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

Subject: Soil - Geophysical Assistance **Date:** June 27 2005

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Purpose:
Electromagnetic induction (EMI) is being used to infer variations in soil salinity and to help delineate salt-affected areas in Kittson County, Minnesota. The purpose of this investigation was to collect soil samples for analysis and the development of predictive model(s) that will be used to relate apparent conductivity (EC_a) to saturated paste conductivity (EC_e). In addition survey protocol for using the EM38 meter to map soil saline was refined. Detailed plots of representative soil polygons were prepared to better understand spatial patterns of soil salinity within polygons.

Participants:
Matt Baltes, GIS Specialist, USDA-NRCS, Thief River Falls, MN
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Cornelius Heidt, Soil Data Quality Specialist, USDA-NRCS, Bismarck, ND
Ron Heschke, Soil Scientist, USDA-NRCS, Thief River Falls, MN
David Potts, MLRA Soil Survey Coordinator, USDA-NRCS, Thief River Falls, MN
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Matt Waterworth, Step Trainee, USDA-NRCS, Thief River Falls, MN

Activities:
All field activities were completed during the period of 6 to 10 June 2005.

Summary:

1. Electromagnetic induction is used to map spatial and temporal variations in apparent conductivity (EC_a) and infer variations in soil salinity. The EMI sensor (EM38 meter) that is being used by the soil staff in Kittson County is designed to assess variations in soil salinity and help distinguish phases of soil salinity. As this update requires EC_a measurements to be geo-referenced for import into GIS, GPS receivers are used with the EM38 meter. However, these tools are not fully integrated and require separate, manual data entry. This slows and encumbers field work and limits the number of observations that are being made. Later, GPS and EC_a data must be separately entered (EC_a data by hand) onto worksheets for importation into GIS. This procedure is slow and liable to errors. This update, as well as subsequent updates within MLRA 56, would greatly benefit from the availability of a data acquisition system that would permit the recording, storage, integration and downloading of both EC_a and GPS data. The acquisition system consists of an EMI meter, a field computer, and a GPS receiver. The update office already has access to several EM38 meters and Garmin GPS receivers. Older EM38 meters will require an RT modification in order to output digital data. With the acquisition

system, the EM38 meter is keypad operated and measurements are automatically triggered. Soil scientists simply walk across soil polygons and both EC_a and GPS data are recoded simultaneously at 1 sec intervals.

2. Survey protocol for conducting a salinity survey with EMI *was* discussed and refined.

3. Both within and outside the salt-affected area, values of EC_a are high and variable within soil polygons. From a national perspective, EC_a in non-saline areas of Northcote soil is considered anomalously high. The ground water is known to have high levels of chlorides and sulfates. The affects of these and other ions on EC_a needs to be better understood.

4. Plots of data collected in detailed grid surveys provide comprehensive information concerning the spatial distribution of EC_a at different scales. This information will be of value in developing map unit descriptions and soil map unit interpretations. Plots of data can be utilize in GIS and compared with overlays of soil boundary lines and tonal patterns on ortho-photographic imagery.

5. Eighteen pedons were sampled to depths of 90-cm. For each pedon, samples were collected at 30-cm depth intervals (0-30, 30-60, and 60-90 cm) and sent to the National Soil Survey Laboratory for analyses of EC_e, clay and moisture contents, and calcium carbonate equivalent. The results of these analyses will be used to develop predictive equations that will hopefully provide a reasonably accurate, practical, and cost-effective method to relate EC_a to EC_e and to map salinity in Kittson County.

6. Wes Tuttle and I are scheduled to return to Kittson County in September 2005. The National Soil Survey Center's mobile EMI platform will be deployed at that time to collect larger quantities of EC_a data over larger grid areas. This data will be used to help define and characterize salt-affected soil map units. Pending the results of laboratory analysis, predictive salinity models for Northcote soil should be developed and available at this time. Additional soil samples will be collected to further test and refine this salinity model.

7. The field study was well organized by Dave Potts. Dave is commended for his efforts.

It was my pleasure to work in Minnesota and to assist members of your staff and the soil staff in Thief River Falls.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
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Salt-Affected Areas in Kittson County:

Background:

In MLRA 56, the Red River Valley of the North, soil salinity is a major cause of soil degradation and reduced crop production. High water tables in this region permit the capillary rise of saline ground water into soil profiles. Approximately 145,000 acres of salt-affected soils occur in Kittson County. Though saline areas were recognized on the General Soil Map of Kittson County, no attempt was made to set up saline map units or to recognize these soils on the order-two soil survey maps (Barron, 1979). On the General Soil Map of Kittson County, areas of salt-affected soils have been indicated with a hachured pattern in areas of the Northcrote, Bearden-Fargo, Hegne-Northcrote, and Wheatville-Augsburg associations. Northcote is the most extensive soil in the area and the focus of this investigation. Northcrote is a member of the very-fine, smectitic, frigid, Typic Epiaquert family.

Methods of Salinity Appraisal:

Four methods are commonly used to appraise soil salinity: (1) visual observation of crop appearance (Soil Survey Division Staff, 1993); (2) sampling and measurement of the saturated paste extract (EC_e) (United States Salinity Laboratory Staff, 1954); Wenner array or four-electrode sensor (Halverson et al., 1977; Nadler, 1981); and electromagnetic induction (Corwin and Rhoades, 1982, 1984, and 1990; Williams and Baker, 1982; Wollenhaupt et al., 1986; McKenzie et al., 1989; Rhoades et al., 1989a and 1989b).

Visual crop observations and saturated paste extract electrical conductivity measurements are commonly used to distinguish and map phases of soil salinity (United States Salinity Laboratory Staff, 1954; Soil Survey Division Staff, 1993). While visual observations are adequate for salinity mapping, results provide only qualitative measures of salinity and are dependent on the presence of plant cover and surface salts. The saturated paste extract method is generally accepted as the most accurate measure of soil salinity (McNeill, 1985). However, this method requires the expenditure of considerable resources for field sampling and laboratory analysis, thus limiting the number of soil samples that can be analyzed.

The Wenner array is bulky and difficult to handle in the field. A towed-array version is available, but it is invasive and can not be used when crops are on fields. In addition, the Wenner array requires good soil-electrode contact.

Electromagnetic induction (EMI) has gained acceptance among soil scientists and agronomists involved in mapping salinity. Compared with other methods, advantages of EMI are its noninvasiveness, speed of operation, low survey costs, and more comprehensive coverage of sites. Presently, EMI is considered the most useful geophysical method for the rapid field identification and mapping of soil salinity (Johnston et al., 1997).

Electromagnetic induction uses electromagnetic energy to measure the bulk, or apparent, electrical conductivity of soils. Apparent conductivity (EC_a) is a depth-weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in EC_a are produced by changes in the types and concentration of ions in the soil solution, the amount and types of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). The EC_a of soils increases with increases in soluble salts, water, and clay contents (Rhoades et al., 1976; Kachanoski et al., 1988). In areas of saline soils, EC_a is principally affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston, et al., 1997).

Electromagnetic induction is used to map spatial and temporal variations in EC_a. Though seldom diagnostic in themselves, lateral, vertical and temporal changes in EC_a have been used to infer changes in soil salinity. In areas of saline soils, van der Lelij (1983) observed that the concentration of dissolved salts is the dominant factor affecting EC_a. William and Baker (1982) estimated that 65 to 70 percent of the variance in EC_a can be explained by changes in the concentration of soluble salts alone. Moderate to high correlations have been found between EC_a and soil salinity. Studies have demonstrated that EMI can provide reasonably accurate estimates of soil salinity (William and Baker, 1982, van der Lelij, 1983, Diaz and Herrero, 1992).

Converting Apparent Conductivity (EC_a) into Saturated Paste Conductivity (EC_e):
A major challenge in using EMI to map soil salinity has been the conversion of apparent conductivity into the more commonly used measure of soil salinity, the conductivity of the saturated paste extract. A number of models have been developed that relate EC_a to EC_e (Wollenhaupt et al., 1986; McKenzie et al., 1989; Rhoades et al., 1989a and 1989b; Corwin and Rhoades, 1990; Slavich, 1990; Cook et al., 1992; Lesch et al., 1995a and 1995b; and Johnston et al., 1996). Most models require the collection of soil samples and the development of regression equations. Models are not perfect and tend to be both time dependent and site specific (Lesch et al., 1998). Lesch and others (1998) noted that errors in instrument calibration, instrument-to-instrument variations, variations in soils, moisture, temperature, and differences in the distribution of salts within soil profiles are factors that contribute to the time and field dependencies of models. Statistical models are often only valid for the geographic area and soil types from which the relationships were derived.

The accuracy of salinity models appears to be adversely affected by spatial and vertical variations in soil moisture and texture. The accuracy of salinity models is less at lower soil water contents (Rhoades et al., 1989b). Slavich and Petterson (1990) observed that calibration relationships become nonlinear in highly saline, clayey soils with high water tables. While soil salinity levels predicted from EC_a data and various calibration models provide reasonable estimates of soil salinity, they are not as accurate as desired (Rhoades et al., 1989a; Johnston et al, 1997). Nevertheless, these models appear to provide reasonable estimates of soil salinity and satisfy most mapping requirements.

Most salinity models are based on the depth response functions for the EM38 meter developed by McNeill (1980):

$$EM_h = 0.43EC_{0\text{-}0.3} + 0.21\ EC_{03\text{-}06} + 0.10\ EC_{06\text{-}09} + 0.06\ EC_{09\text{-}1.2} + 0.20\ EC_{>1..2.} \qquad [1]$$

$$EM_v = 0.14\ EC_{0\text{-}0.3} + 0.22\ EC_{03\text{-}06} + 0.15\ EC_{06\text{-}09} + 0.11\ EC_{09\text{-}1.2} + 0.08\ EC_{1.2\text{-}1.5} + 0.03\ EC_{1.5\text{-}1.8} + 0.27\ EC_{>1..8} \qquad [2]$$

According to McNeill's models, in the horizontal dipole orientation (EM_h), 74% of EMI response is from the upper 90 cm. In the vertical dipole orientation (EM_v), 51% of EMI response is from the upper 90 cm.

In a study conducted on fine-loamy, till-derived soils in North Dakota, Wollenhaupt et al. (1986) used a weighting procedure based on the EM38 meter's response-depth function to condense multiple EC_e measurements into a single, depth-weighted EC_e value, which was correlated by simple linear regression to the measured EC_a. The EC_e measurements were made on samples collected at 30-cm increments. These measurements were weighted according to the EM38 meter's response-depth function for each 30-cm depth increment to a depth of either 120 or 180 cm (horizontal and vertical dipole orientations, respectively). Wollenhaupt et al. (1986) decided to ignore the last terms in McNeill's equations ([1], [2]) and redistributed the fractions by dividing the coefficients for each depth interval by the sum of coefficients for the upper depths. The adjusted weighting factors are shown in equations [3] and [4] for the integrated depth responses in the horizontal and vertical dipole orientations, respectively. The weighted fractions were summed to produce the weighted EC_e. This procedure avoids complex mathematics and is best suited to soils formed in similar parent materials (Wollenhaupt et al., 1986).

$$EM_h = 0.54\ EC_{e\ 0\text{-}0.3} + 0.26\ EC_{e\ 03\text{-}06} + 0.13\ EC_{e\ 06\text{-}09} + 0.08\ EC_{e\ 09\text{-}1.2} \qquad [3]$$

$$EM_v = 0.19\ EC_{e\ 0\text{-}0.3} + 0.30\ EC_{e\ 03\text{-}06} + 0.21\ EC_{e\ 06\text{-}09} + 0.15\ EC_{e\ 09\text{-}1.2} + 0.11\ EC_{e\ 1.2\text{-}1.5} + 0.04\ EC_{e\ 1.5\text{-}1.8} \qquad [4]$$

Initial Predictive Model:

In this study, correlation samples have been collected in 30-cm depth increments to a depth of 90 cm. The maximum sampling depth of 90 cm is arbitrary, but was assigned based on the rooting depths of crops, the presence of a water table at relatively shallow depths, and physical constraints of sampling in clayey soils. The initial model will follow the logic developed by Wollenhaupt et al. (1986). Based on this logic, McNeill's depth-response coefficients for each depth interval will be divided by the sum of coefficients for the upper 90-cm depth. The adjusted weighting factors are shown in equations [5] and [6] for the integrated depth responses in the horizontal and vertical dipole orientations, respectively. The weighted fractions will be summed to produce a weighted EC_e for the soil pedon.

$$EM_h = 0.58\ EC_{e\ 0\text{-}0.3} + 0.28\ EC_{e\ 03\text{-}06} + 0.14\ EC_{e\ 06\text{-}09} \qquad [5]$$

$$EM_v = 0.28\ EC_{e\ 0\text{-}0.3} + 0.43\ EC_{e\ 03\text{-}06} + 0.29\ EC_{e\ 06\text{-}09} \qquad [6]$$

Johnson et al. (1996), developed equations based on an averaged reading and related this to a mean EC_e for the 0 to 1.2 m depth. Johnson et al. (1996) considered the use of mean EC_e for a composite depth a better option than depth-weighted EC_e for the prediction of plant response to soil salinity. The predictive accuracy of this model for the 0 to 90 cm depth interval will also be explored. In addition, the ESAP program developed by the USDA-ARS Salinity Laboratory in Riverside, California, will also be evaluated.

EMI Survey of Kittson County:

To our knowledge, no similar project has ever been conducted. The size of the salt-affected area (140,000 acres), the need for comprehensive coverage, and the requirement to collect EMI measurements and samples over a two year period provides daunting challenges. Most EMI salinity surveys cover smaller areas (< 10,000 acres) and are often conducted on irrigated crop lands that have soil moisture contents adjusted to near field capacity (personal communication with Dennis Corwin, USDA-ARS, George E. Brown Salinity Laboratory, Riverside, CA (06/07/05)). In Australia, extensive surveys of salinity hazards have been conducted with EMI (Williams and Baker, 1982; Kingston, 1985). One survey covered an area of about 10,000 km^2 using a grid spacing of about 5 km. The other survey covered an area of 300 km^2 using a grid spacing of 1 km. In both studies, areas of high salinity were inferred from spatial patterns of EC_a. The Australian survey designs are considered too coarse, while the USDA-ARS Salinity Laboratory's design is too comprehensive for use in a two-year survey that encompasses the salt-affected areas of Kittson County.

Spatiotemporal differences in soil moisture content and temperature affect EC_a. Ideally, EMI soil salinity surveys should be conducted when soil profiles are moist with available moisture contents greater than 30 % (McKenzie et al., 1989). At these available moisture contents, results are not affected by decreases in ionic activity. In the studies conducted by McKenzie and others (1989), correlations coefficients were highest ($r^2 = 0.83$) for soils with moisture contents between 35 and 85% and lower ($r^2 = 0.79$) for soils with moisture contents less than 35 %. However, in soil with available moisture contents greater than 85 %, correlations coefficients were the lowest ($r^2 = 0.70$). Changes in soil salinity are known to have a larger effect on EC_a than changes in soil moisture (de Jong et al., 1979). While some consider differences in soil moisture content not critical for reconnaissance salinity surveys (Hendrickx et al., 1992), the affects of temporal variations in soil moisture contents will have to be monitored in this study.

At the time of this investigation, some ponded conditions existed in all fields of Northcote soil. The ponded waters in swales are not in equilibrium with the soil water and will affect EC_a (personal communication with Scott Lesch, USDA-ARS, George E. Brown Salinity Laboratory, Riverside, CA (06/07/05)). The effects of spatiotemporal variations in soil moisture contents and surface waters not in equilibrium with the soil solution should be evaluated in this study.

For accurate conversion of EC_a to EC_e, soil temperature corrections are considered essential (McKenzie et al., 1989). Apparent conductivity changes 2.2 percent per degree centigrade (McNeill, 1980). In order to reduce temporal variations in EC_a caused by changes in soil temperature, all EC_a measurements should be standardized to an equivalent conductivity at a reference temperature of 25^o C. Reliable measurements for salinity appraisal can not be obtained when frozen layers are present in the soil (McKenzie et al., 1989).

Survey Protocol:
Soil scientist will continue to collect grab samples and measure EC_a with the EM38 meter in both the horizontal and vertical dipole orientations. Soil samples and EMI measurements will be collected randomly throughout the salt-affected area. Traveling to sampling sites will consume a large amount of time and constitute the largest expenditure of resources. To increase efficiency, multiple EMI measurements will be obtained along a transect line at each sampling site.

At each sampling site, a transect line consisting of 5 equally spaced (50-ft interval) measurement points will be established. To minimize the effect of any road or ditches on soil salinity, each transect line should be at least 100-ft away from these features. In addition, transect lines will not be located in areas of buried or overhead utility lines. At each of the 5 measurement points along each transect line, EC_a will be measured with an EM38 meter placed on the soil surface in both the horizontal and vertical dipole orientations. This procedure will result in ten geo-referenced EC_a measurements (five measurement points with two measurements (horizontal and vertical dipole orientations) at each point) for each transect line. This data will be entered into a worksheet. The soil temperature at a depth of about 50 cm will be measured at each transect line site. Both the raw and temperature corrected EC_a will be entered on the spreadsheet. Field personnel will make observations on general soil moisture content (dry, moist, saturated) at the time of the measurements and enter this observation on the spreadsheet. Two averaged, temperature-corrected EC_a values (horizontal and vertical dipole orientations) for the 5 measurement points will be used to represent each transect line. The coordinates of the mid-point of the transect line will be used to identify the site and to facilitate the import of EC_a data into GIS.

At the first measurement point of each transect, three grab samples will be obtained for estimation of the conductivity of the 1:1(soil: water) suspension. Samples will be collected to a depth of 90 cm in 30-cm depth intervals. An Extech ExStik EC400 will be used to measure the conductivity of the 1:1suspension for samples collected in the field. The temperature-corrected EC_a measured with the EM38 meter on the ground surface in both dipole orientations will be referenced to the soil sample point and the three conductivity of the 1:1suspension estimates.

Calibration procedures used for the EM38 meter are correct. However, to remove any remnant magnetic susceptibility, before each measurement on the ground surface, the I/P reading will be adjusted to zero. The National Soil Survey Center will assist with soil sampling and analyses. Detailed EMI surveys will be completed on representative soil polygons with the NSSC mobile EMI unit. Information from these detailed surveys will assist the evaluation and description of salinity within soil polygons.

Equipment:
The EM38DD meter was used in the presently discussed study. This meter is manufactured by Geonics Limited (Mississauga, Ontario).[1] The meter is portable and requires only one person to operate. No ground contact is required with this meter. Lateral resolution is approximately equal to the intercoil spacing. Operating procedures for the EM38DD meter are described by Geonics Limited (2000). The EM38DD meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, the EM38DD meter provides theoretical penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively.

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

The Geonics DAS70 Data Acquisition System was used with the EM38DD meter to record and store both EC_a and GPS data.[1] The acquisition system consists of an EMI meter, an Allegro field computer, and a Garmin Global Positioning System Map 76 receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack).[1] With the acquisition system, the EM38DD meter is keypad operated and measurements are automatically triggered.

To help summarize the results, the SURFER for Windows (version 8.0) software, developed by Golden Software, Inc., was used to construct a two-dimensional simulation.[1] Grids were created using kriging methods with an octant search.

Study Sites:
All study sites were located in areas of Northcote clay, 0 to 2 percent slopes. This soil map unit is extensive in Kittson County where it makes up 24.8 percent (175,540 acres) of the total acreage. It occurs in both the salt-affected and non-salt-affected portions of the county. Because of saturated field conditions and the need for some form of ground cover to support pedestrian EMI surveys, all sites were located in continuous CRP enrolled land or pasture. Table 1 lists the locations of the study sites. Sites # 1, 2, 4, and 5 are located within the salt-affected area and considered saline. Sites 3 and 6 are located outside the salt-affected area and considered non-saline.

Table 1. Locations of Study Sites

Study Site	Location
Kittson #1	NW¼, Section 29, T. 159 N., R. 48 W.
Kittson #2	NE¼, Section 28, T. 162 N., R 50 W.
Kittson #3	NW¼, Section 2, T. 161 N., R 50 W.
Kittson #4	NW¼, Section 24, T. 163 N., R. 49 W.
Kittson #5	NW¼, Section 11, T. 163 N., R 49 W.
Kittson #6	SW¼, Section 2, T. 161 N., R 50 W

Results:
At the time of this investigation, the soil temperature at a depth of 50 cm averaged 11^{o} C. All EC_a measurements have been converted to a reference temperature of 25^{o} C using the appropriate temperature conversion factor (EC_a * 1.375) listed in Agricultural Handbook No. 60 (United States Salinity Laboratory Staff, 1954).

Of the 4352 observations made in this study, 4347 had higher EC_a measured in the in the deeper-sensing vertical dipole orientation than in the shallower-sensing horizontal dipole orientation. This relationship indicates a normal salt profile (salinity increasing with depth) and suggests capillary rise from a saline water table and leaching of salts from surface layers. The basic statistics for EC_a data collected at each site are summarized in Tables 2 and Table 3. Tables 2 and Table 3 summarize measurements that were collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Study sites located in the salt-affected areas (Kittson-1, -2, -4, and -5) had significantly higher averaged EC_a than the sites located in the non-salt-affected areas (Kittson-3 and -6). In most areas of the United States, an EC_a higher than 60 mS/m indicates saline or alkaline conditions. The high EC_a measured areas of Northcote soil is believed to indicate that some level of salinity (slight or very slight) exists at most sites. Although higher EC_a are more pervasive in sites located within the salt-affect area, some levels of salinity are presumed to exist at all sites. An analysis of variance did indicate that a significant (P = 0.0001) difference in EC_a exist between sites located within and outside the delimited salt-affected area. Minimum values of 0.0 mS/m recorded with the EM38DD meter in the horizontal dipole orientation represent calibration and/or measurement errors.

Table 2. Basic Statistics for EMI Surveys conducted with an EM38DD Meter in the Horizontal Dipole Orientation.

(All vales of EC_a corrected to reference temperature of 25° C)

	KITTSON 1	KITTSON-2	KITTSON-3	KITTSON-4	KITTSON-5	KITTSON-6
NUMBER	663	715	555	841	1011	567
MEAN	268.5	266.4	159.6	192.7	296.5	107.9
SD	89.0	41.1	50.9	68.2	56.7	54.7
MININUM	0.0	0.0	0.0	0.0	0.0	30.9
MAXIMUM	604.2	363.9	358.2	422.0	486.1	314.5
25% TILE	202.0	244.6	120.8	143.0	259.7	73.4
75% TILE	329.2	292.7	186.0	233.8	334.6	119.6

Table 3. Basic Statistics for EMI Surveys conducted with an EM38DD Meter in the Vertical Dipole Orientation

(All vales of EC_a corrected to reference temperature of 25° C)

	KITTSON-1	KITTSON-2	KITTSON-3	KITTSON-4	KITTSON-5	KITTSON-6
NUMBER	663	715	555	841	1011	567
MEAN	394.2	394.5	204.7	240.9	407.4	193.3
SD	85.7	39.0	57.0	77.7	55.8	62.5
MININUM	29.6	43.0	25.4	17.5	34.6	107.4
MAXIMUM	622.7	476.9	429.3	432.4	611.5	414.7
25% TILE	338.4	376.8	161.2	182.4	370.0	153.3
75% TILE	449.1	417.8	237.2	289.4	446.7	208.0

Spatial Patterns of EC_a:

Spatial patterns of EC_a within each of the six study sites are shown in Figures 1 to 6. In each figure, separate plots show the distribution of EC_a in the shallower-sensing horizontal or deeper-sensing vertical dipole orientations. In each plot, the isoline interval is 50 mS/m. Identical color scales (0 to 700 mS/m) have been used in all plots to facilitate comparison. The locations of sample points are shown in these plots. At each of these points, samples were collected at 30-cm intervals to a depth of 90-cm for analysis at the National Soil Survey Laboratory, Lincoln, Nebraska.

Plots of EC_a from Kittson Site #1 are shown in Figure 1. In both dipole orientations, the highest and most variable EC_a were measured at this site (see Tables 2 and 3). Spatial patterns of EC_a are highly variable at all scales within this site. Major EC_a patterns appear to follow linear trends within this site. Ponded conditions, though confined to swales, were widely dispersed across the site. Casual observations made during this survey failed to indicate that ponded conditions had any noticeable affect on EC_a measurements. A county road and road ditch parallels the northern border of this site. Evaporative discharge of salts associated with these features is responsible for the zone of anomalously higher EC_a in this portion of the plots. The zone of higher EC_a in the southwest corner of each plot was visually correlated with a barren area of highly saline soils. A linear pattern of lower EC_a extends in a north-south direction across the central portion of these plots. This feature was not evident in the field and no noticeable topographic feature was identified during the survey. Surprisingly, the four sampled pedons were aligned along this feature. The plots shown in Figure 1 indicate that the selected sample sites are unrepresentative of the distribution of EC_a within this study site.

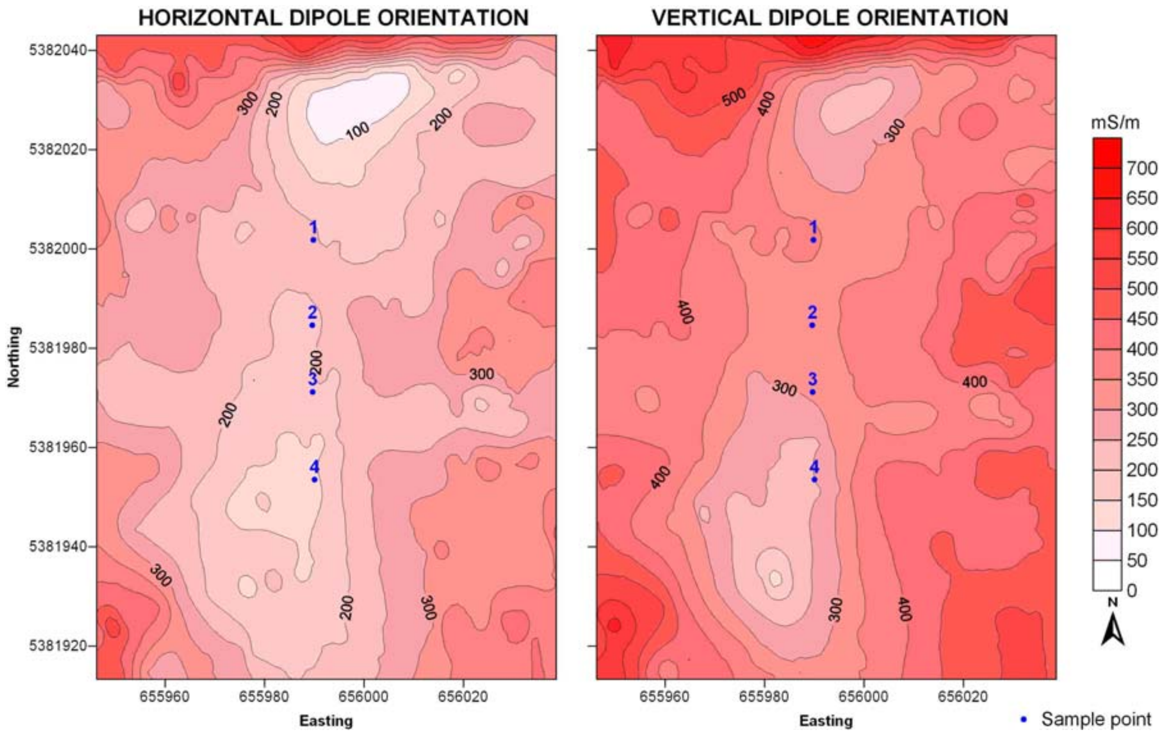

Figure 1. Spatial patterns of EC_a at Kittson County Site #1.

Plots of EC_a from Kittson Site #2 are shown in Figure 2. County and farm roads parallel the northern and eastern borders of this site, but appeared to have not affected salinity patterns except along the site's eastern border. Ponded conditions, though confined to swales were widely dispersed across the site. A large area of ponded soils occurred in the northeast corner of the site, but had no apparent affect on spatial patterns of EC_a. Though not as pronounced as at Kittson County Site #1, spatial patterns of EC_a at Kittson County Site #2 are somewhat linear and some conform to the occurrence of road and road ditches. Spatial patterns of EC_a are highly complex and moderately variable at all scales within Kittson Site #2. With the aid of these plots, soil scientists selected sample sites that were representative of the distribution of EC_a within this study site.

Plots of EC_a from Kittson Site #3 are shown in Figure 3. This site is located in an area that is outside the delineated salt-affected area. In both dipole orientations, this site had the second lowest averaged EC_a. County and farm roads parallel the western and northern borders of this site, respectively. The pattern of high EC_a located near the intersection of these two roads is believed to be caused by evaporative discharge of salts. Ponded conditions, though confined to swales were widely dispersed across the site. Spatial patterns of $EC_{a,}$ though variable at all scales suggests a trend of decreasing ECa towards the southwest. An entrenched stream borders the study site at a short distance in this direction. With the aid of these plots, soil scientists selected sample sites that were representative of the distribution of EC_a within this study site.

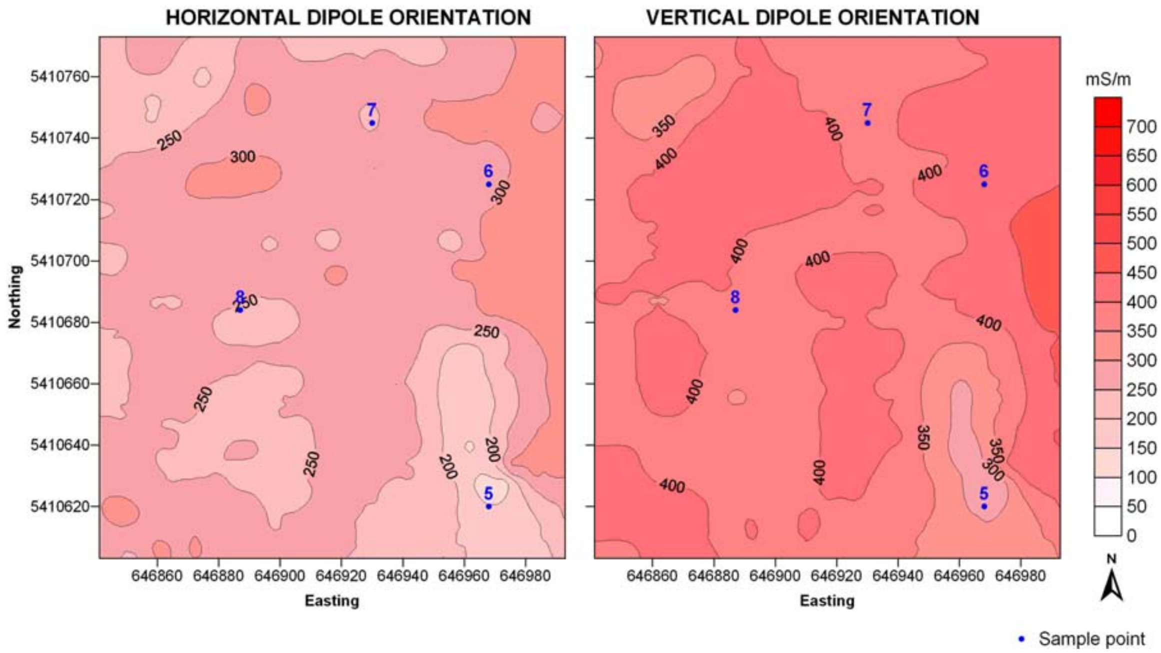

Figure 2. Spatial patterns of EC_a at Kittson County Site #2.

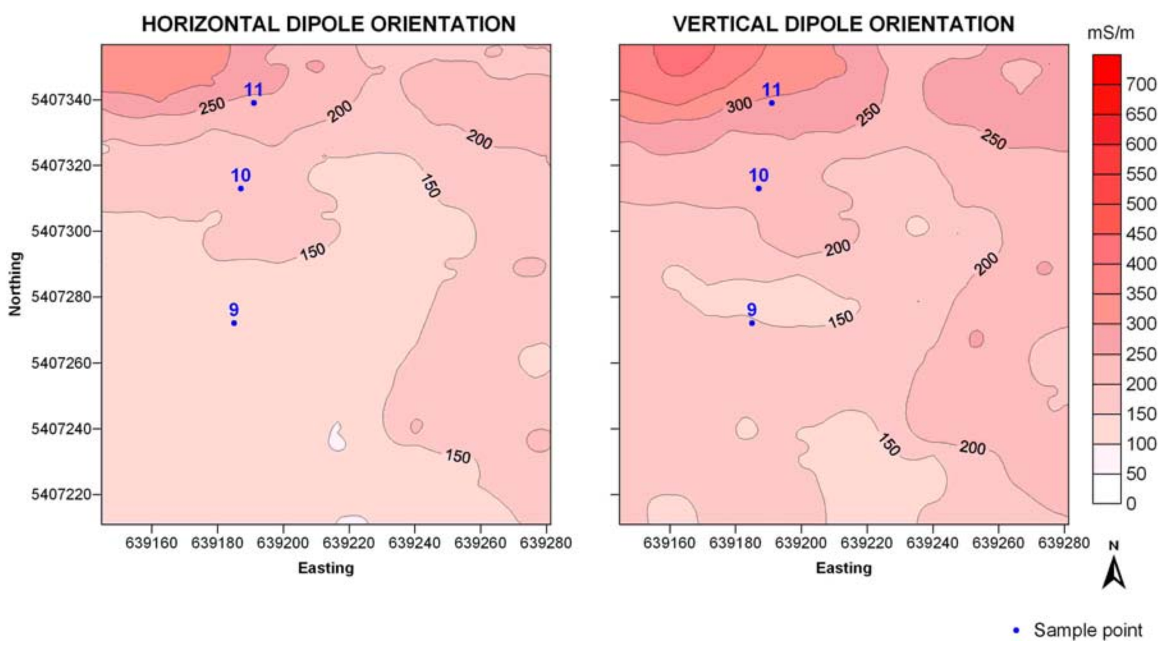

Figure 3. Spatial patterns of EC_a at Kittson County Site #3.

Plots of EC_a from Kittson Site #4 are shown in Figure 4. This site is located in the extreme northeastern portion of the delineated salt-affected area. This is a transitional area between very-fine textured lacustrine and till deposits. County and farm roads parallel the northern and eastern borders of this site, respectively. The disjointed pattern of high EC_a along the eastern border is attributed to evaporative discharge of salts from a road ditch. Ponded conditions, though confined to swales were widely dispersed across the eastern and western portions of the site.

Lower EC_a occurs along a linear zone that cuts diagonally from north-northwest to south-southeast across the central portion of the site. Slightly higher-lying swells occur within this zone.

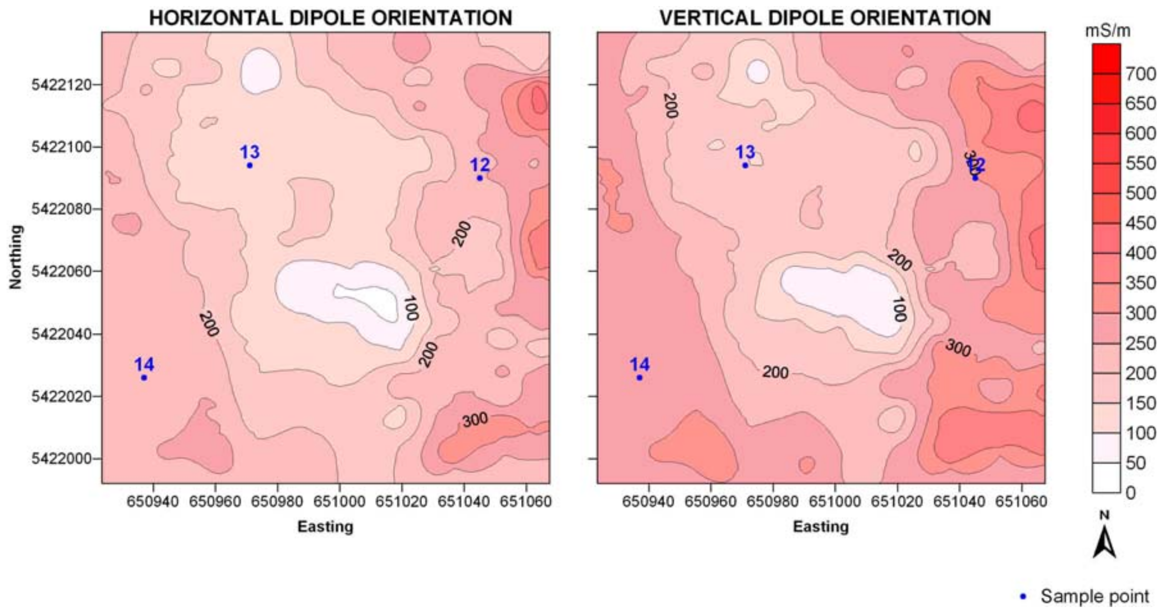

Figure 4. Spatial patterns of EC_a at Kittson County Site #4.

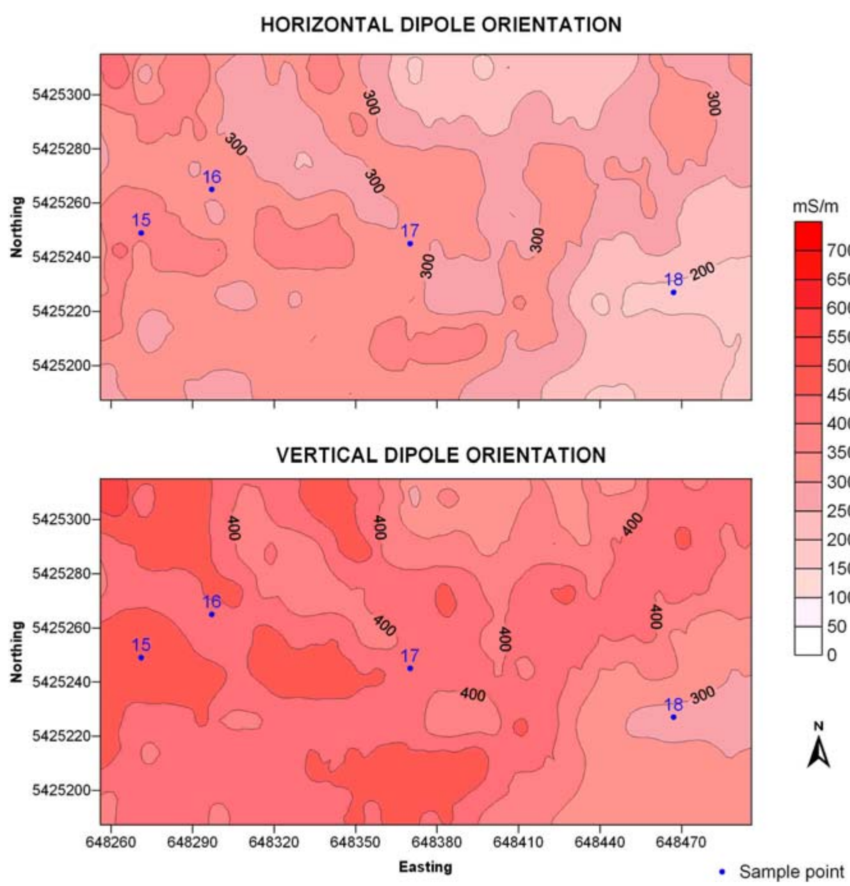

Figure 5. Spatial patterns of EC_a at Kittson County Site #5.

Plots of EC_a from Kittson Site #5 are shown in Figure 5. This site had the highest average EC_a in both dipole orientations (296.5 mS/m horizontal dipole orientation and 407.4 mS/m vertical dipole orientation). County and farm roads parallel the western and northern borders of this site, respectively. Though the affects of road ditches are general lacking, in the extreme northwest corner of the site, higher EC_a are attributed to evaporative discharge of salts from road ditches. Random and chaotic spatial patterns of EC_a characterize this site. Spatial patterns of EC_a are complex with a broad, general trend of decreasing values towards the east. Ponded water, though confined to swales was widely dispersed across the site.

Plots of EC_a from Kittson Site #6 are shown in Figure 6. This site is located outside the delineated salt-affected area. In both dipole orientations, this site had the lowest averaged EC_a. County and farm roads parallel the western and southern borders of this site, respectively. The zone of higher EC_a located in the extreme southeast corner of the site is attributed to evaporative discharge of salts from a road ditch. Ponded conditions, though confined to swales were widely dispersed across the site. Spatial patterns of $EC_{a,}$ though variable at all scales suggests a trend of decreasing ECa towards the northwest. An entrenched stream borders the study site at a short distance in this direction. Similar to patterns at Kittson County Site #3, generally broader, less chaotic spatial patterns of EC_a appear to characterize these supposedly non-saline sites.

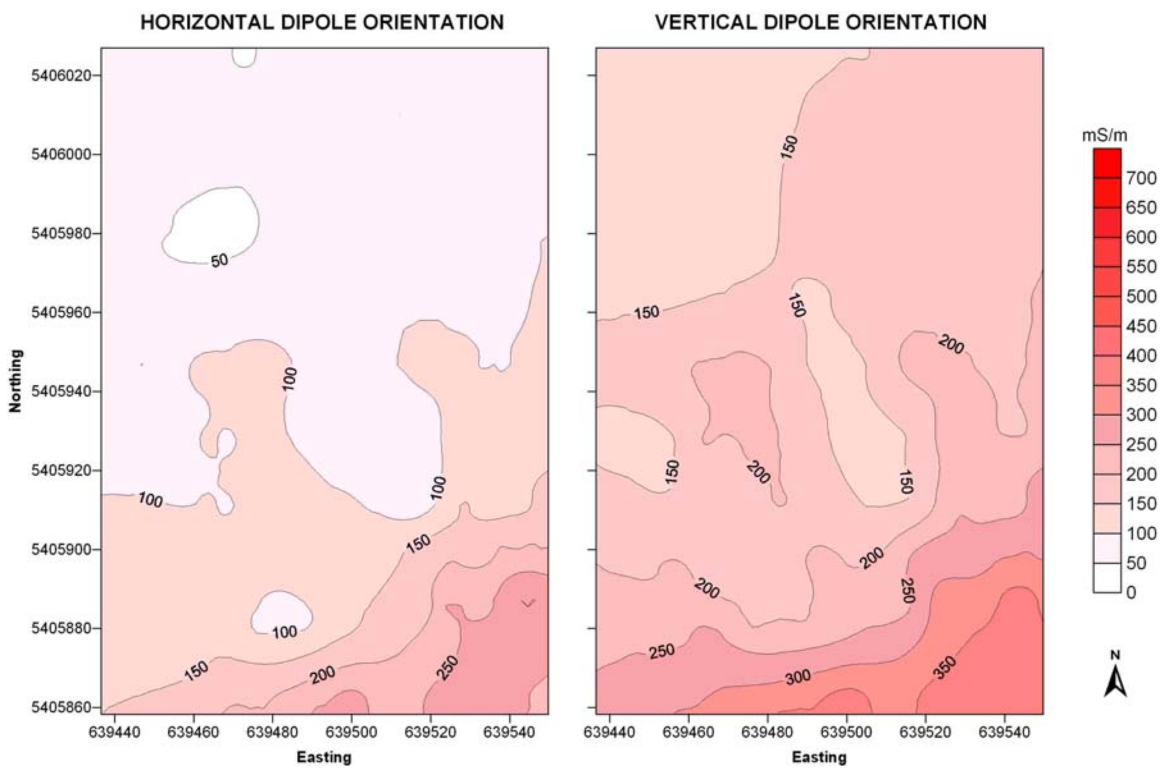

Figure 6. Spatial patterns of EC_a at Kittson County Site #6.

EMI Study of an Interbeach Area in Polk County:

This study was conducted to evaluate the potential of using EMI to map soils on interbeach areas. The study site is located in Dugdale Township in the northwest quarter of Section 27, T. 149 N, R. 44 W. The area consists of very poorly to excessively drained soils that formed in sandy beach deposits and loamy till on beach ridges and inter-beach areas (Saari and Heschke, 2003). The very deep, somewhat poorly drained Grimstad soil formed in a dominantly sandy mantle over loamy glacial till. The very deep, poorly drained and very poorly drained Hedman soil formed in calcareous, loamy glacial till. The very deep, excessively drained Sandberg soil formed in coarse or moderately coarse textured glacial beach deposits. The taxonomic classification of these soils is listed in Table 4.

Table 4. Taxonomic Classification of Soils at the Polk County Site

Soil Series	Taxonomic Classification
Grimstad	Sandy over loamy, mixed, superactive, frigid Aeric Calciaquolls
Hedman	Coarse-loamy, mixed, superactive, frigid Typic Calciaquolls
Sandberg	Sandy, mixed, frigid Calcic Hapludolls

Results:
The site is characterized by very low and moderately low EC_a. Based on 1250 measurements, EC_a averaged 10.7 mS/m with a range of 0 to 27.5 within the study site. One half of the measurements had an EC_a between 6 and 15 mS/m. Figure 7 is plot of EC_a data collected with the EM38DD meter in the vertical dipole orientation. Higher-lying plane and convex slope components had lower EC_a (< 10 mS/m). Lower-lying plane and concave slope components had higher EC_a (>14 mS/m). Electromagnetic induction is responsive to variations in clay and moisture contents. Variations in these properties can be associated with soils. In Figure 7, isolines appear to conform to soil boundaries shown on the soil map. Areas of Sandberg loamy sand, 1 to 6 % slopes (M.U. 258B), have EC_a less than 10 mS/m. Areas of Grimstad fine sandy loam (M.U. 59) and Hedman loam (M.U. 1117) have EC_a greater than 14 mS/m.

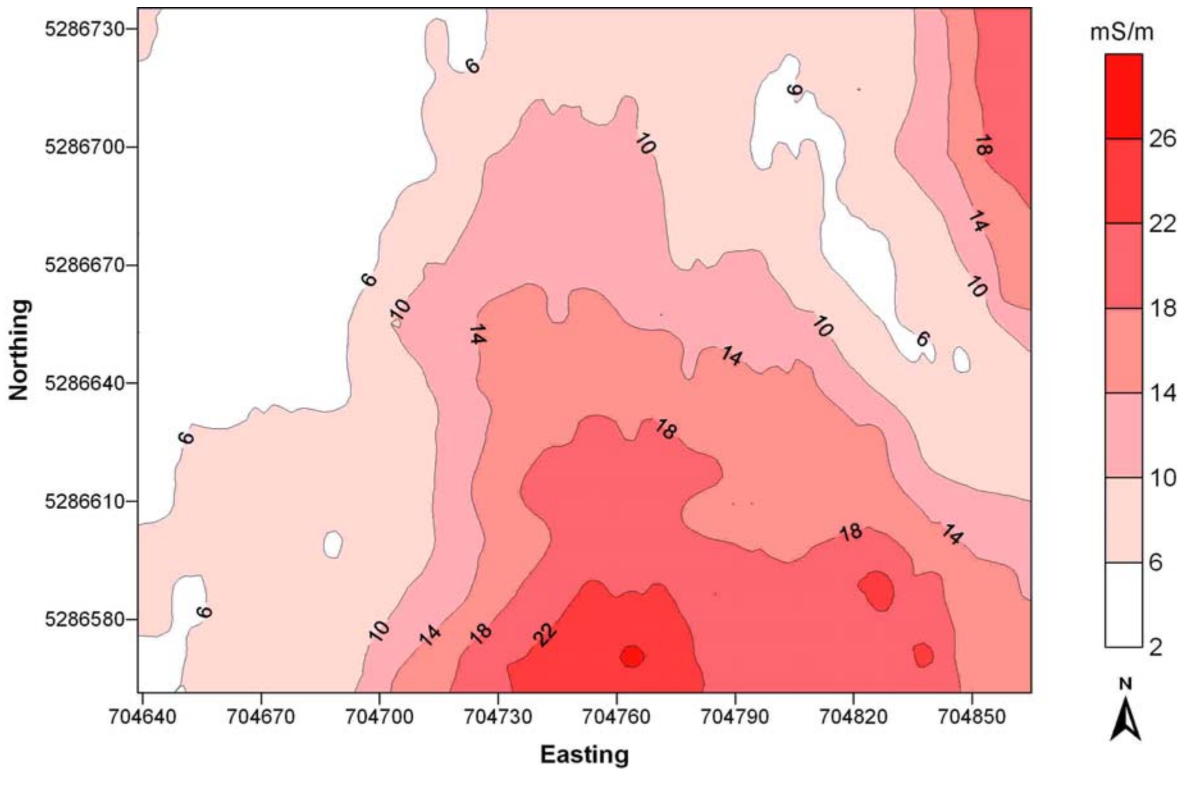

Figure 7. Spatial patterns of EC_a within the Polk County site.

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