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

Subject: -- Geophysical Assistance -- **Date:** 7 January 2003

To: William J. Gradle
State Conservationist
USDA - NRCS
2118 W. Park Court
Champaign, Illinois 61821

Purpose:
The purpose of this investigation was to evaluate mapping and sampling protocol for conducting high intensity soils surveys with geophysical tools.

Participants:
John Bonjeans, Cartographic Aid, USDA-NRCS, Champaign, IL
Mark Bramstedt, Resource Soil Scientist, USDA-NRCS, Watseka, IL
Dale E. Calsyn, Soil Survey Project Leader, USDA-NRCS, Aurora, IL
Jeffrey A. Deniger, Soil Scientist, USDA-NRCS, Aurora, IL
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Don Fehrenbacher, Resource Planning Specialist, USDA-NRCS, Plainfield, IL
Nick Guries, EarthIT, Madison, WI
Karla D. Hanson Soil Scientist, USDA-NRCS, Aurora, IL
Frank Heisner, Soil Scientist, USDA-NRCS, Rock Falls, IL
John Marks, EarthIT, Madison, WI
Robert McLeese, State Soil Scientist, USDA-NRCS, Champaign, IL
Dan Rooney, EarthIT, Madison, WI
Woody Wallace, EarthIT, Madison, WI
Roger Windhorn, Resource Soil Scientist, USDA-NRCS, Champaign, IL
Dan Withers, Cartographic Technician, USDA-NRCS, Champaign, IL
Steve Zwicker, Resource Soil Scientist, USDA-NRCS, Princeton, IL

Activities:
All field activities were completed during the period of 18 to 21 November 2002.

Equipment:
The Veris 3100 soil EC mapping system was used in this study. This system is a towed-array, multi-electrode resistivity unit manufactured by Veris Technologies.[1] Operating procedures are described by Veris Technologies (1998). In isotropic materials, conductivity is the reciprocal of resistivity. The Veris 3100 soil EC mapping system converts measurements of apparent resistivity (ohm-m) into apparent conductivity (mS/m). The Veris 3100 implement provides two depths of penetration: one for the upper 0 to 30 cm (shallow) and one for the upper 0 to 90 cm (deep) of the soil. The depth of penetration is dependent upon the spacing and type of electrode array. The electrode array is a modified Wenner array with 6 unequally spaced electrodes (rotating discs). Voltage is applied to discs number 2 and 5. The wider-spaced discs (number 1 and 6) measure the current across the 0 to 90 cm depth interval; the more closely spaced discs (number 3 and 4) measure the current across the 0 to 30 cm depth interval. The Veris 3100 implement is pulled behind a pickup truck at speeds of about 5 to 10 m/hr. A Trimble 132 GPS receiver was used to geo-reference the measurements made with this system.[1]

[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

The electromagnetic induction meter used in this study was the EM38DD, manufactured by Geonics Limited. [1] Operating procedures are described by Geonics Limited (2000). The EM38DD meter is portable and requires only one person to operate. No ground contact is required with this meter. The EM38DD operates at a frequency of 14,600 Hz. It has effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on).

The Geonics DAS70 Data Acquisition System was used to record and store both EMI and GPS data.[2] The acquisition system consists of an EM38DD meter, Allegro field computer, and Trimble AG114 GPS receiver. With the logging system, the EM38DD meter is keypad operated and measurements can either be automatically or manually triggered.

To help summarize the results of this study, the SURFER for Windows, version 8.0 (developed by Golden Software, Inc.) was used to construct two-dimensional simulations.[2] Grids were created using kriging methods with an octant search.

The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[2] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and connector panel. A 12-volt battery powers the system. This unit is backpack portable, and with an antenna, requires two people to operate. The 400 MHz and 200 MHz antennas were used in this study.

The RADAN NT (version 2.0) software program was used to process the radar profiles (Geophysical Survey Systems, Inc, 2001a). [2] Processing included color transformation, marker editing, distance normalization, and range gain adjustments. Data were processed into a three-dimensional image using the 3D QuickDraw for RADAN Windows NT software (Geophysical Survey Systems, Inc, 2001b). [2]

Also used and evaluated in this study, but not discussed in this report, is a mobile soil mapping system developed by Earth Information Technologies, Corporation (EarthIT).[2] This mobile soil mapping system has been developed for high intensity soil surveys and site investigations. This system includes a soil imaging penetrometer (SIP) that is capable of obtaining continuous, geo-referenced, image profiles (color, structure, texture) of the soil. The system integrates the sampled data with previously collected or existing subsurface and landscape data to determine the optimal placement of further measurements or samples as well as the creation of 3-D maps.

Results:

1. In general, within the La Salle County Soil Project Site, apparent conductivity was comparatively low (typically less than 20 mS/m) and spatially invariable. With both EMI instruments, apparent conductivity increased and became more variable with increasing penetration depths. The vertical response of these EMI devices can be attributed to the comparatively low clay and moisture contents of the surface layers, the higher clay and water contents of the subsoil and the amount of free carbonates in the lower part of the solum and in the substratum. In general the surface layers were lighter textured and drier than the underlying, heavier textured subsoil. In the absence of topographic, soil, and crop yield data; spatial patterns of apparent conductivity cannot be fully assessed over so large (110 acres) and diverse a site.

2. Plots of EMI data showed different amplitudes and spatial patterns. These differences are attributed to differences in soils and soil properties. With minor exceptions, patterns of apparent conductivity are more intricate and do not conform to the high-intensity soil survey map of the site (see figures 7 & 8). At this site, maps of apparent conductivity offer new and additional spatial information, but cannot be used as a substitute for the high-intensity soil survey map. While interpretations have been advanced as to the soil

[2] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

parameters that influence the EMI responses, these interpretations are unconfirmed. Once understood, interpretative models can be developed and used for specific soils and landscapes. Additional efforts need to be expended to understand the site-specific relationship between apparent conductivity and the soil factors that contribute to this measurement.

3. For data collected with the Veris 3100 soil EC mapping system and the EM38DD meter and for comparable depth intervals, general patterns of apparent conductivity are reasonably similar. However, specific patterns do vary with instrument and measurement configuration.

4. Detailed EMI surveys were completed in areas of the soil pits and sampling to provide high resolution EMI data. For the majority of the detail grid sites, apparent conductivity was relatively invariable with standard deviations within recognized survey and instrument errors (1 to 3 mS/m). In a majority of the grids, spatial patterns appear elongated in an east to west direction. As this was also the direction of EMI traverse and tillage, these features are believed to be, in part, a survey (height of meter above ridges or furrows on the ground surface) or management (soil compaction) artifact.

5. The delineation of zones on the enclosed plots is dependent on the range of apparent conductivity values and the number of selected intervals or class breaks. Values of apparent conductivity were comparatively low and invariable within the study site at the time of the survey. Most soils were not highly contrasting in terms of their apparent conductivity. With EMI devices, survey and instrument error can range from 1 to 3mS/m (Sudduth et al., 2001). Because of the restricted range in EMI measurements and concerns for instrument errors, isoline intervals of 3 and 4 mS/m were used in the enclosed plots. This decision is somewhat arbitrary as is the resulting location, size and shape of the delineated conductivity zones.

6. In these soils, the use of GPR is considered inappropriate for most applications. However, processed radar profiles appear suited to the evaluation of traffic pans. Amplitude anomaly maps were used to distinguish and plot linear features that are elongated in an east to west direction and parallel with the direction of tillage. These features are believed to be related to soil tillage and compaction.

Recommendations:

1. The preparation of high-intensity soil maps for site-specific management is, and will remain, principally a private sector pursuit (Mausbach, 1993). However, the Soil Survey Division of the USDA-NRCS should provide standards, guidance, and oversight for the development of high-intensity soil survey maps. The resourcefulness in developing and testing standards for high-intensity soil surveys by the Soil Staff in Illinois is commended.

2. In order to provide continuous, geo-reference coverage of sites, GPS must be integrated with EMI. ArcView GIS has become accessible to many soil scientists and field offices. Integration of EMI and ArcView GIS techniques provides a more expedient and cost-effective method for soil mapping and alternative methods for displaying multiple data sets.

3. To maximize the efficiency of EMI, mobile operations, such as the Veris 3100 soil EC mapping system, are recommended for open farmlands. Hand carrying EMI instruments while walking over large sites is slow, labor intensive, and inefficient. It took me nearly a day to complete the survey of this 110-acre site. It took the Veris unit only a couple of hours to complete the same survey. Freeland and others (2002) recommend the use of mobile EMI surveys over pedestrian EMI surveys for larger survey areas and whenever the total number of observations exceeds 1600 data points. In open fields, mobile surveys results in larger amounts of data collected, more comprehensive coverage of sites, greater acquisition efficiency, and less operator fatigue. The National Soil Survey Center must develop a mobile platform for its EMI equipment.

4. Prior to the preparation of EMI maps, soil pits were excavated based on soil map unit delineations and tactile observations made by soil scientists. While these pits provided useful soil information, they did not correspond with EMI patterns. Additional sampling will be required to verify EMI interpretations. To reduce the number of excavations, field time and expenses, soil pits should be excavated after EMI maps

are prepared and interpreted.

5. There are twelve “Soil Project Sites” located across Illinois. Based on the results of this study, I recommend that this study be expanded and a similar investigation conducted on another Soil Project Site during my scheduled visit to Illinois on the week of 24 March 2003.

It was my pleasure to work again in Illinois and with members of your fine staff. A special thanks is extended to Dan Withers for the preparation of ArcView GIS images shown in this report.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
B. Ahrens, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
B. Hudson, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
R. McLeese, State Soil Scientist, USDA-NRCS, 2118 W. Park Court, Champaign, IL 61821
T. Neely, State Soil Scientist/MO Leader, 6013 Lakeside Blvd., Indianapolis, Indiana 46278
C. Olson, National Leader, Soil Investigation Staff, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
D. Rooney, Earth Information Technologies, Corporation, 2453 Atwood Ave, Madison, WI 53704
W. Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 974, Federal Building, Room 206, 207 West Main Street, Wilkesboro, NC 28697

Background:
The availability of computers, global positioning systems (GPS), geographical information systems (GIS), and geophysical tools are changing the way we map soils. Over the last decade, these technologies have fostered the proliferation of high-intensity yield and soil maps and the rapid expansion of site-specific management or site-specific farming. The integration of these technologies has spurred the use of yield maps that show patterns of crop response and the effects of variable rate applications. While yield maps show the effects of site-specific management, they do not explain the factors that cause the within-field variability. In order to better understand the factors that influence yields, more detailed and accurate soil maps are needed that show the "cause and effect" relationship between soil physical and chemical properties and crop yields.

Standard soil surveys prepared by the USDA are intended for multipurpose land uses and describe the variability of soils at scales of 1:12,000 to 1:31,680 (Soil Survey Division Staff, 1993). Standard soil surveys are not prepared at an appropriate scale to show the variability of soils and landscapes that are needed for more site-specific interpretations (Fenton and Lauterbach, 1999). Standard soil surveys use soil map units that contain similar and contrasting inclusions. The amount, size, and location of inclusions vary with each delineation. Because of scale limitations, areas of similar and contrasting soils are not specifically located nor shown on soil maps (Robert, 1992). While not intended for site-specific management, standard soil surveys are readily available, and do provide useful spatial and interpretive information on soils for soil-specific management (Robert, 1992). Bouma and others (1999) noted, "Standard soil surveys, their databases, and sampling protocols can provide valuable information for site-specific management, even though they do not reflect soil variability to the level of accuracy needed for precision management." While these authors endorse standard soil survey sampling techniques, they strongly urge the collection of additional data designed specifically for site-specific management.

The relationships among crop yields, soil properties, and soil map units are exceedingly complex and have not been adequately defined for site-specific management (Illinois Soil Survey Staff, 1999). For site-specific management, soil functional classifications based on dynamic hydraulic and nutrient regimes show better agreement with crop response than traditional taxonomic classifications (Van Alphen and Stoorvogel, 2000). Many soil properties (i.e., texture, structure, depth, drainage, and topography) assessed and mapped in traditional soil surveys are relevant to crop yields and management (Illinois Soil Survey Staff, 1999). However, chemical properties are important to crop growth and generally have poor correlation with soil map units (Illinois Soil Survey Staff, 1999).

Site-specific management and high-intensity soil surveys require soil maps that are prepared at more appropriate scales (1:6000 or larger) and show in greater detail the variability of soils and soil properties across units of management. For site-specific management, map units should be consociations and contain no dissimilar soils (Roberts, 1992). Compared with standard soil surveys, soil maps for site-specific management are prepared at a higher intensity of field study, and contain more homogeneous map units that are delineated at higher level of resolutions.

The preparation of high-intensity soil maps for site-specific management is, and will remain, principally a private sector pursuit (Mausbach, 1993). However, the Soil Survey Division of the USDA-NRCS should provide standards, models, guidance, and oversight for the development of high-intensity soil survey maps. The preparation of high-intensity soil maps is a formidable task. Unless alternative field methods are developed, high intensity soil maps will be expensive, time-consuming, and labor-intensive to prepare. Alternative methods are needed to complement traditional soil survey techniques, provide more detailed information, and improve the assessment of soil properties. To be effective, these methods must be fast, accurate, relatively inexpensive, and capable of characterizing soil variability at a level of resolution that is commensurate with the scale of intended use (Jaynes et al., 1995).

Alternative methods for mapping and examining soils are being evaluated by the USDA-NRCS. Continuous profiling, towed-array resistivity units and electromagnetic induction meters are two geophysical tools that are being used for high intensity soil surveys and site-specific management. Because of their speed and ease of use, these geophysical methods have significant advantages over conventional soil survey techniques. The efficiency of geophysical tools fosters the collection of larger data sets than is possible with conventional soil survey techniques. Because of the larger number of observations, maps prepared from towed-array resistivity systems and electromagnetic induction meters can provide higher levels of resolution than soil maps prepared with conventional methods (Jaynes, 1995).

Towed-array resistivity systems and electromagnetic induction meters measure the apparent conductivity of soils. Some, especially those in the private sector with business interests, believe that maps prepared from apparent conductivity data provide a “more accurate measurement of changes in .. soil type” and a “better way to draw soil boundaries and create management zones by soil type” than USDA soil surveys (Olson, 2000). Others are more cautious and warn that apparent conductivity maps are “telling you different things in different locations” and “to understand the readings you need to understand your soil and agronomic conditions” (Olson, 2000). Some have found that spatial patterns of apparent conductivity correspond well with the soil patterns shown on soil survey maps, and recommend the use of apparent conductivity maps as a substitute for soil survey maps (Jaynes, 1995).

The last decade has witness rapid technological advancements that have cause some confusion as to the standards that should be used for high intensity soil surveys. Many are perplexed as to the appropriate integration of GIS, GPS, and geophysical methods with traditional methods in standard and high-intensity soil surveys. With the assistance of the Earth Information Technologies, Corporation (Earth IT), tools and field procedures to map, inventory, and analyze soil resources were assessed on a “Soil Project Site” in LaSalle County, Illinois.

Study Site:
The study site is located in the western half of Section 35, Township 32 N., Range 1 E., about 1 mile southwest of Tonica in La Salle County. Interstate Highway 39 bound the site on the east. At the time of the survey, the northern half of the study site was in corn stubble and the southern half was in various forms of fall tillage. The site is topographically diverse with slopes that range from 0 to 10 percent. Two intermittent drainages cross the study site from west to east.

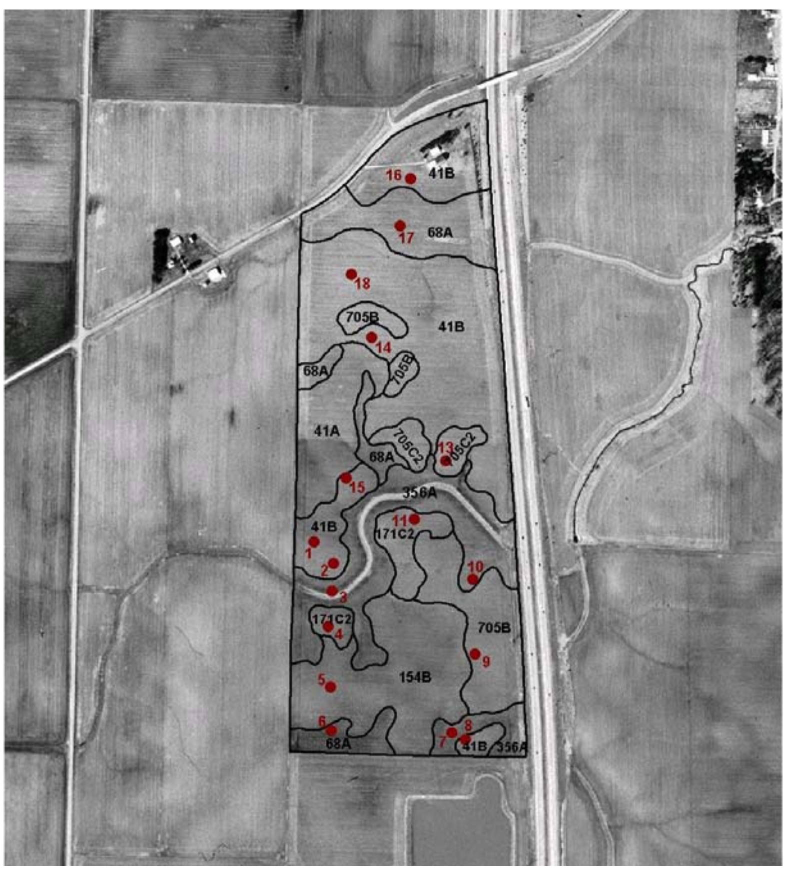

Figure 1. A high-intensity soil map of the study site located in La Salle County. The map shows the location of soil sampling sites (red numbers) used to document the survey.

The Illinois NRCS soil staff recently completed an order-one soil survey of this 110-acre site (see Figure 1). Figure 1 shows the soil delineations, map unit symbols, and the locations of eighteen soil-sampling sites (in red) used to characterize the site. This high intensity soil survey identified eight soil map units (Table 1). Major soils identified within the study site are Buckhart, Catlin, Elpaso, Flanagan, Muscatine, and Sable. These soils formed in loess overlying loamy, calcareous till. The very deep, moderately well drained Buckhart and Catlin soils are on uplands of ground moraines. Buckhart soil is very deep and Catlin soil is deep over loamy, calcareous till. Buckhart and Catlin soils are members of the fine-silty, mixed, superactive, mesic Oxyaquic Argiudoll family. The very deep, somewhat poorly drained Flanagan and Muscatine soils are on uplands. Flanagan is deep and Muscatine is very deep over loamy, calcareous till. Flanagan is a member of the fine, smectitic, mesic Aquic Argiudoll family. Muscatine is a member of the fine-silty, mixed, superactive, mesic Aquic Hapludoll family. The poorly drained Elpaso soil is deep over till, and has been mapped along intermittent drainage channels in the southern part of the study site. Elpaso is a member of the fine-silty, mixed, superactive, mesic Typic Endoaquoll family. The very deep, poorly drained Sable soil formed in loess, and has been mapped along poorly defined drainage channel across the study site. Sable is a member of the fine-silty, mixed, superactive, mesic Typic Endoaquoll family.

Table 1. Soil Legend

Symbol	Map Unit Name
41A	Muscatine silt loam, 0 to 2 percent slopes
41B	Muscatine silt loam, 2 to 5 percent slopes
68A	Sable silty clay loam, 0 to 1 percent slopes
154B	Flanagan silt loam, 2 to 5 percent slopes
171C2	Catlin silt loam, 5 to 10 percent slopes, eroded
356A	Elpaso silty clay loam, 0 to 1 percent slopes
705B	Buckhart silt loam, 2 to 5 percent slopes
705C2	Buckhart silt loam, 5 to 10 percent slopes, eroded Muscatine

Field Procedures:

The Veris 3100 soil EC mapping system was towed behind a 4WD vehicle. Measurements were continuously recorded and geo-referenced with a GPS receiver. An observation (two apparent conductivity measurements (shallow and deep) with coordinates) is recorded every second. By varying the speed of advance, the number and density of observation points can be varied. Moving across the field at speeds of about 5 mph, the Veris 3100 implement recorded 4060 geo-referenced observations in about 1.1 hours of recording time. This procedure resulted in a data density of about 37 observations per acre. During the survey, the Veris 3100 soil EC mapping system maintained good ground contact and no negative values were recorded. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes.

The EM38DD meter was operated in the continuous mode with measurements recorded at 1-sec intervals. The EM38DD was held about 3 inches above the ground surface with its long axis parallel to the direction of traverse. Following the tracks of the Veris 3100 implement and walking at a fairly brisk and uniform pace, the EM38DD meter recorded 11931 geo-referenced measurements in about 3.3 hours of recording time. The actual time of the pedestrian survey was over 6 hours as the operator required periods for rest, data entry, and equipment adjustments at the end of each traverse. Because of the relatively slow speed of advance, the number of EM38DD observations was too closely spaced. The close spacing of observations along traverse lines resulted in noticeable spatial aliasing of the data. Spatial aliasing was reduced by using every other data point (5965 observations). This procedure resulted in a data density of about 54 observations per acre. The meter's measurement stability, caused by changes in air temperature and instrument drift, was monitored over the course of the survey and found to be negligible (< 1 mS/m). Some negative values of apparent conductivity were recorded with the EM38DD meter. Prior to plotting, the EM38DD data were *zero adjusted*. Zero adjustment results in the lowest measurement being made equal to zero and all other data being adjusted upwards by the same number used to make the lowest measurement equal to zero.

For each map unit, a typifying soil was located and sampled with a backhoe. A 30 by 30 m grid was established around each sample site and a detailed EMI survey was conducted with the EM38DD meter. The name of the soil map unit was used to identify each grid site. Survey procedures were simplified to expedite fieldwork. Two parallel 30-m lines, which were spaced 30-m apart, defined the east and west boundaries of the grid. Along each line, survey flags were inserted in the ground at intervals of 2-m. These flags served as grid line end points and provided ground control. The origin (0, 0 m) of each grid was located in the southwest corner of each grid. Walking at a fairly uniform pace between similarly numbered flags on the two opposing parallel lines in a back and forth pattern across each grid area completed a survey. For each traverse line, software was used to adjust the location of each measurement to provide a uniform interval between the observation points.

Results:

Within the study site, apparent conductivity ranged from 0 to 65 mS/m. With both instruments, apparent conductivity increased and became more variable with increasing penetration depths. This vertical trend can be attributed to the comparatively low clay and moisture contents of the surface layers, the higher clay and water contents of the subsoil, and the increase in free carbonates in the lower part of the solum and the substratum.

With the Veris 3100 soil EC mapping system, apparent conductivity averaged 14.8 mS/m and 21.4 mS/m for the shallow (0 to 30 cm) and deep (0 to 90 cm) measurements, respectively. For the shallow measurements, one-half the observations had values of apparent conductivity between 12.1 and 16.4 mS/m. For the deep measurements, one-half the observations had values of apparent conductivity between 16.5 and 24.2 mS/m. With the EM38DD meter, apparent conductivity averaged 13.3 mS/m and 22.8 mS/m in the horizontal and vertical dipole orientations, respectively. In the shallower-sensing, horizontal dipole orientation (0 to 0.75 m), one-half the observations had values of apparent conductivity between 10.6 and 15.6 mS/m. In the deeper-sensing, vertical dipole orientation (0 to 1.5 m), one-half the observations had values of apparent conductivity between 20.0 and 24.8 mS/m.

Table 2. Apparent Conductivity Data collected with the Veris 3100 implement and the EM38DD meter.
(All values are in mS/m.)

	Veris Implement		**EM38DD**	
	Shallow	**Deep**	**Horizontal**	**Vertical**
Average	14.8	21.4	13.3	22.8
Standard Deviation	4.6	7.8	3.7	4.2
Minimum	4.6	7.3	0.0	13.0
Maximum	43.0	65.1	36.8	55.4
25% Quartile	12.1	16.5	10.6	20.0
75% Quartile	16.4	24.2	15.6	24.8

Figure 2 contains plots showing the spatial distribution of apparent conductivity collected with the Veris 3100 soil EC mapping system and the EM38DD meter. In each plot, colors have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 4 mS/m. To remove spurious measurements and lines, the *grid node editor* of Surfer 8 was used to blank or make slight changes (0.1 to 0.2 mS/m) to some of the measured EMI responses.

Figure 2 reveals that, over a majority of the study site, the soils are not strongly contrasting in terms of apparent conductivity. As shown in Figure 2, differences in the EMI device used and the measurement configuration, as well as the number and spacing of observations, result in slightly different amplitudes and spatial patterns. In this area of mostly low and moderate apparent conductivity and fairly broad gradients, it would be unwise to attribute large variations in soils or soil properties into the spatial patterns. For data collected with the Veris 3100 soil EC mapping system and the EM38DD meter and for comparable depth intervals, general patterns of apparent conductivity are reasonably similar. However, specific patterns do vary with instrument and measurement configuration.

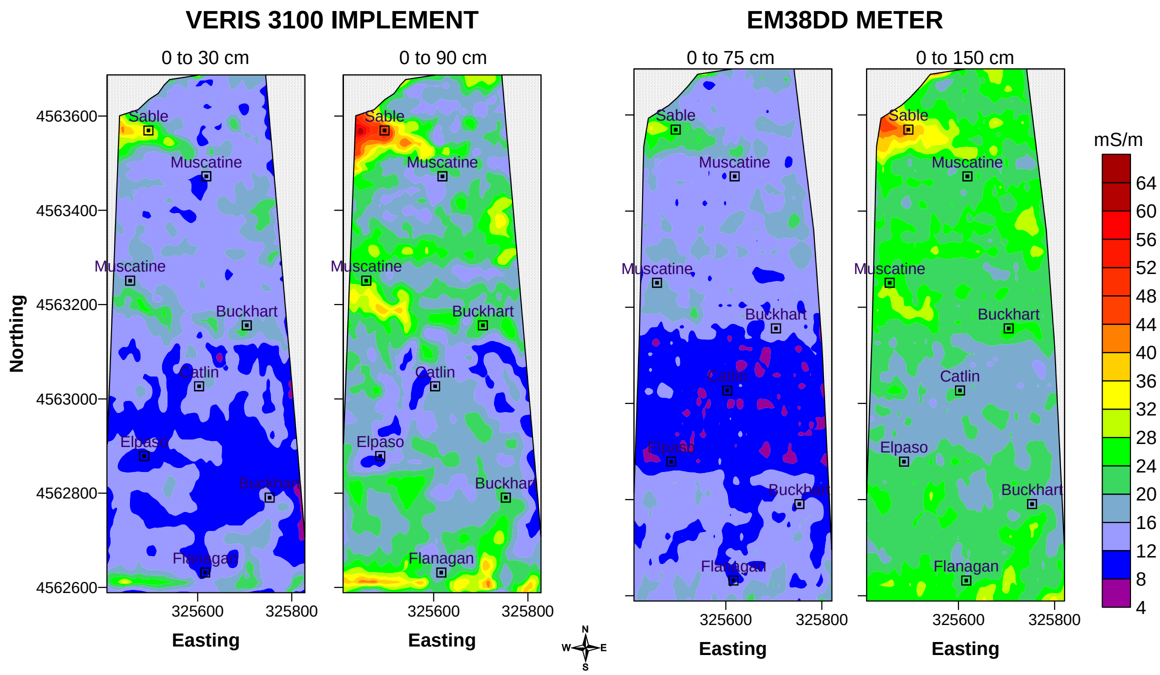

Figure 2. Spatial patterns of apparent conductivity measured with the Veris 3100 soil EC mapping system (two, left-hand plots) and the EM38DD meter (two, right-hand plots).

In Figure 2, the locations of eight soil pits that were excavated and described during this survey are shown in each plot. Each pit is labeled with the soil series name. A small (30 x 30 m) grid was established around each pit and a detailed EMI survey was completed with the EM38DD meter. The purpose of these detailed surveys was to provide high resolution EMI data in the areas of the soil pits. This procedure helps to insure the efficiency and effectiveness of the sampling and mapping procedure.

For the majority of the detail grid sites, apparent conductivity was relatively invariable with standard deviations within accepted survey and instrument errors (Sudduth et al., 2001). In a majority of the plots, spatial patterns appear elongated in an east to west direction. As this was also the direction of EMI traverse and tillage, these features are believed to be, in part, a survey (height of meter above ridges or furrows on the ground surface) or management (soil compaction) artifact.

Figure 3 contains plots of apparent conductivity near the two Buckhart soil pits (see Figure 2). The left- and right-hand plots show data collected in an area of Buckhart silt loam, 2 to 5 percent slopes (map unit 705B), and Buckhart silt loam, 5 to 10 percent slopes, eroded (map unit 705C), respectively. The upper and lower plots show apparent conductivity patterns collected with the EM38DD meter in the shallower-sensing horizontal and the deeper-sensing vertical dipole orientations, respectively. In each plot the isoline interval is 3 mS/m. Distances are in meters.

In both areas of Buckhart soil, apparent conductivity was relatively low and increased slightly with increasing depth (measurements obtained in the vertical dipole orientation are greater than measurements obtained in the horizontal dipole orientation). Apparent conductivity was slightly higher in the more strongly sloping and eroded area of map unit 705C than in the more gently sloping area of map unit 705B. This difference is attributed to a shallower subsoil and a profiled soil column with a higher averaged clay content in areas of map unit 705C.

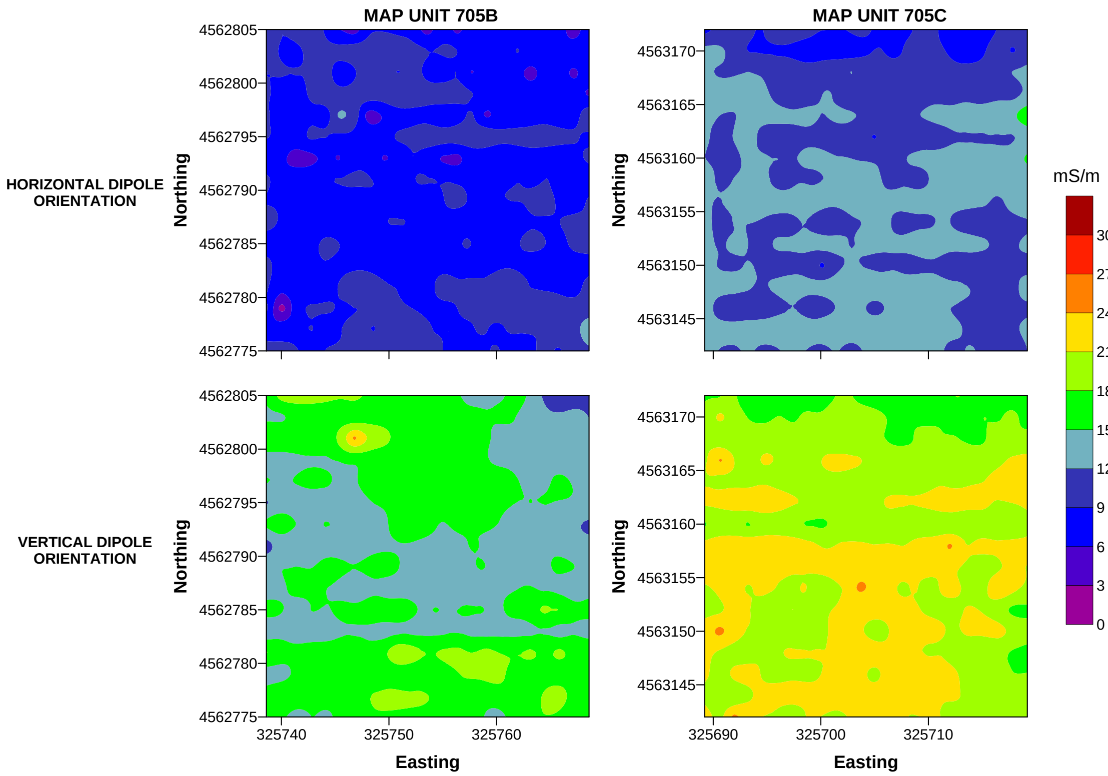

Figure 3. Spatial patterns of apparent conductivity in areas of Buckhart silt loam.

In areas of Buckhart silt loam, 2 to 5 percent slopes, based on 364 observations, apparent conductivity averaged 8.5 and 15.4 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 1.25 to 14.3 mS/m with a standard deviation of 1.59 mS/m. One half of the observations had an apparent conductivity between 7.6 and 9.6 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 10.2 to 25.0 mS/m with a standard deviation of 1.85 mS/m. One half of the observations had an apparent conductivity between 14.2 and 16.5 mS/m.

In areas of Buckhart silt loam, 5 to 10 percent slopes, eroded, based on 368 observations, apparent conductivity averaged 11.7 and 20.3 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 5.7 to 17.2 mS/m with a standard deviation of 1.65 mS/m. One half of the observations had an apparent conductivity between 10.8 and 12.9 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 15.2 to 25.1 mS/m with a standard deviation of 1.90 mS/m. One half of the observations had an apparent conductivity between 19.1 and 21.7 mS/m.

Figure 4 contains plots of apparent conductivity near the two Muscatine soil pits (see Figure 2). The left- and right-hand plots show data collected in an area of Muscatine silt loam, 0 to 2 percent slopes (map unit 41A), and Muscatine silt loam, 2 to 5 percent slopes (map unit 41B), respectively. The upper and lower plots show apparent conductivity patterns collected with the EM38DD meter in the shallower-sensing horizontal and deeper-sensing vertical dipole orientations, respectively. In each plot the isoline interval is 3 mS/m. Distances are in meters.

In both areas of Muscatine soil, apparent conductivity was relatively low to moderate and increased slightly with increasing depth (measurements obtained in the vertical dipole orientation are greater than measurements obtained in the horizontal dipole orientation). No obvious difference in apparent conductivity was discernible between the two Muscatine map units.

In areas of Muscatine silt loam, 0 to 2 percent slopes, based on 414 observations, apparent conductivity averaged 14.2 and 18.1 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 7.3 to 21.4 mS/m with a standard deviation of 2.13 mS/m. One half of the observations had an apparent conductivity between 12.8 and 15.8 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 13.0 to 26.6 mS/m with a standard deviation of 2.21 mS/m. One half of the observations had an apparent conductivity between 16.4 and 19.3 mS/m.

In areas of Muscatine silt loam, 2 to 5 percent slopes, based on 414 observations, apparent conductivity averaged 12.4 and 16.7 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 6.8 to 18.0 mS/m with a standard deviation of 2.19 mS/m. One half of the observations had an apparent conductivity between 10.7 and 13.8 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 10.7 to 24.2 mS/m with a standard deviation of 2.51 mS/m. One half of the observations had an apparent conductivity between 14.8 and 18.5 mS/m.

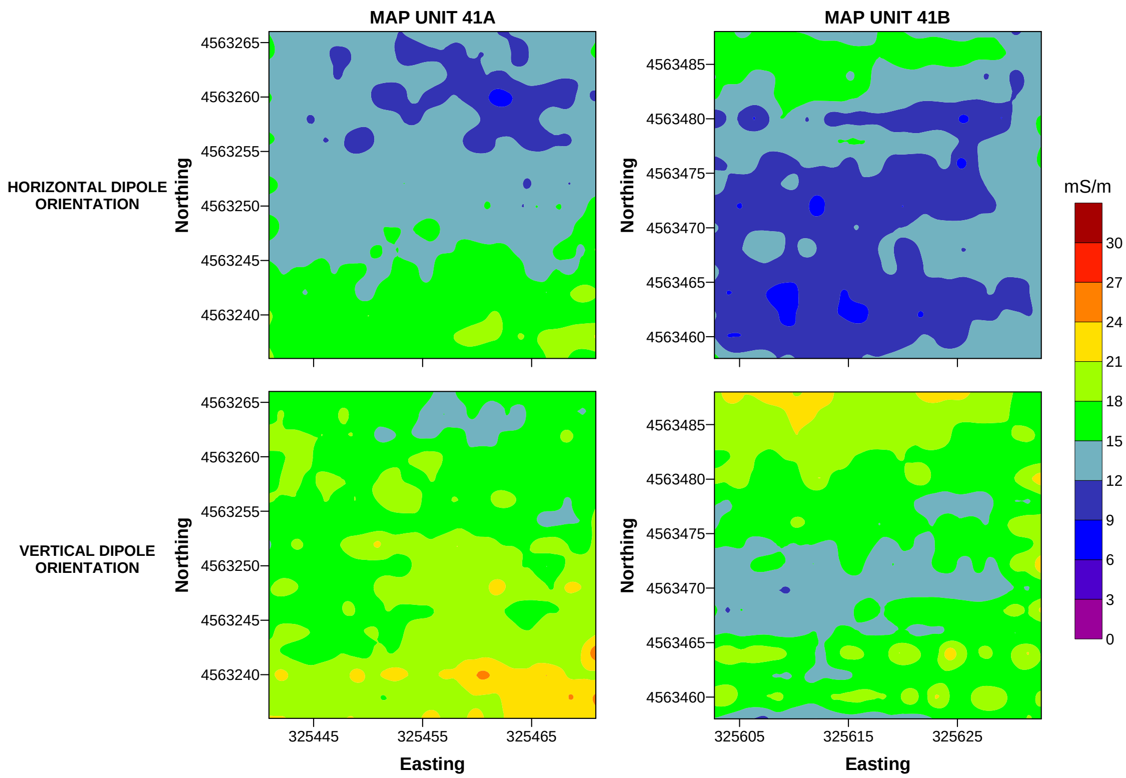

Figure 4. Spatial patterns of apparent conductivity in areas of Muscatine silt loam.

Figure 5 contains plots of apparent conductivity measured near the Catlin and Flanagan soil pits (see Figure 2). The left- and right-hand plots show data collected in an area of Catlin silt loam, 5 to 10 percent slopes, eroded (map unit 171C2), and Flanagan silt loam, 2 to 5 percent slopes (map unit 154B), respectively. The upper and lower plots show apparent conductivity patterns collected with the EM38DD meter in the shallower-sensing horizontal and deeper-sensing vertical dipole orientations, respectively. In each plot the isoline interval is 3 mS/m. Distances are in meters. Though some spatial patterns appear elongated in an east to west direction, others, especially in the vertical dipole orientation, do not and appear random.

Apparent conductivity is unexpectedly similar between these two seemingly dissimilar map units. The mapped area of Catlin soil is more strongly sloping and eroded than the more gently sloping area of Flanagan soil. Flanagan and Catlin soils are taxonomically dissimilar. Flanagan soil has a fine control section and is somewhat poorly drained. Catlin soil has a fine-silty control section and is moderately well drained. However, the two map units are indistinguishable with EMI. Here is an example of ostensibly dissimilar soils producing similar EMI response. It may also be an example of equivalence; where changes in one or more parameters (i.e. clay, moisture, and/or soluble salt contents) offset the affects of another parameter on the EMI response. A practical limitation of all geophysical interpretations is that there are often several possible interpretations that could explain the results.

Equivalence illustrates the ambiguity that can exist in interpretations. It also helps to emphasize the role that soil scientists play in determining which interpretation, of all the possible interpretations, is the one most consistent with the soil and soil properties of a particular area.

In this area of Catlin silt loam, 5 to 10 percent slopes, eroded, based on 364 observations, apparent conductivity averaged 8.0 and 14.3 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 0.4 to 13.0 mS/m with a standard deviation of 1.67 mS/m. One half of the observations had an apparent conductivity between 6.9 and 9.0 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 10.7 to 19.5 mS/m with a standard deviation of 1.59 mS/m. One half of the observations had an apparent conductivity between 13.2 and 15.3 mS/m.

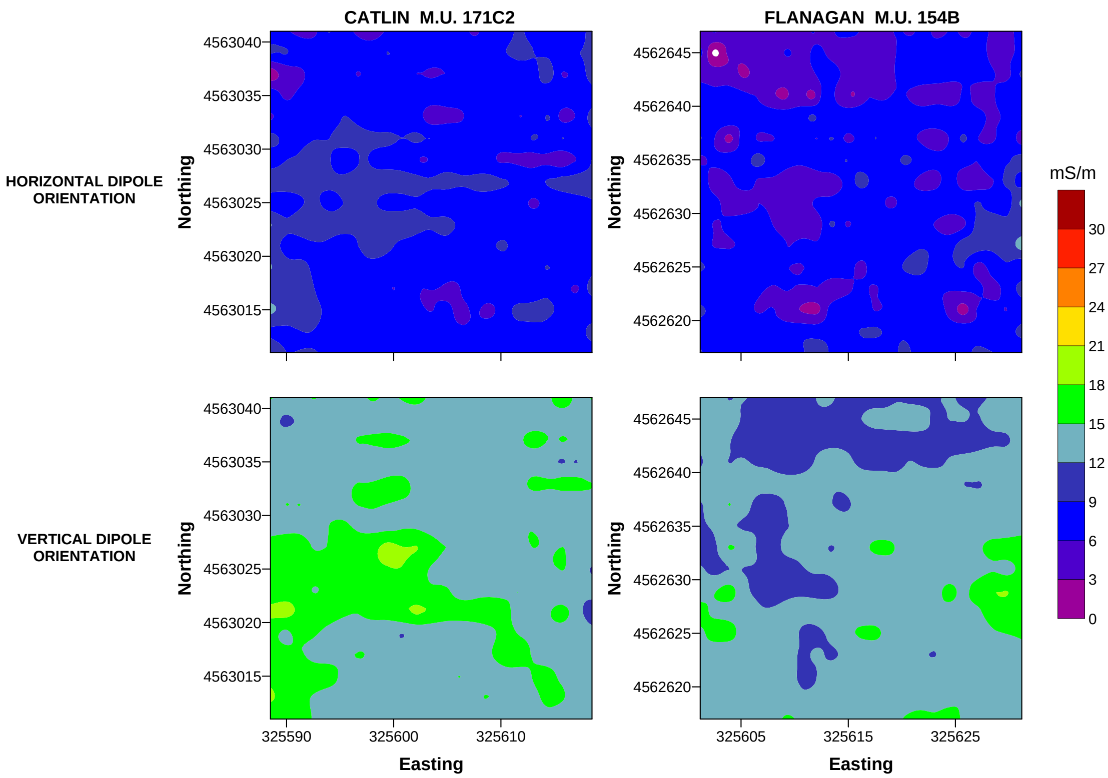

Figure 5. Spatial patterns of apparent conductivity in areas of Catlin and Flanagan silt loams.

Flanagan is the only fine textured soil recognized in the study site. However, areas of Flanagan soil had some of the lowest and least variable apparent conductivity measurements. In this area of Flanagan silt loam, 2 to 5 percent slopes, based on 371 observations, apparent conductivity averaged 6.8 and 13.0 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from –1.8 to 13.5 mS/m with a standard deviation of 1.98 mS/m. One half of the observations had an apparent conductivity between 5.6 and 8.0 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 9.6 to 18.1 mS/m with a standard deviation of 1.47 mS/m. One half of the observations had an apparent conductivity between 12.0 and 13.9 mS/m.

Figure 6 contains plots of apparent conductivity measured around the Elpaso and Sable soil pits (see Figure 2). The left- and right-hand plots show data collected in an area of Elpaso silty clay loam, 0 to 1 percent slopes (map unit 356A), and Sable silty clay loam, 0 to 1 percent slopes (map unit 68A), respectively. The upper and lower plots show patterns of apparent conductivity collected with the EM38DD meter in the shallower-sensing horizontal and deeper-sensing vertical dipole orientations, respectively. In each plot the isoline interval is 3 mS/m. Distances are in meters. Though some spatial patterns appear elongated in an east to west direction, others do not and appear random.

These were the two lowest-lying grids located within the study site. The Sable site was the wettest; the Elpaso site was surprisingly dry. Both sites were drained.

In this area of Elpaso silty clay loam, 0 to 1 percent slopes, based on 387 observations, apparent conductivity averaged 8.3 and 12.0 mS/m in the horizontal and vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from 4.0 to 13.2 mS/m with a standard deviation of 1.49 mS/m. One half of the observations had an apparent conductivity between 7.2 and 9.3 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 7.8 to 17.5 mS/m with a standard deviation of 1.68 mS/m. One half of the observations had an apparent conductivity between 10.8 and 13.0 mS/m.

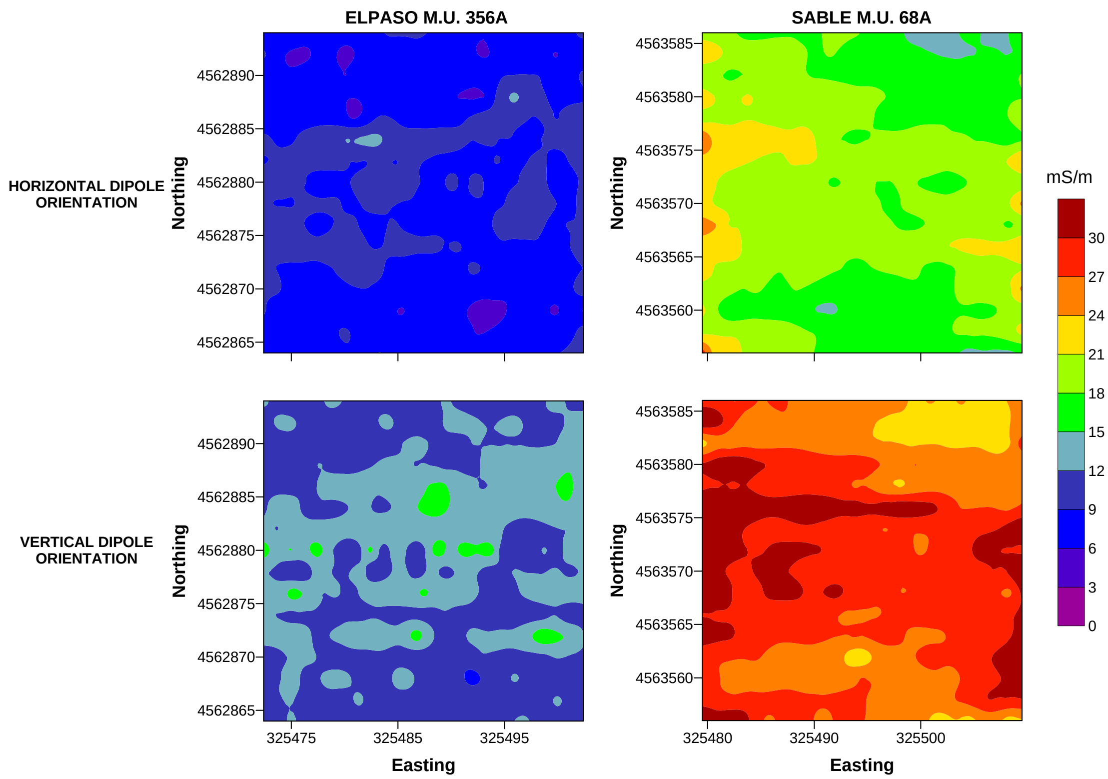

Figure 6. Spatial patterns of apparent conductivity in areas of Elpaso and Sable silty clay loams.

In this area of Sable silty clay loam, 0 to 1 percent slopes, based on 367 observations, apparent conductivity averaged 18.8 and 27.7 mS/m in the horizontal and vertical dipole orientations, respectively. This was the wettest grid area. As would be expected, it also had the highest apparent conductivity. In the horizontal dipole orientation, apparent conductivity ranged from 13.6 to 28.8 mS/m with a standard deviation of 2.20 mS/m. One half of the observations had an apparent conductivity between 17.3 and 20.1 mS/m. In the vertical dipole orientation, apparent conductivity ranged from 21.6 to 36.2 mS/m with a standard deviation of 2.66 mS/m. One half of the observations had an apparent conductivity between 25.8 and 29.5 mS/m.

Discussion:

Interpretations of EMI data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. EMI integrate the bulk physical and chemical properties for a defined penetration depth into a single value. For each soil, intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a characteristic range of apparent conductivity.

Results of an EMI survey are often site-specific. In all EMI investigations, substantial efforts must be expended toward understanding the site-specific relationship between apparent conductivity and the factors that contribute to this measurement. These efforts require the use of traditional soil survey and sampling techniques. Generally, results of EMI surveys are most successful in areas where subsurface properties are reasonably homogeneous and one factor (e.g. salt, clay, or water content) exerts an overriding influence over the apparent conductivity. In these areas, variations in apparent conductivity can be directly related to changes in the dominant factor.

Results from EMI surveys often exhibit a reasonable correspondence with and appear to distinguish different soil map units and map unit inclusions (Hoekstra et al., 1992; Jaynes et al., 1995; Jaynes, 1995; Doolittle et al., 1996). Maps of apparent conductivity often provided reasonable depictions of soil maps. Jaynes (1995) found three ways EMI could be used for soil mapping: 1) to provide a reconnaissance map to site future sampling, 2) to refine maps of sparsely sampled soil properties that can be related to EMI response, and 3) as a direct surrogate measure of as soil property.

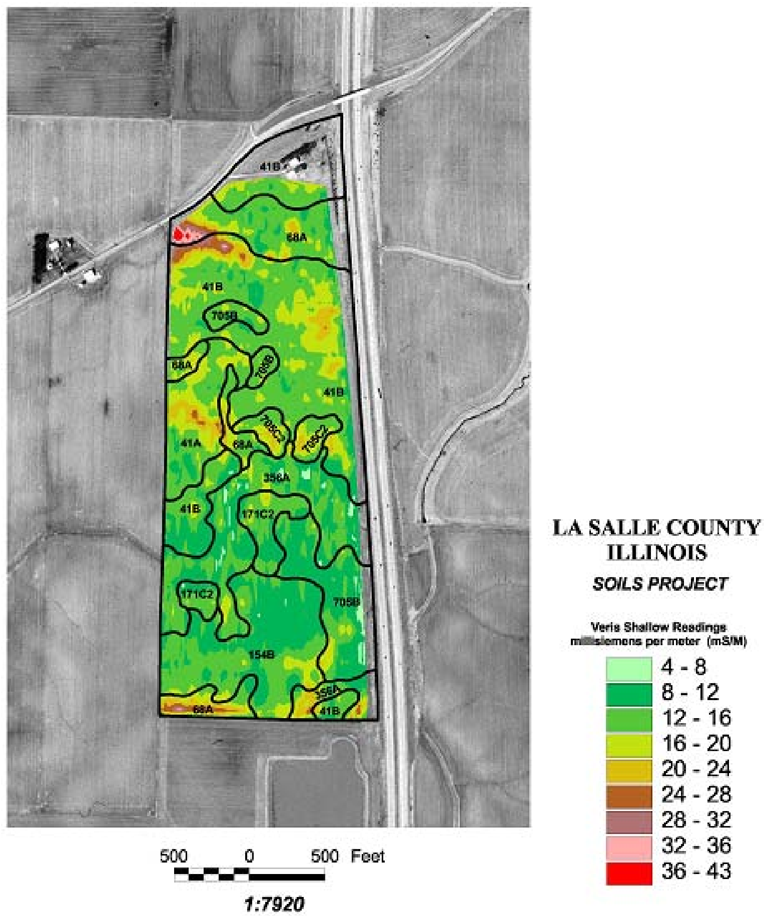

Figure 7. High-intensity soil map overlaid on map of apparent conductivity as measured with the shallow measurements of the Veris 3100 soil EC mapping system.

Figure 7 is an ArcView GIS image of the high-intensity soil map and an apparent conductivity map (Veris 3100 soil EC mapping system; shallow measurement) that have been overlain on an orthophoto of the study site. In Figure 7, the apparent conductivity interval is 4 mS/m. The map of apparent conductivity represents variations in soil properties within the upper 30 cm of the soils.

As evident in Figure 7, patterns of apparent conductivity do not conform to soil map units, but generally cross and show a disregard for soil boundaries. A large portion (70 %) of the study site has surface layers with apparent conductivity between 8 and 16 mS/m. Apparent conductivity appears to be associated with changes in the soil moisture of the surface layers. With the exception of the Sable map units, the surface layers were uniformly moist.

Moister and heavier textured surface layers help to explain the higher apparent conductivity in areas of Sable soil. Areas of Sable soil are distinguishable by their higher (> 20 mS/m) apparent conductivity. However, large portions of the Sable delineations have surface layers with conductivities of 12 to 16 mS/m. These areas are presumed to have drier and/or lighter textured surface layers. In areas of Buckhart, Catlin, and Muscatine map units, included areas of higher (> 16 mS/m) apparent conductivity may correspond with more sloping or convex surfaces where the silt loam surface layers have been eroded and the finer textured subsoil is closer to the soil surface. Overlaying the conductivity map on a three-dimensional surface plot of the study site would help to associate topography with apparent conductivity in areas of Buckhart, Catlin, and Muscatine soils.

The major soils identified and mapped within the study site (Buckhart, Catlin, Elpaso, Flanagan, Muscatine, and Sable) formed in loess overlying loamy calcareous till. Catlin, Elpaso, and Flanagan soils are deep (40 to 60 inches) to till; Buckhart, Muscatine, and Sable soils form entirely in loess. The minimum depth to till is beyond the effective penetration depths of the Veris 3100 soil EC mapping system and the EM38DD meter in the horizontal dipole orientation. For these soils, the minimum depth to till exceeds the maximum sensitivity depth of the EM38DD meter in the vertical dipole orientation. It is doubtful that the till is discerned with these EMI devices or even provides a measurable response. Though belonging to different soil drainage classes, many of the soils within the site have been artificially drained, and with the exception of Sable, were collectively dry at the time of this investigation. Though belonging to either the fine-silty or fine soil textural classes, differences in the clay contents were slight. With the exception of the wetter areas of Sable soil and some convex and eroded surfaces, apparent conductivity was relatively consistent across the study site.

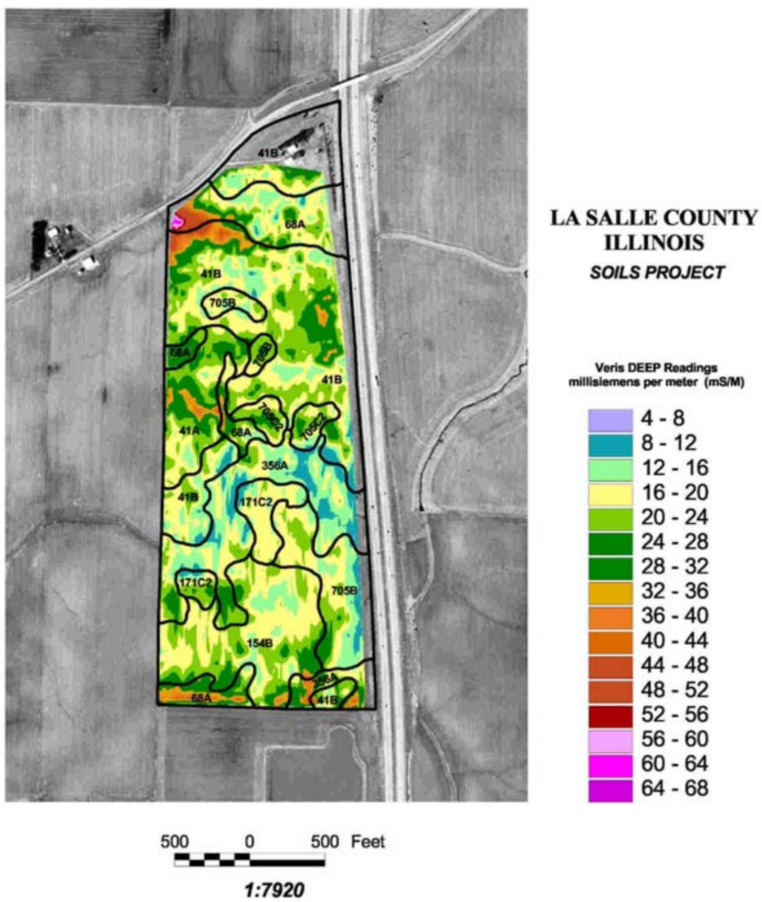

Figure 8. High-intensity soil map overlaid on map of apparent conductivity as measured with the deep measurements of the Veris 3100 soil EC mapping system.

Figure 8 is an ArcView GIS image of the high-intensity soil map and an apparent conductivity map (deep data measured with the Veris 3100 soil EC mapping system) that have been overlain on an orthophoto of the study site.

As the deep Veris measurements were used to construct this plot, patterns represent variations in soil properties within the upper 90 cm of the soils. The isoline interval on the apparent conductivity map is 4 mS/m. As evident in Figure 8, a large portion (53 %) of the study site has apparent conductivity between 16 and 24 mS/m. Spatial patterns of apparent conductivity appear to conform to some soil delineations. Major areas of high (> 32 mS/m) and low (8 to 12 mS/m) apparent conductivity closely match areas that have been mapped as Sable and Elpaso soils, respectively. However, for both soil map units, line placement appears to need slight adjustments. In addition, either areas of Sable soil appear to be over mapped or contain substantial areas of included soils. A large area of Elpaso silty clay loam, 0 to 1 % slopes, (map unit 356A) appears to conform with a sinuous pattern of low to moderate conductivity that extends across the central and southern portions of the study site. An arm of this unit also appears to extend southward along the southeast margin of the site. This area had been mapped as Buckhart silt loam, 2 to 5 percent slopes (map unit 705B). Based on results of the EMI survey additional soil borings should be made in areas of Elpaso soils to confirm cause(s) for the low conductivity and the map unit boundaries.

Kitchen and other (1998) comparing the results of three, order-one soil surveys of the same 88-acre field in central Missouri,
noted the problems in obtaining repeatable results using traditional soil survey methods. While similar patterns were observed, the three order-one soil surveys differed slightly in level of detail, soils mapped, and line placement (Fraisse et al., 2001). As with soil surveys, EMI surveys also will vary in level of detail and line placement. Different EMI sensors and survey designs often result in common similarities, but specific dissimilarities in spatial patterns. Spatial patterns of apparent conductivity are known to be temporally variable (mostly related to changes in soil moisture and temperature). However, broad spatial patterns of apparent conductivity will generally remain consistent over time (Sudduth et al., 1999).

An advantage of geophysical tools is their capacity to collect a large number of measurements in a short period of time. This provides a greater density of measurement per unit area. Because of the greater number of observations, EMI survey typically result in a greater number of small and less continuous units than traditional soil surveys. This is both an asset and a drawback. As an asset, soil boundaries can be more closely *observed* throughout their entire lengths and line placement is more likely to correspond with changes in soil properties. In Figure 8, the need for adjusting the line placement for the areas of Sable soil (map unit 68A) and Elpaso soil (map unit 356A) are examples of the potential for using EMI to improve soil surveys. A drawback is that the large number of small insular units also includes areas formed from instrument, survey, or computational errors rather than from differences in soils and soil properties. This noise must be effectively dealt with prior to the presentation and interpretation of results. Within the study site, apparent conductivity was low to moderately variable (standard deviations of 3.7 to 7.8 mS/m). This necessitated the use of relatively narrow isoline intervals (3 or 4 mS/m) on the enclosed plots. As a consequence, in the enclosed plots, instrument and survey errors (generally < 3 mS/m) may have had a more pronounced effect on some spatial patterns. Most of the detailed plots in figures 3 to 6 contain spatial patterns that are extended in the direction of EMI traverse and tillage. These features represent unwanted noise that was introduced by survey flaws (varying the height of meter above the ground surface) and/or the impact of management (tillage or soil compaction).

In several studies, spatial patterns of apparent conductivity exhibit a reasonable correspondence with and appear to distinguish different soil map units (Jaynes et al., 1995; Jaynes, 1995; Doolittle et al., 1996). However, substantial efforts need to be expended toward understanding the site-specific relationship between apparent conductivity and the factors that contribute to this measurement. Geophysical interpretations are considered preliminary estimates of soils and soil properties. The results of all geophysical investigations are interpretive and do not substitute for direct soil borings. The use of geophysical methods can reduce the number of soil observations, direct their placement, and supplement their interpretations. The parameters that influence apparent conductivity need to be clarified and verified by ground-truth observations.

To maximize the efficiency of EMI, mobile operations, such as the Veris 3100 soil EC mapping system are recommended for open farmlands. Hand carrying EMI instruments while walking over a gridded site has been the most common method of surveying (Freeland at al., 2002). Grids are established by inserting survey flags in the ground at each grid intersection. These flagged position serve as observation points for EMI instruments. The operator walks along each grid line in a sequential fashion stopping at each survey flag to obtain EMI measurements in both dipole orientations. An alternative method uses synchronized measurements of GPS and EMI data as the operator walks across a site. The EMI and GPS data are recorded into a data logger and a mutual time stamp is used to merge the two data sets. This method can provide larger data sets, more continuous coverage of sites, and is less time-consuming as it does not require laying-out a grid and inserting survey flags in the ground. This method was employed with the EM38DD meter in this survey.

Pedestrian EMI surveys are labor intensive and impractical for surveying large management units. The use of field vehicles with EMI and GPS permits greater flexibility and the rapid surveying of large tracts of land (Freeland et al. 2002). Cannon and other (1994) reported that mobile EMI surveys increased productivity by a factor of five over traditional pedestrian surveys. Freeland and others (2002) recommend the use of mobile EMI surveys over pedestrian EMI surveys for larger areas or whenever the total number of observations exceeds 1600 data points. In open fields, mobile surveys results in larger amounts of data collected, more comprehensive coverage of sites, greater acquisition efficiency, and less operator fatigue. However, in many terrains, mobile EMI surveys are impractical and pedestrian surveys must be carried out.

The collection of EMI data does not require knowledge of soils or soil survey techniques. Lesser-trained technicians can collect EMI data. However, as illustrated at this site, an intensive sampling scheme is need to unravel the factors that are influencing the EMI response and a qualified soil scientist is required to properly interpret and correlate the data.

Ground-Penetrating Radar (GPR):

A GPR survey was conducted with the 400 MHz antenna in an area of Elpaso silty clay loam, 0 to 1 percent slopes. The purpose of this survey was to confirm whether GPR could be used to assess soil compaction and the development of traffic pans. A 10 by 10 meter grid was established near the location of the excavated Elpaso pit. Survey procedures were modified to facilitate the construction of 3-D images and the interpretation of near surface soil features. To construct three-dimensional displays, the imagery between adjoining radar profiles is interpolated. As a consequence, the quality and detail of a three-dimensional display will increase as the spacing between survey lines is decreased (Geophysical Survey Systems, Inc., 2001b). As a general rule, lines should be spaced so that the radar beams from adjacent lines overlap at the depth of interest (Geophysical Survey Systems, Inc., 2001b). Generally these lines should be closely spaced (0.5 to 1 m apart).

Radar traverse were conducted at 0.5 m intervals along 21, parallel, 10-m lines. Traverses were conducted in a south-north direction. This direction was orthogonal to the direction of tillage. Surveys were conducted by moving the 400 MHz antenna along the ground surface in a back and forth manner along grid lines that were parallel to the x-axis. Along each line, a measuring line, with marks spaced at 1-m intervals, was stretched between the end points. As the antenna was towed passed each mark, a vertical mark was impressed on the radar profile. The origin (X = 0, Y = 0) of the grid was located in the southeast corner of the survey area. Each line number refers to the y coordinate.

Interpretations:

Figure 9 is a representative radar profile from an area of Elpaso soil. A scale (in nanoseconds) is located along the left-hand side of the radar profile. This scale represents the two-way travel time of the radar pulse. For the upper part of the soil profile, with the 400 MHz antenna, the velocity of propagation was estimated to be about 0.10 m/ns (based on tabled values). Based on this velocity of propagation, a two-way travel time of 30 ns provides a maximum penetration depth of about 1.6-m. The segmented vertical lines at the top of the radar profile represent equally spaced (1 m) reference marks.

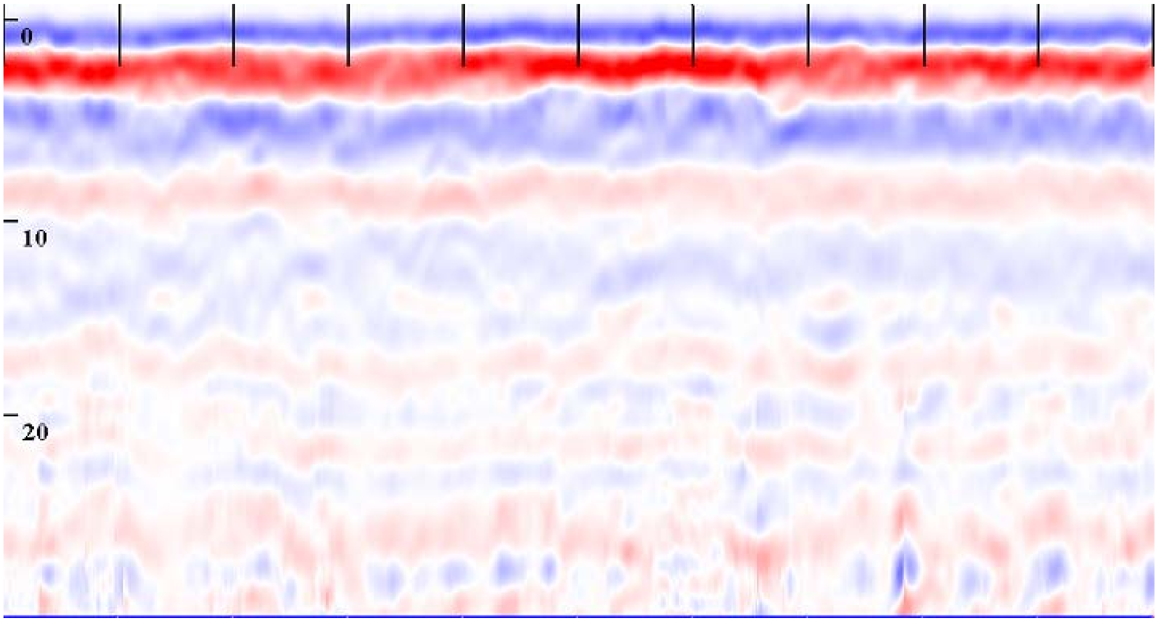

Figure 9. Representative radar profile from the study site.

The radar profile in Figure 9 is depth restricted and of poor interpretative quality. The radar profile is nondescript. Because of the high clay content and proportion of 2:1 expanding lattice clay minerals, Elpaso soil proved highly attenuating to GPR. Depths of signal penetration were restricted to the surface layers. Other than reverberated signals from higher-lying surface and near surface interfaces and background noise, no meaningful information is available below about 15 nanoseconds. The use of GPR in areas of Elpaso soils is inappropriate for most applications below a depth of about 25 to 50 cm. However, in this study we attempted to characterize the shallow traffic pan with GPR.

The 3D QuickDraw for RADAN Windows NT software program was used to prepare a plan-view and to analyze the distribution of reflected signal amplitudes within the survey site. Three-dimensional diagrams of the survey area were created from the 21 closely spaced, parallel radar profiles that were completed within the grid. The spacing between each transect was 0.5 m. Differences in signal amplitudes are analyzed in horizontal time-slices of the study site.

Figure 10 is an example of two time-slices of the survey site. These horizontal slices were made at selected time windows, which, assuming a 0.10 m/ns velocity of propagation, correspond with the soil surface (upper plot) and a depth of about 20 cm (lower plot).

In Figure 10, the origin is the southeast corner of the grid site and the X-axis (in foreground) extends in a north-south direction. Radar traverses were conducted parallel to the X-axis or in north and south directions. These amplitude anomaly maps are useful for recognizing and plotting subsurface features that are difficult to discern on individual radar profiles. Spatial patterns, especially those occurring at a depth of about 20 cm, appear linear and elongated in an east to west direction. As this corresponds with the direction of tillage, these linear features are believed to be related to soil tillage and compaction.

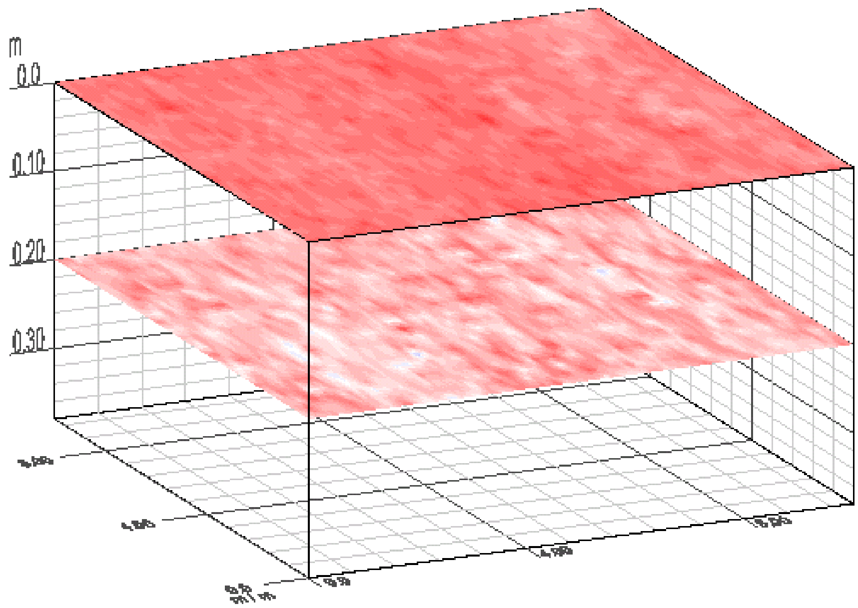

Figure 10. A 0-cm (upper plot) and a 20-cm (lower plot) time-slice of a cultivated area of Elpaso soil.

References

Bouma, J., J. Stoorvogel, B. J. van Alphen, and H. W. G. Booltink. 1999. Pedology, site-specific management, and the changing paradigm of agriculture research. Soil Sci. Soc. Am. J. 63: 1763-1768.

Cannon, M. E., R. C. McKenzie, and G. Lachapelle. 1999. Soil salinity mapping with electromagnetic induction and satellite-based navigation methods. Can. J. Soil Sci. 74: 335-343.

Daniels, D. J. 1996. Surface-Penetrating Radar. The Institute of Electrical Engineers, London, United Kingdom.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. 11-32 pp. IN: Reybold, W. U. and G. W. Peterson (eds.) Soil Survey Techniques, Soil Science Society of America. Special Publication No. 20.

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Fenton, T. E. and M. A. Lauterbach. 1999. Soil map unit composition and scale of mapping related to interpretations for precision soil and crop management in Iowa. 239-251 pp. IN: Robert, P. C., R. H. Rust, and W. E. Larson (Eds.) Proceeding of the 4th International Conference if Site-specific management. St Paul, MN, July 19-22, 1998. American Society of Agronomy. Madison, WI.

Fraisse, C. W., K. A. Sudduth, and N. R. Kitchen. 2001. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. Transaction of the ASAE 44(1): 155-166.

Freeland, R. S., R. E. Yoder, J. T. Ammons, and L. L. Leonard. 2002. Mobilized surveying of soil conductivity using electromagnetic induction. Applied Engineering in Agriculture 18(1): 121-126.

Geonics Limited. 2000. EM38DD ground conductivity meter: Dual dipole version operating manual. Geonics Ltd., Mississauga, Ontario.

Geophysical Survey Systems, Inc, 2001a. RADAN for Windows NT; User's Manual - Condensed. Manual MN43-132 Rev C. Geophysical Survey Systems, Inc., North Salem, New Hampshire.

Geophysical Survey Systems, Inc, 2001b. 3D QuickDraw for RADAN NT; User's Manual. Manual MN43-143 Rev B. Geophysical Survey Systems, Inc., North Salem, New Hampshire.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Illinois Soil Survey Staff. 1999. Standards and specifications for high intensity soil surveys for Agriculture in Illinois. USDA-Natural Resources Conservation Service in cooperation with the Illinois Soil Classifiers Association. Champaign, IL.

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

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1995. Yield mapping by electromagnetic induction. 383-394 pp. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Precision Management for Agricultural Systems. Minneapolis, MN. March 27-30, 1994. American Society of Agronomy, Madison, WI.

Kitchen, N. R., K. A. Sudduth, and T. S. Drummond. 1998. An evaluation of methods for determining site-specific management zones. 133-139 pp. IN: Proc. North Central Extension-Industry Soil Fertility Conference. Brookings, South Dakota. Potash and Phosphate Institute.

Morey, R. M. 1974. Continuous subsurface profiling by impulse radar. 212-232 pp. *IN:* Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, held at Henniker, New Hampshire. Aug. 11-16, 1974.

Mausbach, M. J., D. J. Lytle, and L. D. Spivey. 1993. Application of soil survey information to site specific farming. 57-68 pp. IN: Soil Specific Crop Management. Robert, P. C., R. H. Rust, and W. E. Larson (Eds.) ASA, CSSA, and SSSA. Madison, WI.

Olson, J. 2000. New soil maps spark change; Mapping electrical conductivity in soil shows soil-to-yield relationship. Farm Industry News, March 2000: 78-82.

Roberts, P. 1992. Characterization of soil conditions at the field level for soil specific management. Geoderma 60: 57-72.

Soil Survey Division Staff. 1993. Soil Survey Manual. US Department of Agriculture - Soil Conservation Service, Handbook No. 18, US Government Printing Office. Washington, DC, USA. p. 437.

Sudduth, K. A., N. R. Kitchen, and S. T. Drummond. 1999. Soil conductivity sensing on claypan soils: Comparison of electromagnetic induction and direct methods. 971-990 pp. IN: Robert, P. C., R. H. Rust, and W. E. Larson (Eds.) Proceeding of the 4th International Conference if Site-specific management. St Paul, MN, July 19-22, 1998. American Society of Agronomy. Madison, WI.

Sudduth, K. A., S. T. Drummond, N. R. Kitchen. 2001. Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. Computers and Electronics in Agriculture, 31: 239-264.

van Alphen, B. J., and J. J. Stoorvogel. 2000. A functional approach to soil characterization in support of site-specific management. Soil Sci. Soc. Am. J. 64: 1706-1713.

Veris Technologies. 1998. 3100 Soil EC Mapping System Operations Manual. Publication No. AN 1CM02-02. Veris Technologies, Salina, KS.