Management zones are identified by variations in crop yields and/or soil properties. To divide farmlands into management zones, site-specific management relies on maps showing the location, size, and distribution of soils and soil properties within fields. Electromagnetic induction (EMI) has been used as an accurate, fast and inexpensive means of mapping soils and soil properties at a level of resolution that is comparable with the requirements of site-specific management (Corwin and Lesch, 2003; Bianchini and Mallarino, 2002; Lund and Christy, 1998; Jaynes, 1995 and 1996; Sudduth et al., 1995). As large, high-resolution data sets can be collected from mobile EMI

platforms equipped with global positioning systems (GPS), EMI is well suited to surveying of large farmlands (Adamchuk et al., 2004; Freeland et al., 2002)

In addition to its use in site-specific management, EMI offers immense advantages in soil survey and research. Being non-invasive, measurements can be collected with EMI at a level of resolution not practical with traditional methods and instrumentation. Spatial  $EC_a$  patterns can provide additional detail to existing soil maps (Hedley et al., 2004; Doolittle et al., 2008). A major contribution of EMI to soil surveys has been the identification and delineation of small included areas of dissimilar soils within soil polygons (Fenton and Lauterbach, 1999). Differences in  $EC_a$  are linked to different soils having dissimilar physiochemical properties (Farahani and Flynn, 2007; King et al., 2005; Brevik and Fenton, 2003; Anderson-Cook et al., 2002) and hydrologic processes (Kravchenko, 2008; Waive et al., 2000; Kachanoski et al., 1988).

Electromagnetic induction has been widely used to identify and map management zones in site-specific management and soil inclusions in high-intensity soil surveys. Closely synonymous to management zones and soil map unit inclusions is the concept of *hydropedologic functional units* (HFU). A *hydropedologic functional unit* is a cartographic unit that encompasses hydropedologic processes, soil structure and soil-landscape (Indorante et al., 2009). A HFU is defined as a unique mappable area, at a particular scale of resolution, created through the interaction of soil structures (e.g., physiochemical properties and spatial arrangements) and hydrologic processes (interception, runoff, infiltration, recharge, flow through, and discharge, storage, evaporation, and transpiration) (Indorante et al., 2009). A HFU is a means of cartographically representing important and more detailed hydropedologic soil-landscape functions (Lin et al., 2006a and 2006b). Pedogenic features and processes are mappable at multiple scales (e.g. from pedon description level to soil map level), but the primary level of detail for a HFU is the landscape and landform level.

Hydropedological functional units are in essence management zones that are identified by differences in soil structure and hydrologic processes. Hydropedological functional units identify and emphasize the three pillars of hydropedology: pedology, hydrology, and landscape. During this field visit, several soil delineations were surveyed with EMI to provide examples of HFU in North Dakota.

### **Equipment:**

An EM38-MK2-2 meter (Geonics Limited; Mississauga, Ontario), was used in this investigation.<sup>1</sup> The EM38-MK2-2 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 by distances of either 100 or 50 cm. This configuration provides nominal penetration depths of about 150 and 75 cm in the vertical dipole orientation, and about 75 and 38 cm in the horizontal dipole orientation. In either dipole orientation, the EM38-MK2-2 meter provides measurements of both the quadrature-phase ( $EC_a$ ) and the in-phase (susceptibility) components within the 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.<sup>1</sup> Using the 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).<sup>1</sup>

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<sup>1</sup> Manufacturer's names are provided for specific information; use does not constitute endorsement.

All EC<sub>a</sub> data that were collected on SAS were entered into an Excel spreadsheet and processed thru the ESAP (version 2.35) software program (Lesch, 2005, Lesch et al., 2000). The ESAP-RSSD (*Response Surface Sampling Design*) software was used to generate optimal sampling schemes and identify sampling locations (Lesch et al., 2005). Based on the results of the RSSD program, six optimal sampling locations were selected from the EC<sub>a</sub> data collected in four fields located in Slope and Foster Counties (two in each county) for sampling and characterization.

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.<sup>2</sup> Grids were created using kriging methods with an octant search. Plots of EC<sub>a</sub> data showing the locations of the optimal sampling locations for each SAS or saline soil study site were compiled and copies supplied to soil scientists involved in soil sampling. The sampling locations were cored with the soils described and sampled for laboratory characterization.

### Study Site:

#### Slope County:

The two study sites are located in cultivated field. Figure 1 contains soil maps of the two separate study sites from the Web Soil Survey (<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>). In Figure 1, rectangles have been used to identify the approximate areas that were surveyed with EMI.

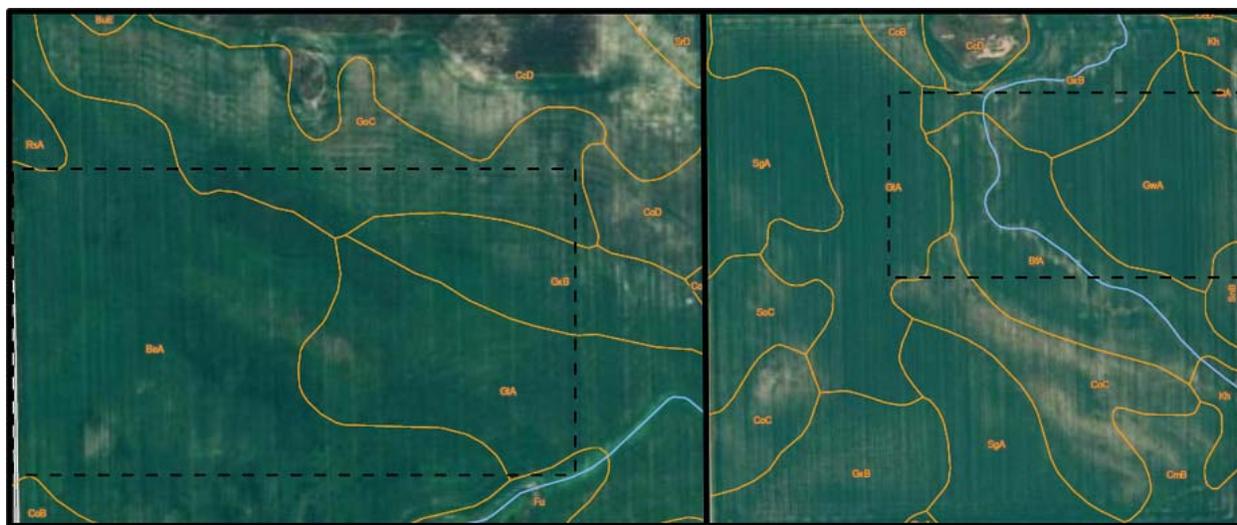


Figure 1. Soil maps of the two sodium-affected soil study sites in Slope County Sites. The approximate study areas are enclosed with segmented lines at Sites 1 (left) and Site 2 (right).

Site 1 (Fig. 1, left) is located in the SW ¼ of Section 18, T. 133 N., R. 101 W. Soils are mapped as Belfield silt loam, 0 to 2% slopes (BeA); Chama-Cabba silt loams, on 6 to 9% (CoC) slopes; Grail silty clay loam, 0 to 2 % slopes (GtA); and Grassna and Golva silt loam, 3 to 6 % slopes (GxB). The taxonomic classifications of these soils are listed in Table 1.

Site 2 (Fig. 1, right) is located in the NW ¼ of Section 29, T. 133 N., R. 101 W. Soils are mapped as Belfield silty clay loam, 0 to 2 % slopes (BfA); Chama-Cabba silt loams, 6 to 9 % slopes (CoC); Grail silty clay loam, 0 to 2 % slopes (GtA); Grassna silt loam, 0 to 2 % slopes (GwA); Grassna and Golva silt

<sup>2</sup> Manufacturer's names are provided for specific information; use does not constitute endorsement.

loams, 0 to 2 % slopes (GxB); Sen silt loam, 3 to 6 % slopes (SnB); and Shambo loam, 0 to 2 % slopes (StA). The taxonomic classifications of these soils are also listed in Table 1.

**Table 1. Taxonomic classifications of the soils recognized at the Slope County sites.**

Soil Series	Taxonomic Classification
Amor	Fine-loamy, mixed, superactive, frigid Typic Haplustolls
Belfield	Fine, smectitic, frigid Glossic Natrustolls
Cabba	Loamy, mixed, superactive, calcareous, frigid, shallow Typic Ustorthents
Chama	Fine-silty, mixed, superactive, frigid Typic Calcicustolls
Grail	Fine, smectitic, frigid Pachic Vertic Argicustolls
Grassna	Fine-silty, mixed, superactive, frigid Pachic Haplustolls
Golva	Fine-silty, mixed, superactive, frigid Typic Haplustolls
Savage	Fine, smectitic, frigid Vertic Argicustolls
Sen	Fine-silty, mixed, superactive, frigid Typic Haplustolls
Shambo	Fine-loamy, mixed, superactive, frigid Typic Haplustolls

Foster County:

The two study sites are located in cultivated field. Figure 2 contains the soil maps of the two separate study sites from the Web Soil Survey (<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>). In Figure 2, rectangles have been used to identify the approximate locations of the surveyed areas.



*Figure 2. Soil maps of the two soil study sites in Foster County Sites. The approximate locations of the study areas are enclosed with segmented lines at Saline Sites 1 (left) and Sodium-Affected Site 2 (right).*

Site 1 (Fig. 2, left) is located in the SW ¼ of Section 18, T. 146 N., R. 66 W. Soils are mapped as Vallers-Hamerly loam, saline, 0 to 3% slopes (G119A); Heimdal-Emrick loam, 0 to 3 % slopes (G229A); Heimdal-Esmond loam, 3 to 6 % slopes (G230B); and Heimdal-Emrick loam, 3 to 6 % slopes (G229B). The taxonomic classifications of these soils are listed in Table 2.

Site 2 (Fig. 2, right) is located in the NW ¼ of Section 31, T. 146 N., R. 66 W. Soils are mapped as Fram-Wyard loam, 0 to 3 % slopes (G211A); Emrick-Cathy loams, 0 to 3 % slopes (G221A); and Larson-

Cathy loams, 0 to 3 % slopes (G225A). The taxonomic classifications of these soils are also listed in Table 2.

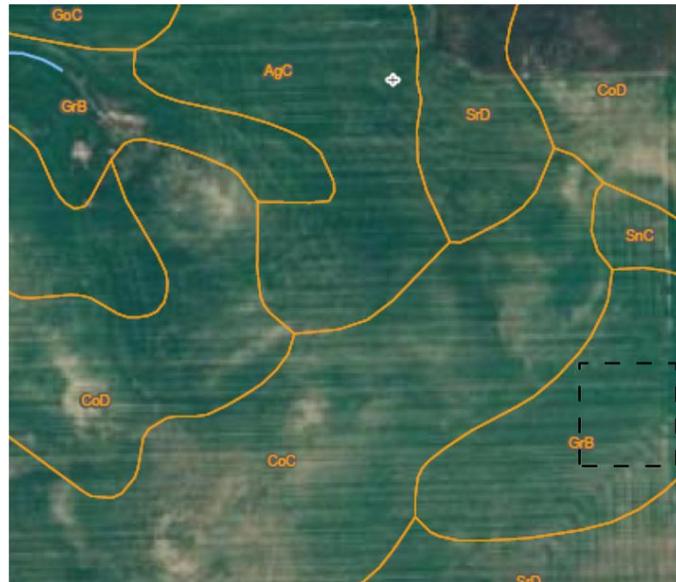
**Table 2. Taxonomic classifications of the soils recognized at the Foster County sites.**

Soil Series	Taxonomic Classification
Cathay	Fine-loamy, mixed, superactive, frigid Glossic Natrudolls
Emrick	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
Esmond	Coarse-loamy, mixed, superactive, frigid Typic Calcudolls
Fram	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
Hamerly	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
Heimdal	Coarse-loamy, mixed, superactive, frigid Calcic Hapludolls
Larson	Fine-loamy, mixed, superactive, frigid Calcic Natrudolls
Vallers	Fine-loamy, mixed, superactive, frigid Typic Calciaquolls
Wyard	Fine-loamy, mixed, superactive, frigid Typic Endoaquolls

**Hydropedologic Functional Unit Sites:**

Slope County:

One site was surveyed with in Slope County for analysis as an HFU. This site is located in a delineation of Grail silt loam, 2 to 6 % slopes (GrB) in the NE ¼ of Section 20, T. 133 N., R. 101 W. (Fig. 3). Adjoining delineations include Chama-Cabba silt loams, on 6 to 9 % slopes (CoC); Sen silt loam, 6 to 9% slopes (SnC) and Sen-Amor soils, 9 to 15 % slopes (SrD). The taxonomic classifications of these soils are listed in Table 1.



*Figure 3. A soil map of the HFU study site in Slope County. The approximate location of the study area is enclosed with segmented lines.*

Grand Forks County:

Two HFU sites were surveyed in Grand Forks County. One site is located in delineations of Barnes-Svea loams, on 0 to 3 (G143A) and 3 to 6 (G143B) % slopes, in the SW ¼ of Section 29, T. 149 N., R. 55 W. (Fig. 4). The taxonomic classifications of these soils are listed in Table 3.



Figure 4. Soil maps of the Barnes-Svea HFU sites in Grand Forks County. The approximate location of the study area is enclosed with segmented lines.

The second HFU site (Fig. 5) in Grand Forks County is located in an interbeach area (Glacial Lake Agassiz) west of Northwood in the NW ¼ of Section 14, T. 149 N., R. 55 W. Soil delineations include Svea loam, 0 to 3 % slopes (12); Gilby loam (67); Renshaw loam, 0 to 3 % (89) and 3 to 6 % (89B) slopes; and Arvilla sandy loam, 0 to 6 % slopes (G271B).



Figure 5. Soil maps of the Interbeach HFU sites in Grand Forks County. The approximate location of the study area is enclosed with segmented lines.

**Table 3. Taxonomic classifications of the soils recognized at the Grand Forks County sites.**

Soil Series	Taxonomic Classification
Arvilla	Sandy, mixed, frigid Calcic Hapludolls
Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
Buse	Fine-loamy, mixed, superactive, frigid Typic Calciudolls
Cresbard	Fine, smectitic, frigid Glossic Natrudolls
Gilby	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
Renshaw	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Calcic Hapludolls
Svea	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls
Wyand	Fine-loamy, mixed, superactive, frigid Typic Endoaquolls

**Survey Procedures:**

The EMI surveys were completed by towing the EM38-MK2-2 meter, which was mounted in a plastic sled, behind an ATV at speeds of 3 to 4 m/sec. The mobile surveys were completed by driving the ATV at a uniform speed in a back and forth manner across each site. The EC<sub>a</sub> data discussed in this report were temperature corrected to a standard temperature of 25° C. In each field, the soil temperature was measured at a depth of 50 cm was about 5.6 C ° (42° F).

**Results:**

**EMI Surveys of SAS and Saline Soil Sites:**

Slope County:

At both SAS study sites, EC<sub>a</sub> increased and became more variable with increasing soil depth (measurements for the shallower-sensing, 50-cm intercoil spacing were lower and less variable than those for the deeper-sensing, 100-cm intercoil spacing). This trend suggests variations in soil properties (e.g., soluble salt, clay and moisture contents) increase with increasing soil depth. This vertical trend is considered a reflection of dominant hydropedologic processes (e.g., depth to the water table, leaching, distribution of soluble salts).

**Table 4. Basic statistics for EMI surveys conducted in two areas of sodium-affected soils in Slope County**

	Site 1	Site 1	Site 2	Site 2
	100 cm	50 cm	100 cm	50 cm
<b>Observations</b>	4553	4553	2248	2248
<b>Minimum</b>	9.06	-17.51	10.80	4.34
<b>25%-tile</b>	101.11	65.12	63.92	44.57
<b>75%-tile</b>	192.48	131.41	87.03	61.51
<b>Maximum</b>	350.95	258.83	194.46	138.72
<b>Mean</b>	145.30	98.95	77.86	54.12
<b>Std. Dev.</b>	68.64	48.05	25.85	17.53

Table 4 provides the basic statistics for the EMI survey that were conducted at Site 1 (colored blue in Table 4) in Slope County. At Site 1, EC<sub>a</sub> averaged about 145 mS/m and ranged from about 9 to 351 mS/m for measurements obtained with the deeper-sensing, 100-cm intercoil spacing. One-half the EC<sub>a</sub> measurements acquired with the 100-cm intercoil spacing were between about 101 and 192 mS/m. For

the shallower-sensing, 50-cm intercoil spacing,  $EC_a$  averaged about 99 mS/m and ranged from about -18 to 259 mS/m. Negative values are believed to represent the presence of metallic artifacts scattered across the site. One-half the  $EC_a$  measurements acquired with the 50-cm intercoil spacing were between about 65 and 131 mS/m. In general,  $EC_a$  is considered relatively high across this site and suggests the presence of soluble salts and excess sodium.

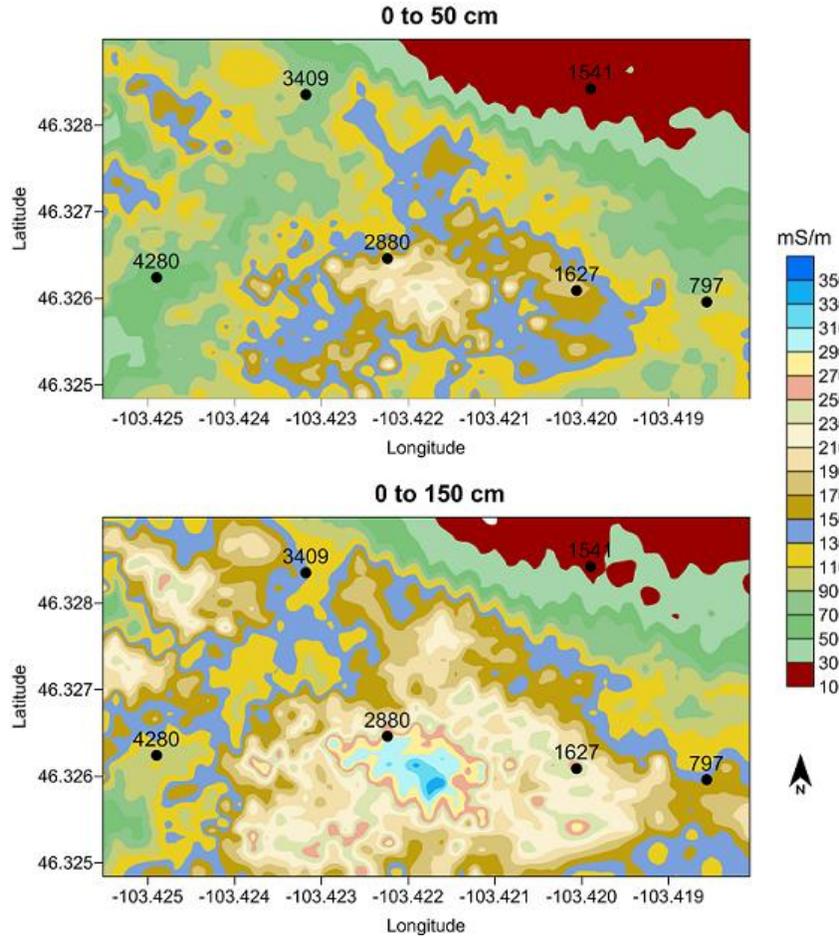


Figure 6. Plots of  $EC_a$  data collected with the EM38MK2-2 meter with the shallower-sensing 50-cm (upper plot) and the deeper-sensing 100-cm (lower plot) intercoil spacings at Slope County Site 1. The point symbols and numbers are for the six-point RSSD generated from the ESAP software program.

Figure 6 contains plots of the  $EC_a$  data collected with EM38-MK2-2 meter at Site 1 in Slope County. In both plots, similar color scales and ramps have been used. Spatial  $EC_a$  patterns indicate that soils have lower  $EC_a$  on higher-lying areas of Chama-Cabba silt loams, on 6 to 9% (CoC) slopes located in the northeast corner of the site (see Fig. 1, left, for location of delineation). The well drained, medium-textured Chama and Cabba soils formed in materials weathered from soft siltstone, mudstone and shale on uplands. Chama and Cabba soils are moderately deep and shallow to sedimentary beds, respectively. The EMI survey indicates that these soils and beds are composed of relatively electrically resistive materials.

In Figure 6, a zone of higher conductivity extends across lower-lying delineations of Belfield silt loam, 0 to 2% slopes (BeA); and Grail silty clay loam, 0 to 2 % slopes (GtA) (see Fig. 1, left, for location of delineation). These plots suggest the presence of a large, zone of higher conductivity in the lower-lying southern portion of the survey area. Though undetermined at this time, higher soluble salt, moisture and/or clay contents would result in the higher conductivity. The topographic position of this portion of the study area (lower-lying and at the base of more steeply sloping Chama-Cabba complex, which is underlain by sedimentary beds) suggests a seepage area. Within this zone of higher  $EC_a$ , soils (Belfield and Grail) are deep and very deep, well or moderately well drained and formed in alluvium. While the presence of SAS soils identified on the soil map are implied by the higher  $EC_a$ , spatial patterns of higher  $EC_a$  do not conform to soil delineations (Fig. 1, left) suggesting that this area is not properly mapped.

Figure 7 contains a three-dimensional plot of Site 1 with  $EC_a$  (collected in the deeper-sensing, 100-cm intercoil spacing) data superimposed. Elevations were obtained from the AG114 GPS receiver and should be considered as merely close approximations of true values. This 3D rendition of the  $EC_a$  data illustrates spatial patterns and the linkage among soils, landscapes and hydrologic processes.

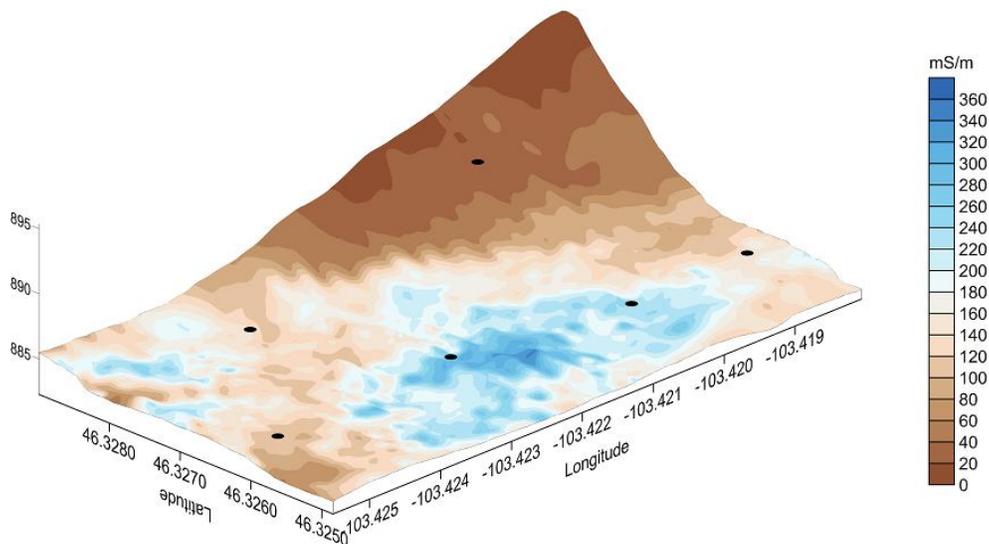


Figure 7. A three-dimensional plot of  $EC_a$  data collected with the EM38MK2-2 meter at Slope County Site 1. The point symbols are for the six-point RSSD generated from the ESAP software program.

Table 4 provides the basic statistics for the EMI survey that were conducted at Site 2 (colored red in Table 4) in Slope County. At Site 2,  $EC_a$  averaged about 78 mS/m and ranged from about 11 to 194 mS/m for measurements obtained with the deeper-sensing, 100-cm intercoil spacing. One-half of these  $EC_a$  measurements were between about 64 and 87 mS/m. For the shallower-sensing, 50-cm intercoil spacing,  $EC_a$  averaged about 54 mS/m and ranged from about 4 to 139 mS/m. One-half of these  $EC_a$  measurements were between about 45 and 62 mS/m. Compared with Site 1, at Site 2,  $EC_a$  is significantly lower and less variable.

Figure 8 contains plots of the  $EC_a$  data collected with EM38-MK2-2 meter at Site 2 in Slope County. In both plots, similar color scales and ramps have been used. Spatial  $EC_a$  patterns indicate that soils in the extreme southwestern corner of the site have the lowest  $EC_a$ . This slightly higher-lying area is mapped as Chama-Cabba silt loams, on 6 to 9% (CoC) slopes (see Fig. 1, right). The highest  $EC_a$  were measured in the extreme eastern portion of the study area in delineations of Grail silty clay loam, 0 to 2 % slopes

(GtA); Sen silt loam, 3 to 6 % slopes (SnB); and Shambo loam, 0 to 2 % slopes (StA). Based on the results of the EMI survey, this slightly higher-lying area is more likely to contain SAS than other portions of the survey area. The higher  $EC_a$  in the extreme eastern portion of the study site suggests higher concentrations of soluble salts and excess sodium than other portions of the site.

Compared with Site 1, where areas of SAS Belfield soils are more extensive, areas of these soils have only been delineated along an intermittent drainageway that passes through Site 2. The delineation of Belfield silty clay loam, 0 to 2 % slopes (BfA), is located in the west-central portion of Site 2 (Fig. 1, right). Though delineated as a SAS,  $EC_a$  data measured within the Belfield map unit are surprisingly low  $EC_a$  and the polygon is indistinguishable with EMI. Within Site 2, spatial  $EC_a$  patterns do not conform well to mapped soil delineations. Arguably the speed and intensity of mapping in these two areas of Slope County are incompatible with the level of resolution possible with modern high-intensity soil mapping tools.

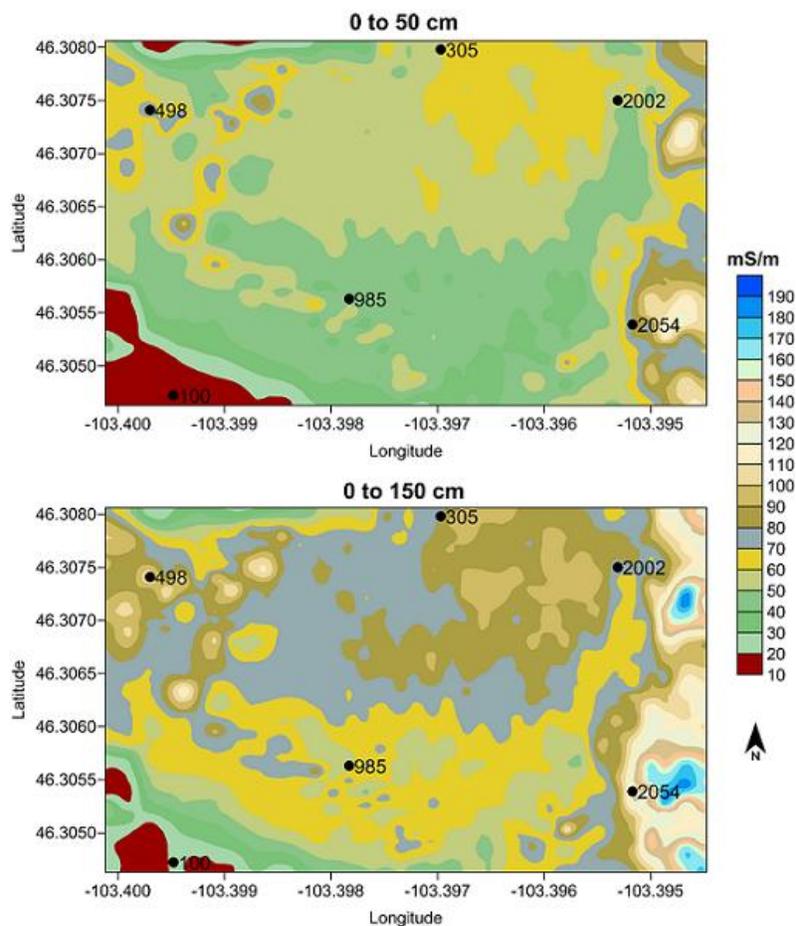


Figure 8. Plots of  $EC_a$  data collected with the EM38MK2-2 meter with the shallower-sensing 50-cm (upper plot) and the deeper-sensing 100-cm (lower plot) intercoil spacings at Slope County Site 2. The point symbols and numbers are for the six-point RSSD generated from the ESAP software program.

#### Foster County:

A saline soil site and a SAS site were selected in Foster County. At both sites,  $EC_a$  increased and became slightly more variable with increasing soil depth (measurements for the shallower-sensing, 50-cm

intercoil spacing were lower and slightly less variable than measurements for the deeper-sensing, 100-cm intercoil spacing). This trend suggests that the soluble salts, moisture, and/or clay contents increase with increasing soil depth and is a manifestation of existing hydrogeologic processes (e.g., soil type, physiochemical properties, depth to the water table, seepage, and evaporative discharge). At the Foster County sites (Table 5), compared with the Slope County sites (Table 4), EC<sub>a</sub> and basic statistics did not vary as greatly with depth.

**Table 5. Basic statistics for EMI surveys conducted in areas of saline and sodium-affected soils in Foster County**

	Saline Site	Saline Site	Sodium Site	Sodium Site
	100 cm	50 cm	100 cm	50 cm
<b>Observations</b>	2584	2584	1113	1113
<b>Minimum</b>	-74.73	43.38	35.50	-65.61
<b>25%-tile</b>	71.08	57.04	55.06	46.05
<b>75%-tile</b>	177.71	160.20	93.10	73.12
<b>Maximum</b>	391.91	378.26	197.07	204.09
<b>Mean</b>	129.41	112.38	77.96	63.71
<b>Std. Dev.</b>	75.66	72.15	29.17	27.00

Table 5 provides the basic statistics for the EMI surveys that were conducted in areas of saline soils (colored blue) and SAS (colored red) in Foster County. At the Saline Site, EC<sub>a</sub> averaged about 129 mS/m and ranged from about -75 to 392 mS/m for measurements obtained with the deeper-sensing, 100-cm intercoil spacing. Negative values are believed to represent metallic artifacts scattered across this cultivated area. One-half the EC<sub>a</sub> measurements acquired with the 100-cm intercoil spacing were between about 71 and 178 mS/m. For the shallower-sensing, 50-cm intercoil spacing, EC<sub>a</sub> averaged about 112 mS/m and ranged from about -43 to 378 mS/m. One-half the EC<sub>a</sub> measurements acquired with the 50-cm intercoil spacing were between about 57 and 160 mS/m.

Figure 9 contains plots of the EC<sub>a</sub> data collected with EM38-MK2-2 meter at the Saline Site in Foster County. In both plots, similar color scales and ramps have been used. Spatial EC<sub>a</sub> patterns indicate that, within this site, the highest EC<sub>a</sub> occurs on lower-lying areas of Vallery-Hamerly loam, saline, 0 to 3% slopes (G119A), that are located in the northern and northwest portions of the site (Fig. 2, left, for location of delineation). Higher-lying, better drained areas of Heimdal-Emrick loam, 0 to 3 % slopes (G229A); Heimdal-Esmond loam, 3 to 6 % slopes (G230B); and Heimdal-Emrick loam, 3 to 6 % slopes (G229B) in the central, eastern, and southern portions of the site, all have lower EC<sub>a</sub>. These soils belong to the coarse-loamy textural family and have lower clay contents than Hamerly and Vallery soils. The spatial EC<sub>a</sub> patterns evident in Fig. 9 conform remarkably well to the soil delineations (Fig. 2, left) and suggest that this area is suitably mapped. The high-intensity EMI survey results in no obvious improvements to the Order 2 soil map of this site.

Table 5 provides the basic statistics for the EMI survey that was conducted in an area of SAS in Foster County. At the SAS Site, EC<sub>a</sub> averaged about 78.0 mS/m and ranged from about 36 to 197 mS/m for measurements obtained with the deeper-sensing, 100-cm intercoil spacing. One-half of these measurements were between about 55 and 93 mS/m. For the shallower-sensing, 50-cm intercoil spacing, EC<sub>a</sub> averaged about 64 mS/m and ranged from about -66 to 204 mS/m. Negative values are believed to represent metallic artifacts scattered across the cultivated area. One-half the EC<sub>a</sub> measurements acquired with the 50-cm intercoil spacing were between about 46 and 73 mS/m.

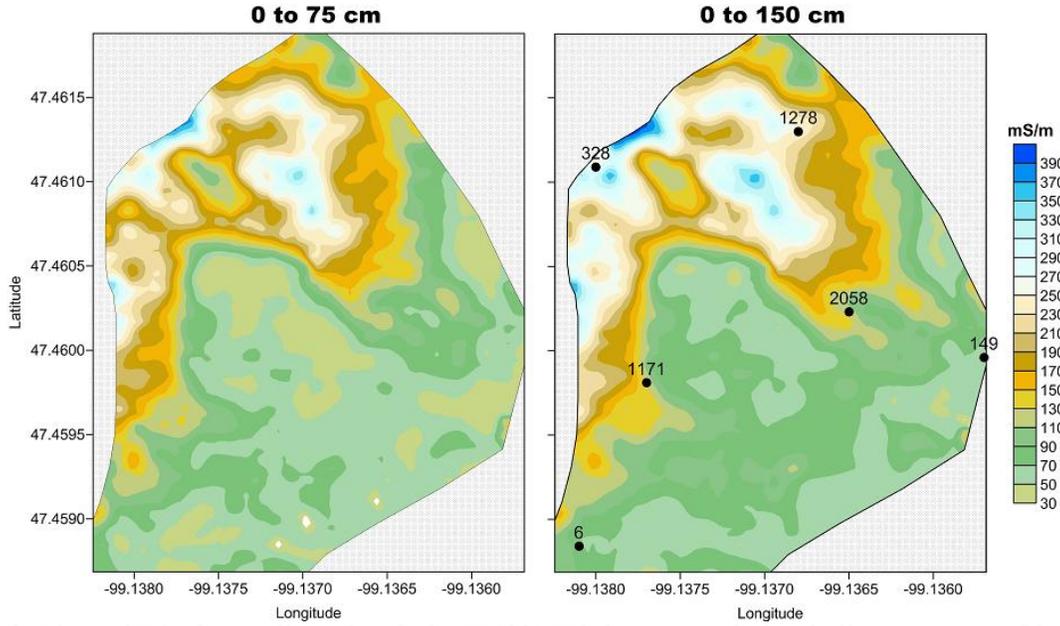


Figure 9. Plots of  $EC_a$  data collected with the EM38MK2-2 meter with the shallower-sensing 50-cm (left-hand plot) and the deeper-sensing 100-cm (right-hand plot) intercoil spacings at the Saline Soil Site in Foster County. The point symbols and numbers are for the six-point RSSD generated from the ESAP software program.

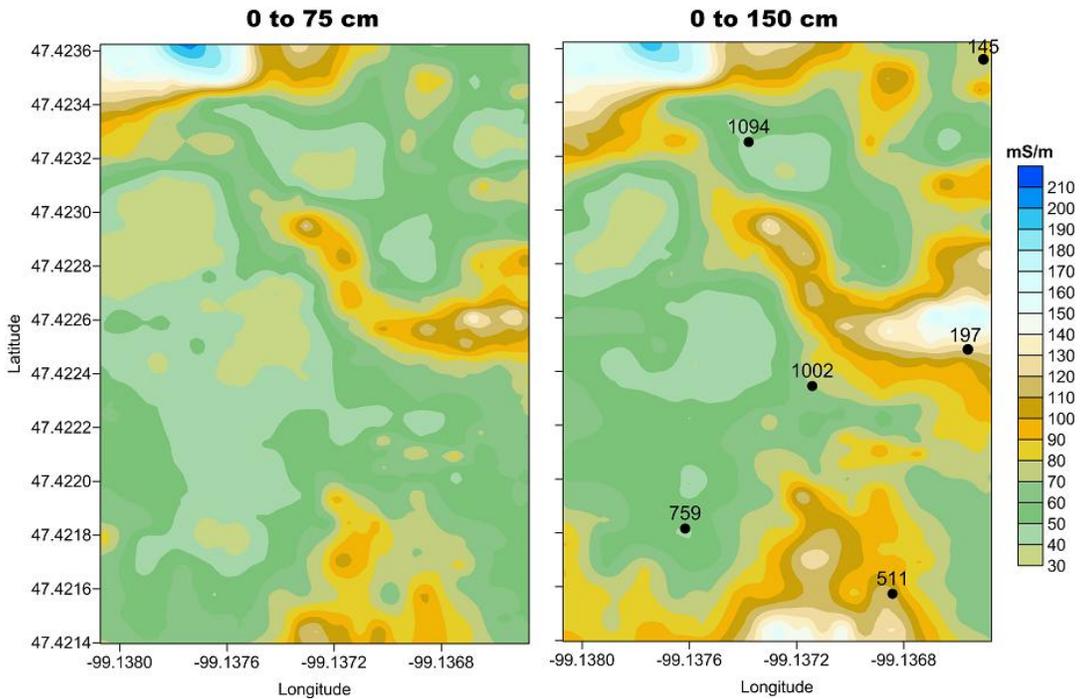


Figure 10. Plots of  $EC_a$  data collected with the EM38MK2-2 meter with the shallower-sensing 50-cm (left-hand plot) and the deeper-sensing 100-cm (right-hand plot) intercoil spacings at the SAS Site in Foster County. The point symbols and numbers are for the six-point RSSD generated from the ESAP software program.

Figure 10 contains plots of the  $EC_a$  data collected with EM38-MK2-2 meter at the SAS Site in Foster County. In both plots, similar color scales and ramps have been used. Spatial  $EC_a$  patterns indicate that soils have lower  $EC_a$  on slightly higher-lying areas of Fram-Wyard loam, 0 to 3 % slopes (G211A), which are mapped in the eastern and southeastern portions of the site (Fig. 2, right, for location of delineation). The very deep, somewhat poorly drained Fram and Wyard soils formed in till or water sorted sediments over till. These are non-SAS soils. Areas mapped as Emrick-Cathy loams, 0 to 3 % slopes (G221A), in the northern portion and Larson-Cathy loams, 0 to 3 % slopes (G225A) in the southeastern portion of the site (Fig. 2, right, for location of delineations) have higher  $EC_a$ . The very deep, moderately well drained Cathay soils and the moderately well and somewhat poorly drained Larson soils formed in till. These are SAS. A comparison of the order 2 soil (Fig. 2, right) and the high-intensity  $EC_a$  (Fig. 10) maps suggests that while the placement of some boundary lines can be improved, the area is suitably mapped.

### Hydropedological Functional Units:

In Slope County, a portion of a Grail silt loam, 2 to 6 % slopes (GrB), delineation was surveyed with the EM38MK2-2 meter. Immediately after the EMI survey, two cores were extracted from the study area and the soils were identified. In areas of relatively high and low conductivity, Grail (fine, smectitic, frigid Pachic Vertic Argiustolls) and Farnuf (fine-loamy, mixed, superactive, frigid Typic Argiustolls) soils were identified, respectively. The very deep, well drained Farnuf and well to moderately well Grail soils formed in alluvium on fans and terraces. Differences in  $EC_a$  are principally attributed to difference in clay and moisture contents of the two soils.

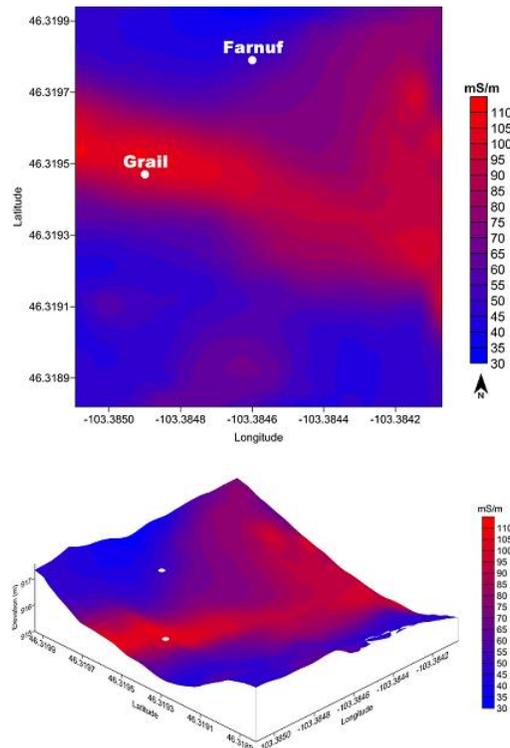


Figure 11. Two- and three-dimensional plots of  $EC_a$  data collected with the EM38MK2-2 meter with the deeper-sensing, 100-cm (nominal depth of 0 to 150 cm) intercoil spacings at the Grail HFU Site in Slope County. The point symbols identify the locations of soil cores extracted after the EMI survey.

Figure 11 contains 2D and 3D renditions of the  $EC_a$  data from the Grail Site. Although the area was mapped as a consociation of Grail soils, based on  $EC_a$  data the site appears to contain a large proportion of Farnuf soils. The Grail soils (essentially colored red in Fig. 11) are restricted to lower-lying drainage areas and Farnuf (basically colored blue in Fig. 11) occupying higher side slopes. From a hydropedological standpoint, and based on  $EC_a$  data and scant core data, the delineation appears to be composed of two distinct HFUs. The Grail HFU is restricted to lower-lying portions of the delineation, which are believed to be slightly wetter and to receive periodic saturation-excess runoff and subsurface lateral flow. Based on color alone, in Fig. 11, areas of Grail-like soils are best expressed along the drainageway that extends from west to east across the study area. The Farnuf HFU occupies higher-lying portions of the delineation and is therefore assumed to be slightly drier than the Grail HFU. The lower clay content and higher permeability of Farnuf soils would contribute to the downward infiltration of water. While the transition from one soil to the other is generally abrupt, in the eastern and northeast portions of the site, the boundary between these two soils appears more diffuse and here the transition in soil properties are assumed to be more gradual.

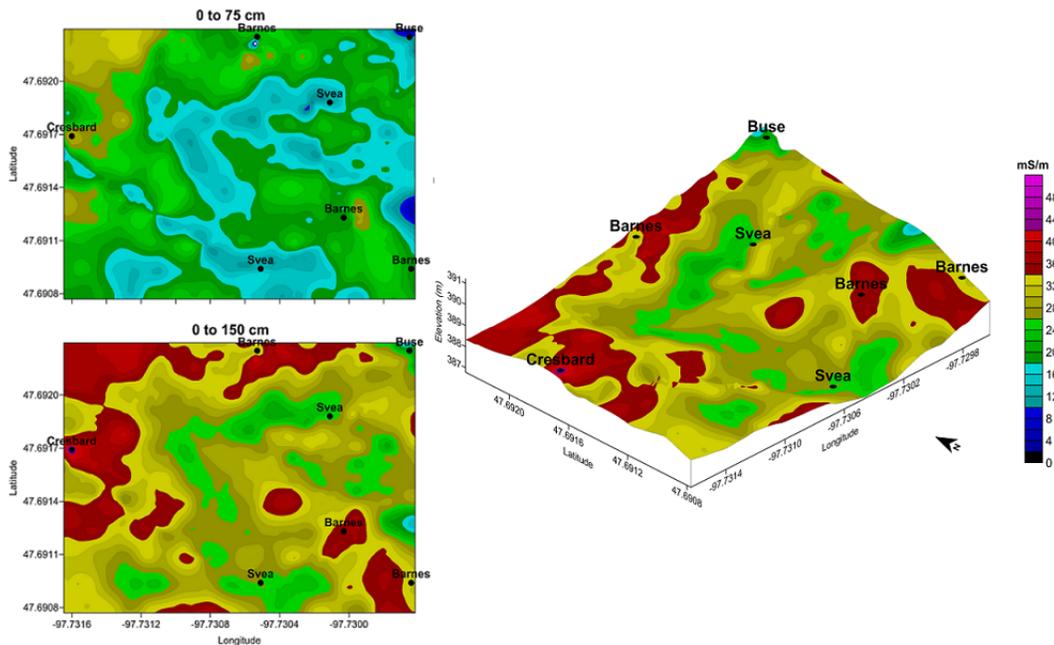


Figure 12. Two- and three-dimensional plots of  $EC_a$  data collected with the EM38MK2-2 meter in an area of Barnes Svea complexes in Grand Forks County. On the  $EC_a$  maps, the names of the soils identified in extracted soil cores are provided.

In Grand Forks County, delineations of Barnes-Svea loams, on 0 to 3 and 3 to 6 % slopes, were surveyed with the EM38MK2-2 meter. Following the EMI survey, seven cores were extracted from the study area and the soils were identified. The core extracted in a higher-lying area of Buse soils had the lowest  $EC_a$  with a value of 10 and 22 mS/m (for the 0 to 75 and 0 to 150 cm depth intervals, respectively). The two cores extracted from areas of Svea soils (14 and 25-26 mS/m for the 0 to 75 and 0 to 150 cm depth intervals, respectively) had lower  $EC_a$  than the three cores extracted from areas of Barnes soils (19-21 and 31-26 mS/m for the 0 to 75 and 0 to 150 cm depth intervals, respectively). The one core extracted in an area of Cresbard soils had the highest  $EC_a$  (24 and 42 mS/m for the 0 to 75 and 0 to 150 cm depth intervals, respectively). Differences in  $EC_a$  are principally attributed to the presence and shallower depths to the subsoil (Bw or Bt horizon) (Barnes and Cresbard), difference in soluble salts (Cresbard) and soil

drainage. Svea soils are located on lower side slopes and have a thicker surface layer and deeper depths to Bw horizons than the Barnes soils, which are located on higher-lying plane and convex surfaces. Based on  $EC_a$  data, the Bw horizons of these soils is hypothesized as having slightly higher clay contents than the surface layers. The shallower depths to Bw horizons in Barnes soils would therefore help to explain its higher  $EC_a$  than Svea soils, which has thicker surface layers with presumably lower clay contents.

Within the Barnes-Svea site (Fig. 12), spatial  $EC_a$  patterns for both depth intervals are exceedingly complex and more variable than those of the Grail site (Fig. 11) in Slope County. This pattern is believed to reflect the sites greater topographic and hydrologic complexities than the Grail site. While the Barnes-Svea site has lower  $EC_a$  than the Grail site, measurements change more non-uniformly; also a reflection of the site's greater topographic and hydrologic diversity.

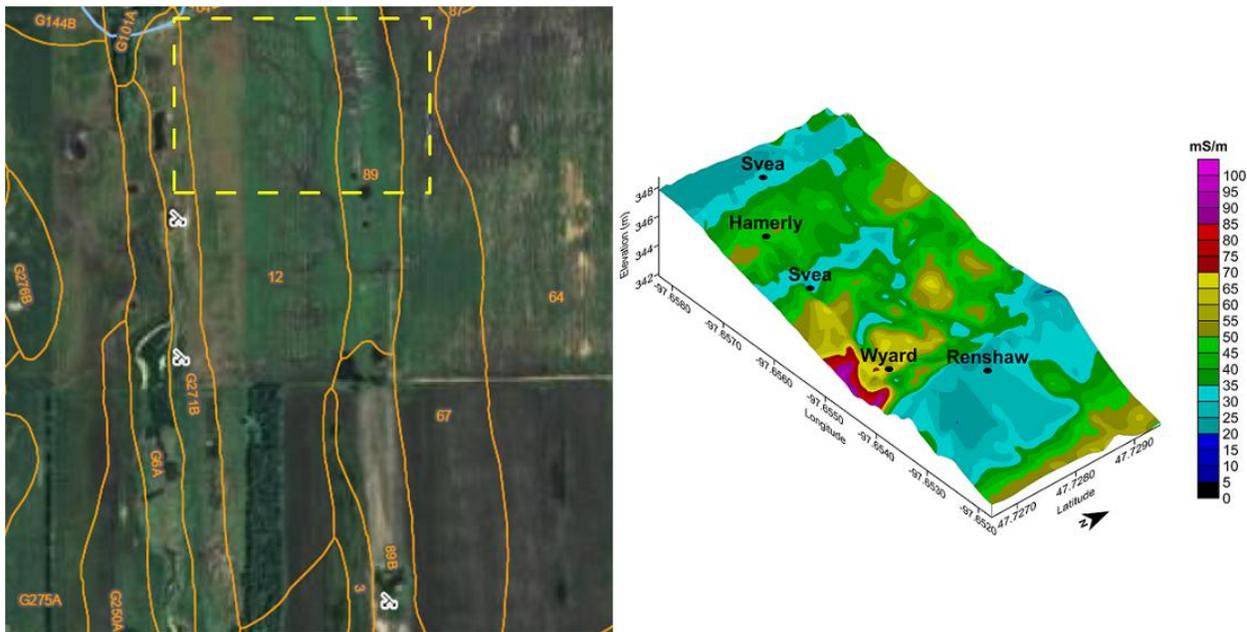


Figure 13. Soil map and a three-dimensional plot of  $EC_a$  data collected with the EM38MK2-2 meter operated in the VDO and in the deeper-sensing 100 cm intercoil spacing on Interbeach Area of Grand Forks County. On the 3D  $EC_a$  map, the names of the soils identified in extracted soil cores are provided.

In Grand Forks County, an “interbeach area” of Glacial Lake Agassiz was also surveyed with EMI. As shown in Fig. 13, long, narrow, parallel soil delineations comprise this interbeach area. The narrow, linear, better-drained, predominantly coarse-textured beach ridges are mapped as of Renshaw (89, 89B) and Arvilla (6271) soils. The wider areas between the beach ridges are mapped as medium-textured, well to moderately well drained Svea (12) and somewhat poorly drained Antler (64) and Gilby (67) soils.

Immediately after the EMI survey, five cores were extracted from the interbeach study area and the soils were identified. The highest  $EC_a$  were recorded in areas of somewhat poorly drained, medium-textured Wyard (58 and 63 mS/m for the 0 to 75 and 0 to 150 cm depth intervals, respectively) and Hamerly (38 and 49 mS/m for the 0 to 75 and 0 to 150 cm depth intervals, respectively) soils. The comparatively high clay and moisture contents of these soils would account for their higher  $EC_a$ . The lowest  $EC_a$  was recorded in an area of fine-loamy over sandy and sandy skeletal Renshaw soils (21 and 25 mS/m for the 0

to 75 and 0 to 150 cm depth intervals, respectively). The observed Renshaw (Calcic Hapludolls) profile was bordering and perhaps more closely resembled a somewhat poorly drained Divide (Aeric Calciaquolls) profile. This would account for the seemingly high  $EC_a$  for a somewhat excessively drained soil formed in loamy sediments overlying sands and gravels.

Spatial  $EC_a$  patterns within the interbeach area reveal an orderly and predictable sequence of soils. The sequence of soils is based on the interaction of parent materials, hydrology, and topography. This interaction results in different hydropedologic functions that are manifested in the development of differences in soil types. Hydropedological functional units (HFU) can provide a conceptual framework that focus attention onto interacting soil properties and hydrologic processes.

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