United States Department of Agriculture

Natural Resources Conservation Service

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Subject: Geophysical Assistance

Date: 10 March 1999

To: Philip D. Camp
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Purpose:
The purpose of this field trip was to provide electromagnetic induction (EMI) training and field assistance to the USDI-BIA. Fieldwork assessed the appropriateness of using field measurements of soil electrical conductivity to accurately estimate and map soil salinity. Training and field studies were completed at the Colorado River Indian Reservation (CRIT), Parker, Arizona.

Participants:
Ed Bullod, Soil Scientist, USDI-BIA, Gallup, NM
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Bob Hetzler, Area Soil Scientist, USDI-BIA, Phoenix, AZ
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Bobbie Olher, Civil Engineer, USDI-BIA, Phoenix, AZ
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Jim Rhoades, Soil Scientist, Ag Salinity Consulting, Riverside, CA
Dana Scott, Water Technician, CRIT, Water Resource Department, Parker, AZ
Denton Slovacek, Manager, Hatch Company, Loveland, CO
Shelly Ward, Conservationist, USDI-BIA, Parker, AZ

Activities:
All field activities were completed during the period of 22 to 26 February 1999. Training consisted of formal presentations by Jim Rhoades, Scott Lesch, and myself. In addition, Scott Lesch provided a field demonstration of the USDA Salinity Lab's "salt buggy." The last two days were spent in the field mapping soil salinity with the EM38 meter and evaluating the appropriateness of the *salt program* that was developed by USDA-ARS.

Equipment:
The electromagnetic induction meter used was the EM38, manufactured by Geonics Limited*. This meter is portable and requires only one person to operate. McNeill (1986) has described principles of operation. No ground contact is required with this meter. This meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter operates at a frequency of 14,600 Hz. It has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

The position of each observation points was obtained with Rockwell Precision Lightweight GPS Receivers (PLGR). The receiver was operated in the continuous mode. The mixed satellite mode was used. This receiver was operated using an external power source (portable 9-volt battery). The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1983. The horizontal zone was 11S. Horizontal units were expressed in meters.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,* was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation.

Results:
1. The use of the multiple linear regression equations developed by USDA-ARS, U. S. Salinity Laboratory and the EM38 meter provides a reasonably accurate, practical, and cost-effective method to map spatial salinity patterns at the field scale within the Colorado River Indian Reservation.

2. Participants received training on the use and operation of the EM38 meter. Data was converted into electrical conductivity measurements using predictive equations contained on Microsoft Excel worksheet *.

3. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations contained in this report will be verified by samples collected in the field and sent to Dr. Rebecca Burt at the National Soil Survey Laboratory, Lincoln, Nebraska.

It was my pleasure to be of assistance to you and the Bureau of Indian Affairs.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

Salinity Appraisal with EMI

Background

Electromagnetic induction methods map spatial variations in apparent electrical conductivity (EC_a). Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Electromagnetic induction uses electromagnetic energy to measure the bulk or apparent electrical conductivity of soil below the transmitter and receiver coils. Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the types and concentration of ions in 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 apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). Apparent conductivity is principally affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston, 1997). In areas of saline soils, it has been estimated that greater than 65 percent of the variation in apparent conductivity can be explained by changes in salinity alone (Williams and Baker, 1982).

Electromagnetic induction has been extensively used by soil scientists to identify, map, and monitor soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982 and 1990; Johnston et al., 1996; McKenzie et al., 1989; Rhoades and Corwin, 1981; Rhoades et al., 1989a and 1989b; Slavich and Peterson, 1990; and Wollenhaupt et al., 1986). A goal of these investigation has been to relate apparent conductivity (EC_a) measured with the EM38 meter directly to the electrical conductivity of the saturated paste extract (EC_e) using simple linear regression equations. To predict soil salinity, EMI methods require a minimum amount of soil sampling and analysis. Predictive models are often sufficiently accurate to establish trends in soil salinity. However, because of the non-uniform response distribution with depth, the conversion of EMI measurements into meaningful measures of soil salinity has been difficult (Johnston et al., 1997).

Extensive data were collected by USDA-ARS Salinity Laboratory to develop improved predictive models (Rhoades et al., 1989a and1989b, Corwin and Rhoades, 1992). Different predictive equations were developed for soil profiles in which EC_a increased with depth, i.e., normal salt profile; decreased with depth, i.e., inverted salt profile; and remained constant with depth, i.e., uniform salt profile. In these models, data are transformed (fourth-root transformation) to obtain a normal distributions. In addition, these models require estimates of the average clay content within the soil profile. The *salt program* developed by Dr. Jim Rhoades and others at the Salinity Laboratory provides estimates of soil electrical conductivity (EC_e) within depth intervals of 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm. Reasonable estimates (r^2 of 0.78) of soil salinity can be made in the field using these predictive equations, measurements of apparent conductivity obtained with EMI meters, and estimates of soil water and clay contents made by the "feel" methods (Rhoades et al., 1990). These estimates assumed that the water content of the soils is at or near field capacity and that the soils are isotropic. Rhodes and others (1990) found that the accuracy of these estimates is slightly reduced by differences in the location and volume of the sample used to measure soil salinity (EC_e) and apparent conductivity (EC_a). Higher correlations ($r^2 = 0.97$) were obtained when the same volume of soil for measurements of EC_e and EC_a (Rhoades et al., 1990).

EMI surveys in the Colorado River Indian Reservation

Selected sites within the Colorado River Indian Reservation included a wide range of soils, soil textures, salinity levels, and water contents. These soils formed in alluvium on flood plains. These soils often have complex and abrupt, vertical and horizontal changes in texture. They are highly stratified and can have significant differences in clay, soluble salt, and moisture contents over short distances. Soil horizons and subsurface layers are often segmented, and varied in arrangement and thickness. These soils have varying concentrations of soluble salts and calcium carbonates. The number, composition, arrangement, and lack of continuity of these layers will weaken predictive relationships. Because of diversion, drainage, and irrigation, the water table and soil moisture content of most soils fluctuates greatly. Within the irrigated lands of the Colorado River Indian Reservation, simultaneous changes in clay, moisture, and soluble salt contents produce equivalent solutions that obscured interpretations and results.

At each site, multiple measurements were made with the EM38 meter. McNeill (1980) found a 2.2 percent change in conductivity per degree (centigrade) change. All measurements should be standardized to an equivalent electrical conductivity at a reference temperature of 25° C. However, as soil temperatures were not recorded, no corrections could be made to the EMI data. Clay content was approximated by the textural family of the delineated soil map unit and approximated by the "feel" method.

Soil samples were grouped into textural, salinity profile, and depth categories. Soil texture affects the relationship between apparent conductivity and saturated paste extract conductivity (Halvorson et al., 1977). With the *salt program*, the broad groups of available textural classes used were 15, 20, 25, 30, 35, and 40 percent clay. The salinity classes are: non-saline (<2 dS/cm), very slightly saline (2 to < 4 dS/cm), slightly saline (4 to < 8 dS/cm), moderately saline (8 to < 16 dS/cm), and strongly saline (> 16 dS/cm).

Multiple fields and soil map units were gridded and mapped with EMI. Grid surveys were conducted in delineated areas of selected map units (Nelson, F. L., 1986). The names of these map units are shown in Table 1. Table 2 contains the taxonomic classification of the soils sampled. Surveys were conducted in areas that had been mapped with coarse-loamy to fine textural classes and non-saline to strongly saline salinity classes.

Table 1

Soil Map Units traversed with EMI techniques

Symbol	Map Unit Name
9	Gadsen silty clay
8	Cibola-Agualts clay loams
11	Gilman fine sandy loam, 0 to 1 percent slopes
10	Gadsen silty clay, strongly saline

Table 2

Taxonomic Classification

Soil	Classification
Agualt	Coarse-loamy over sandy or sandy-skeletal, mixed, superactive, calcareous, hyperthermic Typic Torrifluvents
Cibola	Fine-silty over sandy or sandy-skeletal, mixed, calcareous, hyperthermic Typic Torrifluvents
Gadsen	Fine, smectitic, calcareous, hyperthermic Vertic Torrifluvents
Gilman	Coarse-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvents

Basic statistics for the sampled map units are presented in Table 3. Each soil and soil map unit has a distinct range of apparent conductivity. This range will vary slightly because of sample size, soil properties, variations in map unit composition, management, and salt content. In general, coarser textured soils have lower conductivity than finer textured soils. Saline phases of a soil have higher conductivity than non-saline phases.

Table 3
Basic Statistics
EMI Transects
CRIT Soil Survey Area
(All values are in mS/m)

Map Unit	Meter	Orientation	Minimum	Maximum	Quartiles 1st	Quartiles 3rd	Average
Gadsen silty clay	EM38	Horizontal	5.0	182.0	47.0	130	86.86
(N = 79)	EM38	Vertical	16.0	188.0	79.5	179	118.70
Gilman fine sandy loam	EM38	Horizontal	20.0	57.0	34.0	32.2	38.87
(N = 30)	EM38	Vertical	18.0	59.0	45.0	45.0	38.40
Gadsen silty clay, saline	EM38	Horizontal	104.0	197.0	175.0	182.0	174.81
(N = 49)	EM38	Vertical	106.0	197.0	188. 0	191.0	180.37

Systematic EMI Surveys
The purpose of systematic EMI surveys is to identify the distribution and extent of soil and salinity patterns and to assess the relative level of salinity or other soil properties within these patterns.

1. Gadsen, Cibola, and Agualt soils
Four random traverses were conducted across delineated areas of Gadsen silty clay and Cibola-Agualt clay loams. At intervals of 15 paces, measurements were obtained with the EM38 meter in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface. This procedure produced seventy-nine observation points. The locations of these observation points are shown in the left-hand plot in Figure 1.

Figure 1 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (center plot) and vertical (right-hand plot) dipole orientations. In Figure 1, the center plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The right-hand plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 10 mS/m.

Apparent conductivity of the upper 30 inches of the soil profile averaged 86.9 mS/m. One-half of the observations had an apparent conductivity between 47 and 130 mS/m. The apparent conductivity of the upper 60 inches of the soil profile averaged 118.7 mS/m. One-half of the observations had an apparent conductivity between 79.5 and 179.5 mS/m. The increased conductivity with depth was attributed principally to increased salinity at greater soil depths.

The spatial patterns evident in Figure 1 are believed to principally reflect the spatial distribution of soil salinity. The vertical distribution of soil salinity conformed to a normal salt profile. The *salt program* provided estimates of soil electrical conductivity directly from measurements of the apparent conductivity made with the EM38 meter. For this site, these estimates assumed that the water content of the soils is at or near field capacity, the soils are isotropic, and the clay content is about 40 percent. In reality, none of these assumptions were completely correct. However, derived estimates were considered reasonable.

Figure 2 shows the spatial distribution of soil electrical conductivity estimated from EM38 measurements and the salt program. All measurements are expressed in deciSiemens per meter (dS/m). Electrical conductivity averaged 4.45, 6.42, and 7.75 dS/m within the 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm depth intervals, respectively. For the upper 30 cm, one-half of the observations had electrical conductivity between 2.67 and 4.27 dS/m. For the 30 to 60 cm depth interval, one-half of the observations had electrical conductivity between 2.78 and 8.98 dS/m. For the 60 to 90 cm depth interval, one-half of the observations had electrical conductivity between 4.60 and 1.17 dS/m. Based on estimates made with the *salt program* for the 0 to 30 cm depth interval, 72 percent of the observation points were very slightly saline, 20 percent were slightly saline, 6 percent were moderately saline, and 2 percent were strongly saline.

2. Gilman Fine Sandy Loam

Four random traverses were conducted across a delineated area of Gilman fine sandy loams. At intervals of 15 paces, measurements were obtained with the EM38 meter in both the horizontal and vertical dipole orientations. This procedure produced thirty observation points. The locations of these observation points are shown in the left-hand plot in Figure 3.

Figure 3 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (center plot) and vertical (right-hand plot) dipole orientations. In Figure 3, the center plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The right-hand plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 4 mS/m.

Apparent conductivity of the upper 30 inches of the soil profile averaged 38.86 mS/m. One-half of the observations had an apparent conductivity between 34 and 45 mS/m. The apparent conductivity of the upper 60 inches of the soil profile averaged 38.4 mS/m. One-half of the observations had an apparent conductivity between 32.2 and 45 mS/m. Values of apparent conductivity remained uniform and did not significantly change with increasing soil depth.

The spatial patterns evident in Figure 3 are believed to principally reflect the spatial distribution of soil salinity. The vertical distribution of soil salinity conformed to a uniform salt profile. The *salt program* was used to provide estimates of soil electrical conductivity directly from measurements of the apparent electrical conductivity made with the EM38 meter. These estimates assumed that the water content of the soils is at or near field capacity, the soils are isotropic, and the clay content is about 15 percent. In reality, none of these assumptions were completely correct. However, estimates were considered reasonable.

Figure 4 shows the spatial distribution of soil electrical conductivity estimated from EM38 measurements and the salt program. All measurements are expressed in deciSiemens per meter (dS/m). Electrical conductivity averaged 3.31, 3.85, and 3.74 dS/m within the 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm depth intervals, respectively. For the upper 30 cm, one-half of the observations had electrical conductivity between 2.83 and 3.85 dS/m. For the 30 to 60 cm depth interval, one-half of the observations had electrical conductivity between 3.13 and 4.72 dS/m. For the 60 to 90 cm depth interval, one-half of the observations had electrical conductivity between 3.18 and 4.52 dS/m. Based on estimates made with the *salt program* for the 0 to 30 cm depth interval, 100 percent of the observation points were very slightly saline.

3. Gadsen silty clay, strongly saline

Four random traverses were conducted across delineated areas of Gadsen silty clay, strongly saline. At intervals of 20 paces, measurements were obtained with the EM38 meter in both the horizontal and vertical dipole orientations. This procedure produced forty-nine observation points. The locations of these observation points are shown in the left-hand plot in Figure 5.

Figure 5 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (center plot) and vertical (right-hand plot) dipole orientations. In Figure 5, the center plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The right-hand plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 10 mS/m.

Apparent conductivity of the upper 30 inches of the soil profile averaged 174.81 mS/m. One-half of the observations had an apparent conductivity between 175 and 188 mS/m. The apparent conductivity of the upper 60 inches of the soil profile averaged 180.37 mS/m. One-half of the observations had an apparent conductivity between 182 and 191 mS/m. Values of apparent conductivity remained uniform and did not significantly change with increasing soil depth.

The spatial patterns evident in Figure 5 are believed to reflect the spatial distribution of soil salinity. The vertical distribution of soil salinity conformed to a uniform salt profile. The *salt program* was used to provide estimates of soil electrical conductivity directly from measurements of apparent electrical conductivity made with the EM38 meter. These estimates assumed that the water content of the soils is at or near field capacity, the soils are isotropic, and the clay content is about 40 percent.

Figure 6 shows the spatial distribution of soil electrical conductivity estimated from EM38 measurements and the salt program. All measurements are expressed in deciSiemens per meter (dS/m). Electrical conductivity averaged 11.93, 15.03, and 11.27 dS/m within the 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm depth intervals, respectively. For the upper 30 cm, one-half of the observations had electrical conductivity between 11.94 and 13.03 dS/m. For the 30 to 60 cm depth

interval, one-half of the observations had electrical conductivity between 14.80 and 16.20 dS/m. For the 60 to 90 cm depth interval, one-half of the observations had electrical conductivity between 11.01 and 11.98 dS/m. Based on estimates made with the *salt program* for the 0 to 30 cm depth interval, 6 percent of the observation points were slightly saline, and 94 percent were moderately saline.

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EMI Survey of an area of Gadsden Silty Clay and Cibola-Agualt Clay Loams

Measured Apparent Conductivity (ECa)

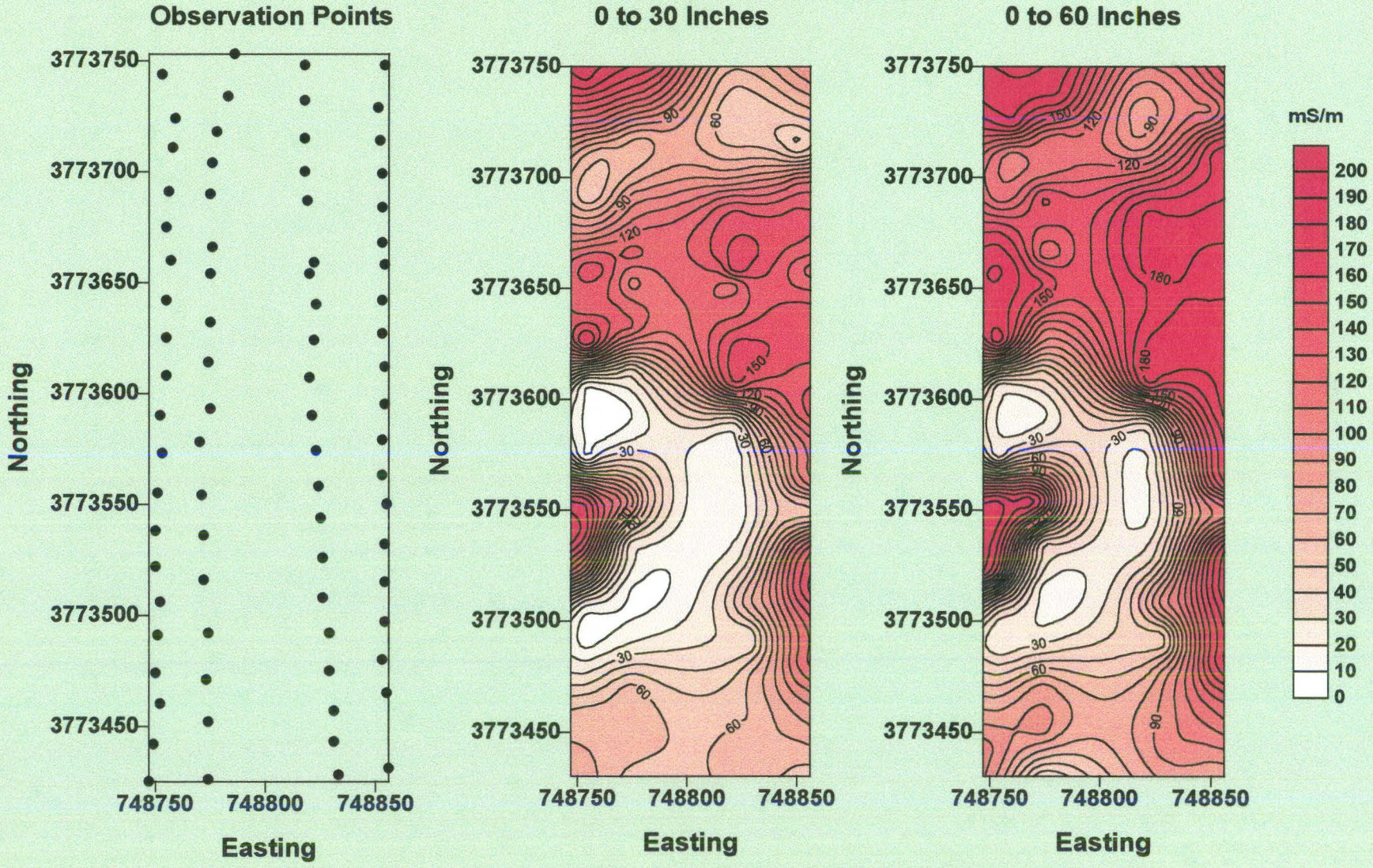

Figure 1

EMI SURVEY
AREA OF GADSEN, CIBOLA, AND AGUALT SOIL
Estimated Soil Salinity (ECe)

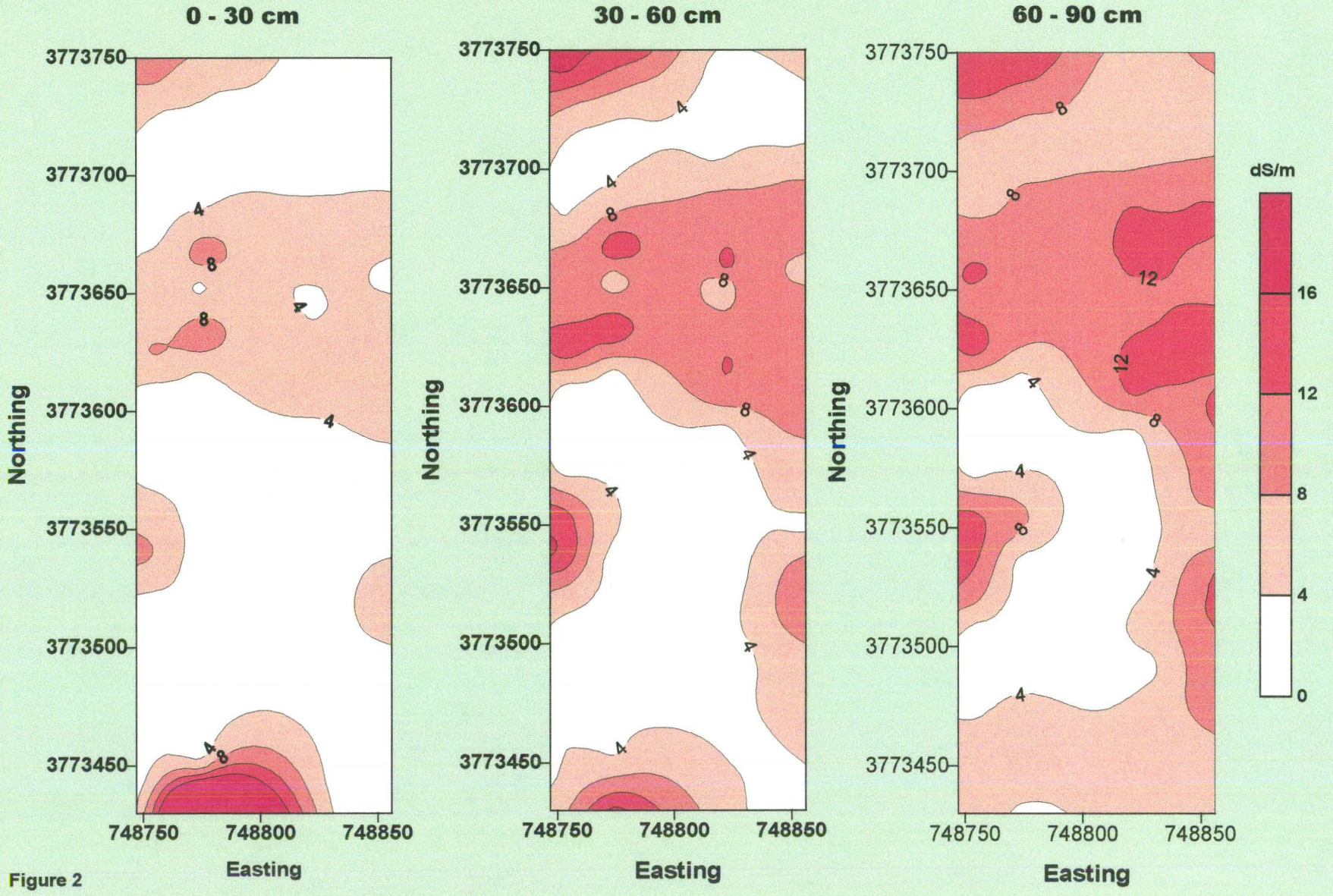

Figure 2

EMI Survey of an area of Gilman Fine Sandy Loam

Measured Apparent Conductivity (ECa)

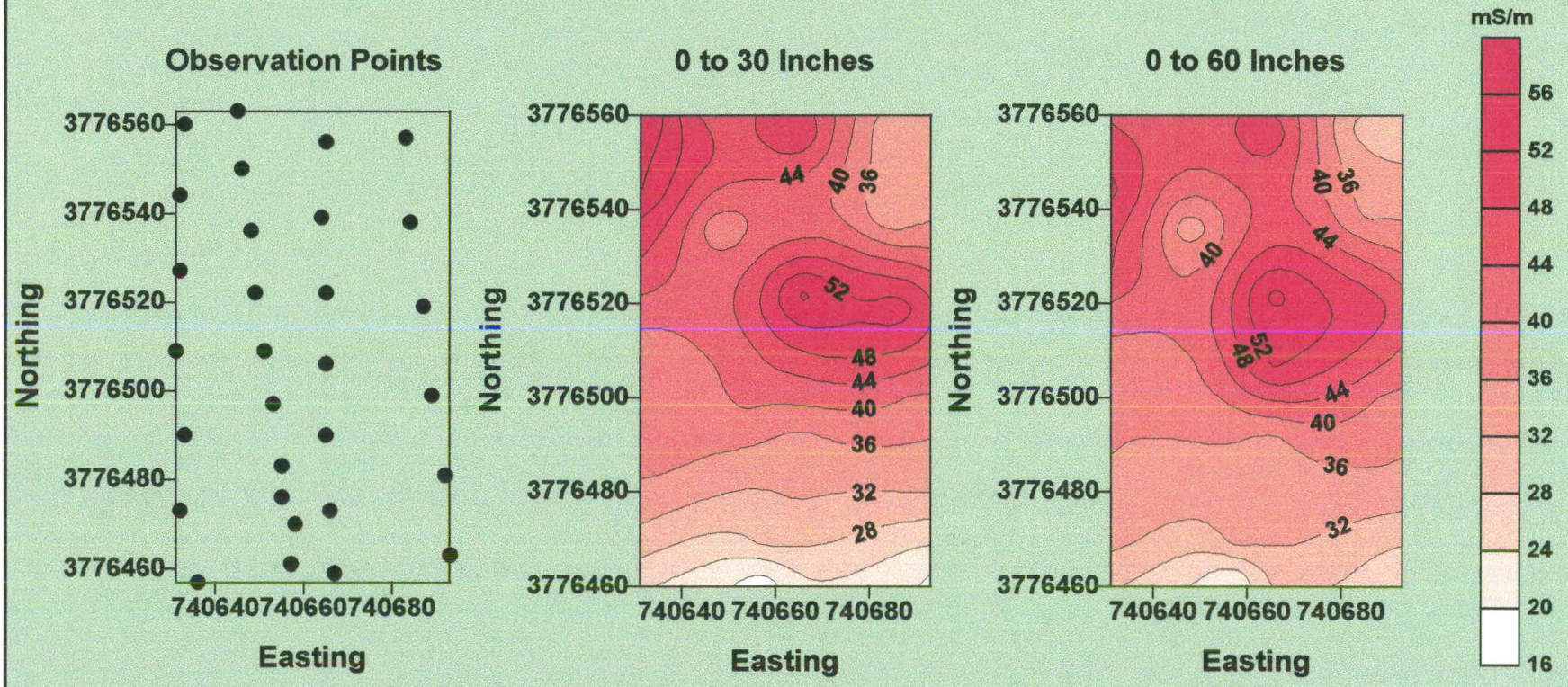

Figure 3

EMI Survey of an area of Gilman Fine Sandy Loam

Estimated Soil Salinity (ECe)

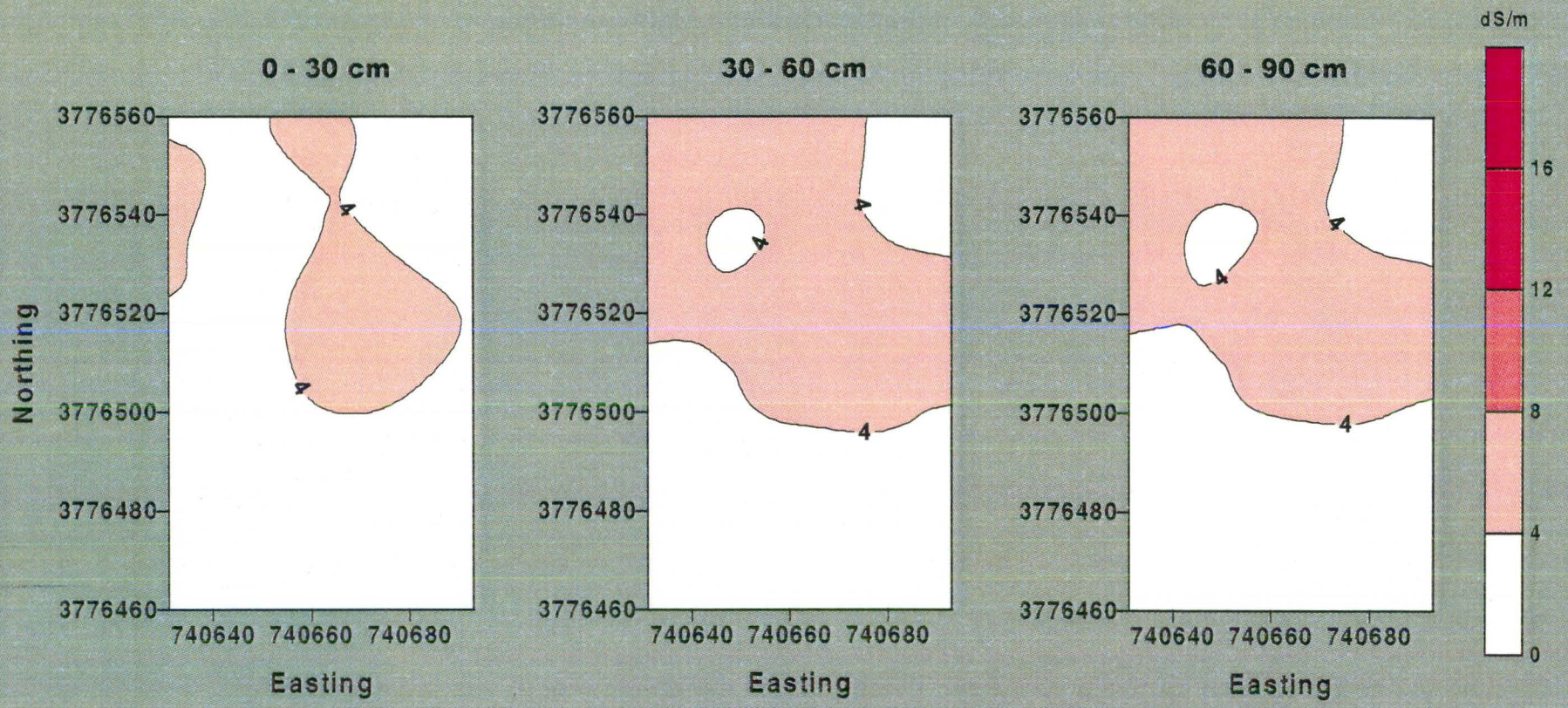

Figure 4

EMI Survey of an area of Gadsden Silty Clay Strongly Saline

Measured Apparent Conductivity (ECa)

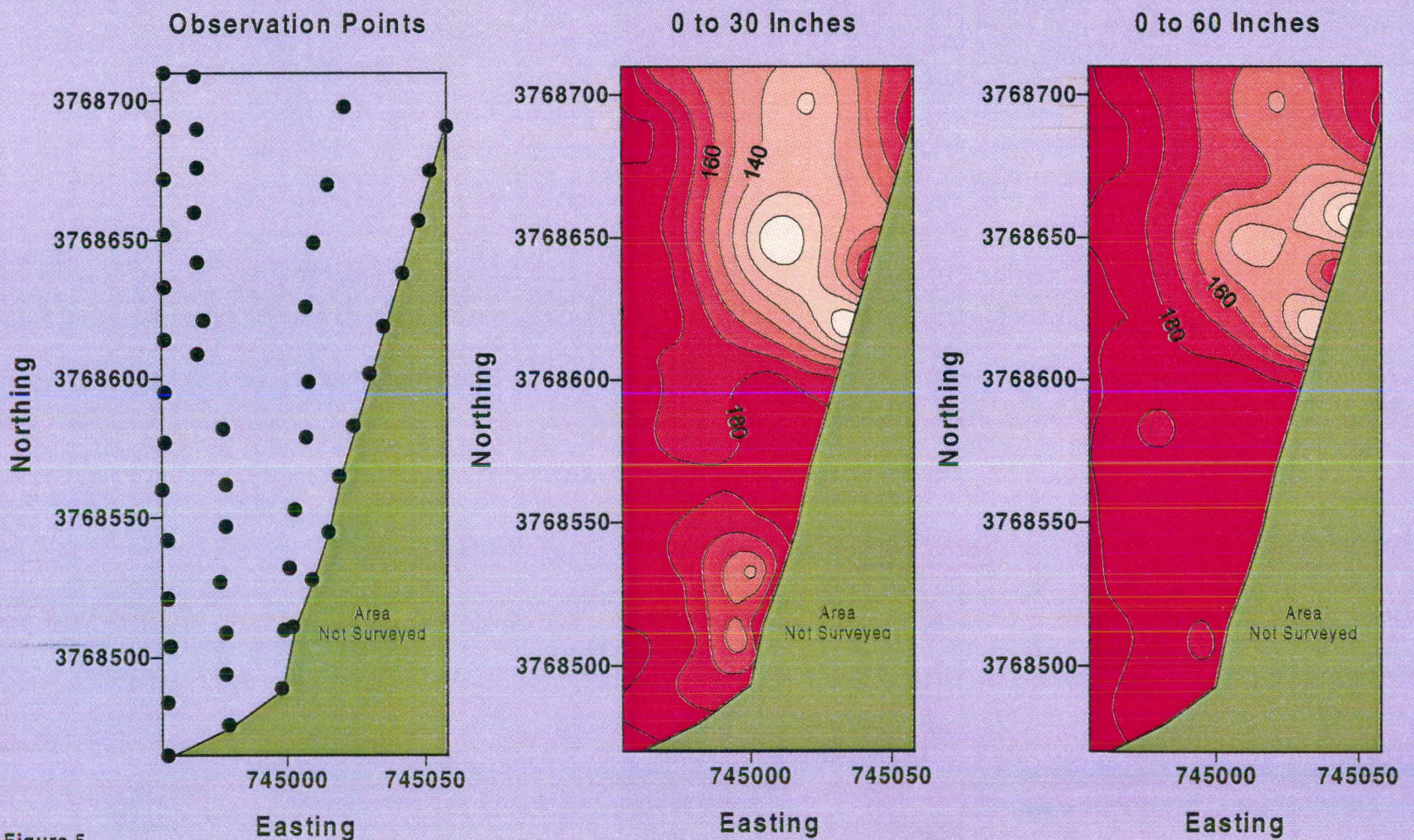

Figure 5

EMI Survey of an area of Gadsden Silty Clay Strongly Saline

Estimated Soil Salinity (ECe)

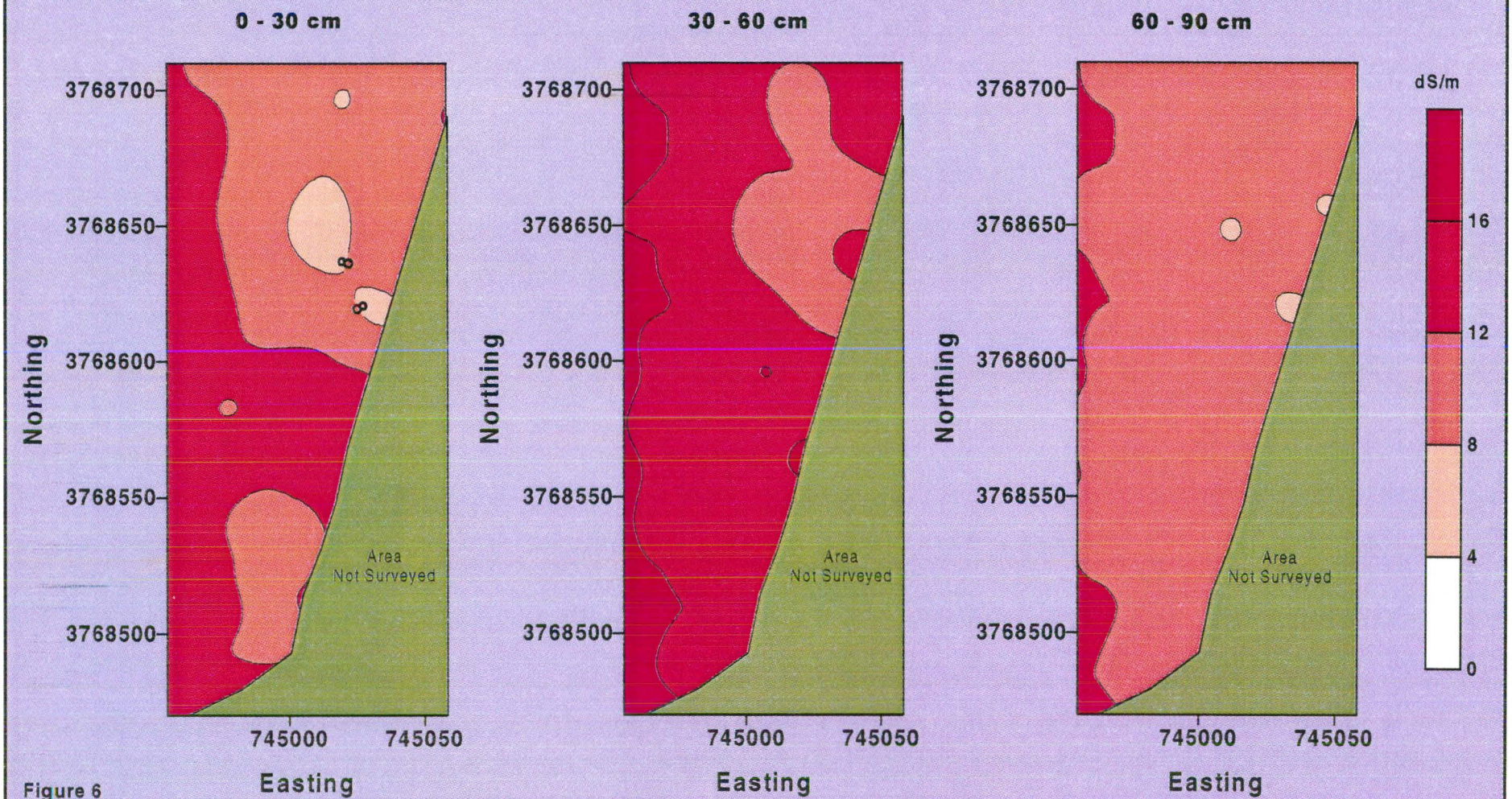

Figure 6