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

Subject: -- Geophysical Assistance --

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To: Roger A. Hansen
State Conservationist
USDA - NRCS
Parkade Center, Suite 250
601 Business Loop 70 West
Columbia, Missouri 65203

Purpose:
The purpose of this investigation was to evaluate the feasibility of using electromagnetic induction and towed array resistivity methods to help assess soil properties and determine the suitability of alluvial soils for rice production in Southeastern Missouri.

Participants:
H. Doyle Burch, Resource Conservationist, USDA-NRCS, New Madrid, MO
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Allan Johnson, Soil Scientist/Wetland Team Leader, USDA-NRCS, Jackson, MO
Steve Hefner, Resource Conservationist, USDA-NRCS, Dexter, MO
Sam Indorante, MLRA Project Leader, USDA-NRCS, Carbondale, IL
Paul Kremmel, Resource Analyst, USDA-NRCS, Edwardsville, IL
Matt McCauley, Zone Soil Scientist, USDA-NRCS, Benton, IL
Dennis Potter, Liaison Soil Scientist, USDA-NRCS, Columbia, MO
Clay Robertson, Resource Conservationist, USDA-NRCS, Dexter, MO

Activities:
All field activities were completed during the period of 15 to 18 November 1999.

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

The electromagnetic induction meters used in this study were the EM38 and the EM31 manufactured by Geonics Limited.[1] These meters are portable and require only one person to operate. McNeill (1980) and Geonics Limited (1998) have described principles of operation for the EM31 and the EM38 meters, respectively. No ground contact is required with these meters. The

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

depth of observation is "geometry limited" and is dependent upon intercoil spacing, coil orientation, and frequency. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter has a 1 m intercoil spacing and operates at a frequency of 14,600 Hz. It has theoretical observation depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical observation depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

A GEM300 multifrequency sensor, developed by Geophysical Survey systems, Inc., [2] was also used in this study. The GEM300 sensor is a newly developed EMI device. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.6 m). Won and others (1996) have described the use and operation of this sensor. With the GEM300 sensor, the depth of observation is considered "skin depth limited" rather than "geometry limited". The skin-depth represents the maximum depth of observation and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. The theoretical observation depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

The positions of observation points for the EM38 and EM31 meters were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[2] The receiver was operated in the continuous and the mixed satellite modes. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1983. Horizontal units were expressed in meters. The locations of all observation collected with the GEM300 sensor were processed and adjusted by the MAGMAP96 software program. [2]

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

After reviewing the computer simulations of each site, soil samples were collected at selected observation points. At each of these observation points, the soil was described to a depth of 100 cm. In addition, samples were collected in 25 cm intervals to a depth of 100 cm and shipped to the National Soil Survey Center for textural analysis. A total of 14 soil profiles were described (see Appendix A). Additional measurements were made with each geophysical device over the each of the sampled observation points.

Results:

1. Electrical resistivity and electromagnetic induction methods can be used to create detailed maps showing the spatial distribution of apparent conductivity across units of management. These methods measure vertical and lateral variations in values of apparent electrical resistivity or conductivity. These values are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used.

2. With the exception of Site 3, each device produced similar results. Though more intricate, spatial patterns of apparent conductivity conformed to mapped soil patterns. As these patterns appear to reflect differences in clay content, these devices can be used to help determine the suitability of management units for rice production. With knowledge of soil and reasonable sampling, variations in apparent conductivity can be associated with changes in soil types and soil properties within and across map units. At Site 3, field conditions produced poor ground contact for the Veris 3100 implements coulter-electrodes and erroneous measurements. At this site, closely similar and over lapping soil properties could explain the poor definition of map soil delineations with apparent conductivity measurements. Greater variations in soil properties were suspected to occur within than between the mapped soil delineations.

3. Based on casual observations made during the course of soil sampling, under existing soil moisture and temperature conditions, soils having apparent conductivity values less than 20 mS/m are considered marginal for rice. Apparent conductivity values less than 20 mS/m are associated with soils having low clay contents. However, more testing is needed to confirm this interpretation.

4. The Veris 3100 soil EC mapping system, a towed, multi-electrode resistivity unit, is a relatively inexpensive, versatile mapping tool that allows large open areas to be rapidly and comprehensibly surveyed. Because of these qualities, the Veris 3100 implement is considered an appropriate device for surveying large, open areas in the Missouri Bootheel and

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other agricultural areas within the Southern Mississippi River Valley Alluvium (MLRA 131). All data are geo-referenced and can easily be exported into plotting packages.

5. Compared with the Veris 3100 soil EC mapping system, the EM38 meter and the GEM300 sensor are more versatile, providing all season and terrain mapping potentials. These devices can be used during the "mud season" when fields are impassable to the Veris 3100 implement. These devices can also be used after seeding and crop emergence when the intrusive nature of the Veris 3100 implement is too destructive. The EM38 meter and the GEM300 sensor can be mounted on non-metallic booms, attached to GPS and laptop computers, and towed by ATVs across large, open fields (Davis, 1997; Dan Delea, GSSI, personal communication).

6. In this study, the GEM300 sensor was operated only in the vertical dipole orientation. When operated in the horizontal dipole orientation, this sensor is more sensitive to variations in soil properties within surface and near surface layers. Additional tests should be conducted with this sensor comparing the correlation of data collected in different dipole orientations with measured soil properties (i.e., clay content).

7. These geophysical tools will have immediate and beneficial applications for soil scientists involved with high intensity soil mapping projects, site assessments, and precision farming initiatives. These tools represent an expedient substitute or adjunct to traditional mapping techniques. The use of these geophysical tools should be more fully understood and explored by soil scientists and conservationists within this region.

8. A dilemma for field soil scientists using these methods will be to understand what these methods do and do not tell us. Soil scientist and conservationists will need to relate soils and soil properties to the spatial patterns appearing on computer simulations, select meaningful isoline intervals on computer simulations, and understand the limitations of these methods.

9. Geophysical interpretations are considered preliminary estimates of site conditions. 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. Interpretations should be verified by ground-truth observations.

It was my pleasure to work again in Missouri and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
H. Burch, Resource Conservationist, USDA-NRCS, New Madrid, MO
J. Culver, Acting Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
C. Ditzler, Director, Soil Quality Institute, USDA-NRCS, 2150 Pammel Drive, Ames, IA 50011
Charles Fultz, State Soil Scientist/MO Leader, USDA-NRCS, Room 3416 Federal Building, 700 West Capitol Avenue, Little Rock, AR 72201-3225
A. Green, Assistant State Conservationist, USDA-NRCS, Parkade Center, Suite 250, 601 Business Loop 70 West, Columbia, MO 65203
S. Hefner, Resource Conservationist, USDA-NRCS, 18450 Ridgeview Lane, Dexter, MO 63841
S. Indorante, MLRA Project leader, USDA-NRCS, 150 East pleasant Hill Road, Carbondale, IL 62901
R. McLeese, State Soil Scientist, USDA-NRCS, 1902 Fox Drive, Champaign, IL 61820
M. McCauley, Resource Soil Scientist, USDA-NRCS, 711 N. DuQuoin, Benton, Il 62812
L. Norfleet, Soil Scientist, Soil Quality Institute USDA-NRCS, 411 S. Donahue Drive, Auburn, AL 36832
D. Potter, Liaison Soil Scientist, USDA-NRCS, Parkade Center, Suite 250, 601 Business Loop 70 West, Columbia, MO 65203
H. Smith, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250

Background:

In Southeast Missouri, between 155,000 to 175,000 acres are planted annually to rice (Steve Hefner, personal communication). From 1997 to 1999, the Missouri Bootheel has experienced about a 35 percent increase in rice acreage. In recent years, NRCS field offices have received an increasing number of requests to determine the suitability of lands for rice production. To accomplish this, soil maps are needed showing the location, size, and distribution of soils and soil properties within fields. Unfortunately, soil maps prepared by the USDA do not show in sufficient detail the spatial distribution of soil types and soil properties that are needed for these determinations.

Rice is well suited to the clayey, poorly and very poorly drained soils that have formed on flood plains and low terraces of the Southern Mississippi River Valley Alluvium (MLRA 131). This region has extensive areas of clayey soils with slow to very permeability. The slow permeability of these soils enhances the maintenance of a 2 to 4 inch water depth in flood-irrigated fields and improves water use efficiency. However, many flood plain map units have high textural and taxonomic variability (Daniels and Hammer, 1992) and not all soils are suited to rice. Many areas of medium and fine textured soils contain small, included areas of coarser textured soils. These dissimilar inclusions represent sand boils or lenses. Sand boils and lenses vary in size and are difficult to detect. Many map units are described as having "sandy spots" or small, included areas "where the surface layer is sandy loam or loamy sands" (Brown, 1977), but information on their number and distribution within map units is not given or known. These features are caused by liquefaction, a phenomenon that occurs in water saturated soils during severe earthquakes. In 1811 and 1812, this region experienced severe earthquakes along the New Madrid fault system. Because of water management concerns and higher operating and maintenance costs, areas with sand boils and lenses are considered marginal land for rice production.

Because of abrupt horizontal and vertical changes in soil textures on flood plains, accurate soil maps are difficult to prepare and most have low predictive value (Daniels and Hammer, 1992). To meet the needs for rice production in MLRA 131, a new generation of soil maps must be prepared. These soil maps will have more appropriate scales (1:6000 or larger) and show in greater detail the variability of soils, soil properties, and capabilities within soil map units and across fields. The preparation of these maps will be a formidable and expensive task. Unless alternative field methods are developed, these high intensity soil maps will be prohibitively expensive, time-consuming, and labor-intensive to prepare. Alternative methods are needed to complement traditional survey techniques, provide more comprehensive coverage, and improve the mapping and assessment of soil properties. To be effective, these methods must be accurate, inexpensive, fast, and provide meaningful maps of soils or soil properties at a level of resolution that is comparable with current and future application technology (Jaynes, 1996).

A New Generation of Soil Mapping Tools:

Alternative methods for mapping soils and soil properties are being evaluated by NRCS. Continuous profiling resistivity units and electromagnetic induction (EMI) meters are two geophysical tools that are being used for high intensity soil surveys and precision farming initiatives. In electrical resistivity, current is directly injected into the soil through current electrodes and the potential difference in current flow is measured between the potential electrodes. When a current is applied to a uniform soil material, a potential field is created. The potential field is a source at one electrode and a sink at the other. As the electrode spacing increases, a larger and deeper volume of soil is profiled. Theoretically, the electrode spacing is assumed to be roughly equivalent to the observation depth. Lateral resolution is approximately equal to the spacing between the potential and current electrodes.

A towed, multi-electrode resistivity unit was first described by Sorensen (1994). The Veris 3100 soil EC mapping system is a towed array, continuous profiling, electrical resistivity unit that injects electrical currents into the soils through coulter-electrodes. Profiling is accomplished through an arrangement of electrodes referred to as an "array." Electrical resistivity requires the electrodes to be well grounded in the soil. Poor ground contact can result in erroneous data (negative values) and is can be experienced in dry, coarse-textured, fragmental, and frozen soils, or soils having a large cover of plant residue. Compared with EMI, resistivity methods provide better depth resolution and are less susceptible to interference from cultural sources (buildings, fences, utility lines).

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). A transmitter produces a magnetic field that induces current to flow through the subsurface. This flow of current sets up a secondary magnetic field in the soil. By comparing the difference in the magnitude and phase of these magnetic fields, the device measures the apparent conductivity of the profiled materials. No ground contact is needed with EMI. Compared with resistivity methods, EMI is noninvasive and data acquisition is generally faster. In addition, EMI is more sensitive than resistivity to thin highly conductive subsurface layers.

Interpretation of Data:
Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type 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 will increase with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Interpretations of EMI or resistivity 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. Electrical resistivity and EMI integrate the bulk physical and chemical properties of soils within a defined observation depth into a single value. As a consequence, measurements can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993; Doolittle et al., 1996). For each soil, intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique or characteristic range of apparent conductivity values.

Electromagnetic induction has been used to assess and map soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982, 1984, and 1990; Slavich and Petterson, 1990), sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), and edaphic properties important to forest site productivity (McBride et al., 1990). In addition, electromagnetic induction has been used to measure soil water contents (Kachanoski et al., 1988), cation exchange capacity (McBride et al., 1990), field-scale leaching rates of solutes (Slavich and Yang, 1990, Jaynes et al., 1995) and herbicide partition coefficients (Jaynes et al., 1995). Recently, EMI has been used as a soil-mapping tool to assist precision farming (Jaynes, 1995; Jaynes et al., 1995; Sudduth et al., 1995).

Electromagnetic induction is not suitable for use in all soil investigations. Generally, the use of EMI has been most successful in areas where the effects of one property (e.g., clay, water, or salt content) dominate over other properties. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989). In the level flood plains of the Missouri Bootheel, variations in apparent conductivity are principally related to changes in the amount of clay within the soil profile. Variations in the amount of clay also influence the soil moisture content and cation exchange capacity of soils. Increases in clay, moisture, and cation exchange capacity will increase the apparent conductivity of soils. In this study, soils with high apparent conductivity values were assumed to be finer textured than soils with low apparent conductivity values.

Discussion:
<u>Site #1</u>
The study site was located in the northwest quarter of Section 12, Township 22 N, Range 13 E, near the town of Howardville. The cultivated field had been graded. The site is in a mapped area of Wardell loam and Sharkey silty clay loam (Brown, 1977). The deep, poorly drained Wardell soil formed in loamy alluvium. The Wardell soil is a member of the fine-loamy, mixed, thermic Mollic Ochraqualfs family. The very deep, poorly and very poorly drained Sharkey soils formed in clayey alluvium. The Sharkey soil is a member of the very-fine, smectitic, thermic Chromic Epiaquerts family. The upper plot in Figure 1 approximates the soil map of the study site. Because of land leveling, soils and topographic patterns were visually indistinguishable. Slopes were less than 1 percent.

Figure 2 shows the track and the locations of observation points for the Veris 3100 implement within Site 1. Moving across the field at speeds of about 5 mph, the Veris 3100 implement recorded 2858 observation points in a very short time. An observation (two apparent conductivity measurements with coordinates) is recorded every second. By varying the speed of advance, the number and density of observation points can be varied. Variations in the speed of advance across the field are evident by the spacing of observation points in Figure 2 (note the turn areas at the end of each traverse line).

Figures 3 and 4 show the spatial distribution of apparent conductivity within the upper 30 and 90 cm of the soil, respectively. In each plot, the isoline interval is 10 mS/m. In each plot, the locations of the five soil sampling sites are also shown (see Appendix A). A general comparison of the two plots reveals that apparent conductivity increased with increasing soil depth. This vertical trend is attributed to increased clay and moisture contents with increasing soil depths. Basic statistics for the Veris data are listed in Table 1. Within Site 1, for the upper 0 to 30 cm of the soil, apparent conductivity averaged 14.72 mS/m with a range of 2.60 to 53.50 mS/m. Half of the observation points had values of apparent conductivity between 10.60 and 17.60 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 26.07 mS/m with a range of –27.00 to 83.00 mS/m. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes. Half of the observation points had values of apparent conductivity between 17.20 and 31.10 mS/m.

Table 1
Basic Statistics
Veris 3100 Survey
Study Site #1
(All values are in mS/m)

	Shallow	Deep
AVERAGE	14.72	26.07
MINIMUM	2.60	-27.00
MAXIMUM	53.50	83.00
FIRST	10.60	17.20
MEDIAN	14.00	23.25
THIRD	17.60	31.10

Spatial patterns evident in figures 3 and 4 principally reflect differences in clay contents and correspond with changes in soil types. These patterns closely mimic the soil patterns shown in Figure 1 (upper). The Sharkey and Wardell soils are dissimilar and have contrasting ranges of apparent conductivity. In Figure 4, the sinuous area of Sharkey soils has a higher apparent conductivity than the surrounding areas of Wardell soils. High apparent conductivity values in the northeast corner of the site suggest an area of Sharkey-like soils that was overlooked during soil mapping (see Figure 1, upper). Within the Sharkey unit, depth to fine textured layers is variable. In Figure 3, the depth to these fine textured layers is believed to be very shallow in areas having apparent conductivity greater than 40 mS/m.

Figure 5 shows the locations of the 11782 observation points recorded with the GEM300 sensor. In Figure 5, the observation points are so closely spaced that they appear as straight lines. The sensor had been programmed to record an observation every ½ second. This sampling interval is considered too short and excessive for soil investigation. In subsequent surveys, this interval was expand to record one observation point every two seconds. In this study and for all sites, three frequencies were selected: 2010, 9810, and 14850 Hz.

The skin depth can be estimated with the following formula given by McNeill (1996):

$$D = 500/(s*f)^{-2} \qquad [1]$$

Where s is the ground conductivity (mS/m) and f is the frequency (kHz). At Site 1, with the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 29.17, 36.91, and 32.09 mS/m at frequencies of 2010, 9810, and 14610 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths (observation depths) were about 2.1 m at 2010 Hz, 0.83 m at 9,810 Hz, and 0.73 m at 14,610 Hz.

Table 2
Basic Statistics
GEM300 Survey
Study Site #1
(All values are in mS/m)

	Frequency (Hz)		
	2010	9810	14610
AVERAGE	29.17	36.91	32.09
MINIMUM	0.00	18.64	14.00
MAXIMUM	122.15	91.45	83.88
FIRST	18.99	28.18	23.38
MEDIAN	26.51	33.17	28.16
THIRD	35.69	42.50	37.55

Table 2 summarizes the GEM300 data collected at Site 1. With a frequency of 2010 Hz, apparent conductivity ranged from 0.0 to 122.15 mS/m. Half of the observation points had values of apparent conductivity between 18.99 and 35.69 mS/m. With a frequency of 9810 Hz, apparent conductivity ranged from 18.64 to 91.45 mS/m. Half of the observation points had values of apparent conductivity between 28.18 and 42.50 mS/m. With a frequency of 14610 Hz, apparent conductivity ranged from 14.00 to 83.88 mS/m. Half of the observation points had values of apparent conductivity between 23.38 and 37.55 mS/m.

Two, closely space, ½ inch diameter fiber optic cables and a 2 ½ inch diameter coax cable are buried at a depth of about 48 in (122 cm) and cross Site 1. These cables were detected with the GEM300 sensor at each operating frequency. The location of these cables (a diagonal line crossing the southern portion of Site 1 from southwest to northeast) is most clearly expressed in the data collected at 2010 Hz (Figure 6); the lowest frequency and deepest observation depth recorded by the GEM300 sensor for this survey. However, though less clearly expressed, the cables are also evident in the data recorded at 9810 and 14610 Hz (see figures 7 and 8). This indicates skin depths greater than estimated using equation [1]. The relatively higher apparent conductivity values recorded at this site with the GEM300 sensor reflect the influences of these cables on measurements.

Spatial patterns evident in figures 6, 7, and 8 are believed to principally reflect differences in clay contents and changes in soil types. As with the Veris 3100 implement, spatial patterns obtained with the GEM300 sensor closely mimic the soil patterns shown in Figure 1 (upper). Areas of Sharkey soils have higher clay contents and apparent conductivity than areas of Wardell soils. High apparent conductivity values in the northeast corner of the site suggest an area of Sharkey-like soils that was overlooked during soil mapping (see Figure 1, upper). In each of these figures, the buried utility cables provided a clearly identifiable linear pattern that masks some soil patterns.

Figure 9 shows the locations of the 162 observation points recorded with the EM38 and EM31 meters. Table 3 summarizes the apparent conductivity measurements collected with the EM38 and EM31 meters at Site 1. The apparent conductivity of the upper 0.75 meter (measured with the EM38 meter in the horizontal dipole orientation) averaged 14.15 mS/m with a range of 4.0 to 44.0 mS/m. Half of the observations had values of apparent conductivity between 9.0 and 16.0 mS/m. These values are closely similar to the shallow (0 to 30 cm) measurements obtained with the Veris 3100 implement. The apparent conductivity of the upper 1.5 meters (measured with the EM38 meter in the vertical dipole orientation) averaged 19.4 mS/m with a range of 6.0 to 59.0 mS/m. Half of the observations had values of apparent conductivity between 13.0 and 23.8 mS/m.

Table 3
Basic Statistics
Geonic Limited Meters
Study Site #1
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM38H	14.15	4.0	44.0	9.0	11.0	16.0
EM38V	19.44	6.0	59.0	13.0	16.0	23.8
EM31H	23.99	12.0	63.0	17.0	20.0	29.0
EM31V	24.01	12.0	67.0	17.0	20.0	28.8

Measurements obtained with the EM31 meter in the horizontal and vertical dipole orientations were nearly identical. This is remarkable considering the complex and variable stratigraphy of the site. The apparent conductivity of the upper 3 meters (measured with the EM31 meter placed on the soil surface in the horizontal dipole orientation) averaged 24.0 mS/m with a range of 12.0 to 63.0 mS/m. Half of the observations had values of apparent conductivity between 17.0 and 29.0 mS/m. These values most closely match the deeper (0 to 90 cm) measurements obtained with the Veris 3100 implement. The apparent conductivity of the upper 6 meters (measured with the EM31 meter placed on the soil surface in the vertical dipole orientation) averaged 24.0 mS/m with a range of 12.0 to 67.0 mS/m. Half of the observations had values of apparent conductivity between 17.0 and 28.8 mS/m.

Figures 10 and 11 show the spatial distribution of apparent conductivity collected with the EM38 meter in the horizontal and vertical dipole orientation, respectively. Figures 12 and 13 show the spatial distribution of apparent conductivity collected with the EM31 meter in the horizontal and vertical dipole orientation, respectively. In each plot, the isoline interval is 5 mS/m. The locations of the five soil sampling sites are also shown. Spatial patterns in these plots are believed to principally reflect differences in clay contents and changes in soil types. As with the Veris 3100 implement and the GEM300 sensor, spatial patterns obtained with the EM38 and the EM31meters closely mimic the soil patterns shown in Figure 1 (upper).

The utility cables, buried at a depth of about 120 cm, were only detectable in the data collected with the GEM300 sensor and the EM31 meter in the vertical dipole orientation. The theoretically depth of observation for the EM38 meter in the vertical dipole orientation is supposedly 150 cm. The theoretically depth of observation for the EM31 meter in the horizontal dipole orientation is supposedly 300 cm. The absence of these utility cables in figures 11and 12 suggest that the observation depths of these meters in these orientations are perhaps more restricted than theorized in these moderately conductive soils.

At Site 1, data obtained with the GEM300 sensor, though comparable, were slightly higher and more variable than those collected with the Veris 3100 soil EC mapping system, EM38 and EM31 meters. The dissimilarity in apparent conductivity measured among these devices is attributed to differences in system calibration by manufacturers, intercoil and electrode spacing, depth and volume of soil profiled, and frequencies. Apparent conductivity values are seldom diagnostic in themselves. However, spatial patterns and relative magnitude of apparent conductivity do provide inferential clues as to differences in soils and soil properties. Similar spatial patterns were obtained with each device. These spatial patterns corresponded with mapped soil delineations. With minor exceptions and regardless of device, purported observation depths, or sampling frequency, the plotted spatial patterns were similar with all devices.

Soil samples were obtained at five observation points within Site 1. Brief profile descriptions of these soils are described in Appendix A. Table 4 shows the apparent conductivity values collected with the various devices at each of these observation points. With each device, soils containing higher clay contents had higher apparent conductivity. Soils with lower clay contents had lower apparent conductivity. The data shown in Table 4 will be compared with textural analysis data when it becomes available from the NSSC.

Table 4
Comparison of Apparent Conductivity Data
Collected at Sample Sites with various EMI Devices
Study Site #1
(All values are in mS/m)

Sample#	EM 38H	EM 38V	EM 31H	EM 31V	2010(C)	9810(C)	14610(C)	Veris S	Veris D
1	21.0	33.0	38.0	36.0	71.3	68.3	60.7	8.3	19.7
2	39.0	50.0	52.0	45.0	51.2	47.3	39.6	18.1	59.2
3	15.0	17.0	21.0	18.0	35.5	31.8	23.0	16.3	28.5
4	7.0	10.0	17.0	16.0	26.3	22.7	15.1	7.1	12.5
5	8.0	11.0	15.0	15.0	28.1	23.9	16.1	12.1	23.1

Site #2

The study site was located in western ½ of Section 24, Township 23 N, Range 14 E. The site was in a field of bean stubble. Several soil delineations were mapped on this site. The middle plot in Figure 1 approximates the soil delineations mapped within the Site 2. Within the site are areas of Forestdale silt loam, Forestdale silty clay loam, and Acadia silt loam, loamy substratum (Brown, 1977). The very deep, poorly drained Forestdale soils formed in clayey and silty alluvium in depressions on low terraces and natural levees. The Forestdale soil is a member of the fine, smectitic, thermic Typic Endoaqualfs family. The very deep, somewhat poorly drained Acadia soils formed in clayey alluvium in depressions. The Acadia soil is a member of the fine, smectitic, thermic Aeric Ochraqualfs family. Slopes were less than 1 percent.

Comparative studies were conducted with the Veris 3100 implement, GEM300 sensor, and EM38 meter. The observation depth, area coverage, number of observations, and survey times varied with each method. The mobile Veris 3100 implement had the shallowest observation depth, covered the entire site in the shortest period of time, and collected the largest number of observations (3774). The hand-held GEM300 sensor provided the deepest observation depth, covered the entire site, and recorded 3409 observations in the second fastest time. The EM38 meter covered most of the site and recorded the fewest (287) observations. Unless automated and motorized, the EM38 meter provides the slowest and most labor-intensive surveying method. In the open farmland of the Southern Mississippi River Valley Alluvium (MLRA 131), mobile systems provide faster, less labor-intensive, and more efficient operations. Both the electromagnetic induction meters and the GEM sensor can be mounted on wooden trailers and towed behind a four wheel ATV (Davis et al, 1997).

Figure 14 shows the track and the locations of the 3774 observation points obtained with the Veris 3100 implement within the Site 2. The long axis of the field is orientated in a southwest to northeast direction

Basic statistics for the Veris data collected at Site 2 are listed in Table 5. Apparent conductivity increased with increasing soil depth. This vertical trend is attributed principally to increased clay and moisture contents with increasing soil depths. For the upper 0 to 30 cm of the soil, apparent conductivity averaged 7.38 mS/m with a range of –12.0 to 25.5 mS/m. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes. Half of the observations had values of apparent conductivity between 4.9 and 9.2 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 47.5 mS/m with a range of 5.8 to 168.3 mS/m. Half of the observations had values of apparent conductivity between 30.9 and 56.3 mS/m. Values of apparent conductivity in excess of 70 mS/m were obtained at some observation points with the Veris 3100 implement. These values imply not only high clay and moisture contents, but also the possibility of high soluble salts contents.

Table 5
Basic Statistics
Veris 3100 Survey
Site #2
(All values are in mS/m)

	Shallow	Deep
AVERAGE	7.38	47.51
MINIMUM	-12.00	5.80
MAXIMUM	25.50	168.30
FIRST	4.90	30.90
MEDIAN	6.90	40.35
THIRD	9.20	56.30

Figures 15 and 16 show the spatial distribution of apparent conductivity within the upper 30 and 90 cm of the soil, respectively. In each plot, the isoline interval is 10 mS/m. A closer isoline interval (1 to 5 mS/m) would provide more intricate patterns for each depth interval, but would add little to the interpretability of these plots. Also shown in Figures 15 and 16 are the locations of the six soil sampling sites (see Appendix A).

Spatial patterns evident in figures 15 and 16 are believed to principally reflect differences in clay contents. If this assumption is correct, the absence of isoline in Figure 15 suggests that surface textures are relatively uniform across most of this site. In Figure 15, two soil-sampling points (4 and 5) were within an area with comparatively high apparent conductivity (>10 mS/m). Not surprisingly, depths to finer textured materials were shallowest at these sampling points (see Appendix A). In addition, these two sampling points were taken within the mapped soil delineation with the heaviest surface texture. Spatial patterns of apparent conductivity evident in Figure 16 are more intricate than the soil patterns shown in Figure 1 (middle). Soils with high conductivity are located in the southwest and northeast portions of the site. These areas had been principally mapped as phases of Forestdale. The central portion of the site has lower and less varying values of apparent conductivity. This area had been principally mapped as Acadia silt loam, loamy substratum. At existing soil temperatures and moisture contents, areas having apparent conductivity values of less than 20 mS/m are believed to have low clay contents and are considered marginal land for rice production. These areas (<20 mS/m) are widely dispersed across this management unit.

Figure 17 shows the locations of the 3409 observation points recorded with the GEM300 sensor. The location of these observation points were processed and adjusted by the MAGMAP96 software program. To run this program, field dimensions of 1550 by 2200 ft, and a distance of 100 ft between traverse lines were assumed. With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 35.0, 38.6, and 32.1 mS/m at frequencies of 2010, 9810, and 14610Hz, respectively. Based on equation [1] and these averaged conductivities and frequencies, the estimated skin depths (observation depths) are about 1.9 m at 2010 Hz, 0.8 m at 9,810 Hz, and 0.7 m at 14,610 Hz.

Table 6 summarizes the results of the GEM300 sensor survey within Site 2. With a frequency of 2010 Hz and an estimated observation depth of about 1.9 m, apparent conductivity ranged from –45.1 to 89.2 mS/m. Half of the observation points had values of apparent conductivity between 23.6 and 48.9 mS/m. With a frequency of 9810 Hz and an estimated observation depth of about 0.8 m, apparent conductivity ranged from 14.3 to 92.2 mS/m. Half of the observation points had values of apparent conductivity between 26.0 and 49.8 mS/m. With a frequency of 14610 Hz and an estimated observation depth of about 0.7 m, apparent conductivity ranged from 8.6 to 85.1 mS/m. Half of the observation points had values of apparent conductivity between 19.3 and 43.4 mS/m.

Table 6
Basic Statistics
GEM300 Survey
Study Site #2
(All values are in mS/m)

	Frequency (Hz)		
	2010	9810	14610
AVERAGE	35.6	38.6	32.1
MINIMUM	-45.1	14.3	8.6
MAXIMUM	89.2	92.2	85.1
FIRST	23.6	26.0	19.3
MEDIAN	31.0	32.7	26.2
THIRD	48.9	49.8	43.4

Spatial patterns evident in figures 19, 20, and 21 are believed to principally reflect differences in clay contents and changes in soil types. However, in Figure 18, a system error produced erroneous (negative) values along traverse line 1000. This error appeared to be restricted to measurements obtained at 2010 Hz as data collected at frequencies of 9810 Hz (Figure 19) and 14610 Hz (Figure 20) do not appear to be affected. This line of data collected at 2010 Hz should be deleted from the data set.

Despite the fact that locations of observation points were not geo-referenced and were "rubber-sheeted" by the MAGMAP96 software program, patterns of apparent conductivity measured with the GEM300 sensor (figures 18, 19, and 20) are similar to those simulated from the deep measurements of Veris 3100 implement (Figure 16). However, values of apparent conductivity measured with the GEM300 sensor were generally lower and less variable. In this and previous studies, because of differences in manufacturers calibrations, measurements obtained with the GEM300 sensor were slightly higher than those obtained with the Veris 3100 implement or EM38 and EM31 meters. No explanation is offered for the reversal of this trend for the GEM 300 sensor and the Veris 3100 implement at this site. As with the Veris 3100 implement, spatial patterns obtained with the GEM300 sensor are more intricate but generally conforms to the mapped soil patterns (Figure 1, middle).

Figure 21 shows the locations of the 287 observation points recorded with the EM38 meter at Site 2. No measurements were made with the EM31 meter at this site. Because of limited time, the complete site was not surveyed with the EM38 meter. The locations of these observation points were recorded with a Rockwell GPS receiver. In Figure 21, the positional accuracy of one set of coordinates is obviously in error.

Table 7 summarizes the apparent conductivity measurements collected with the EM38 meter at Site 2. The apparent conductivity of the upper 0.75 meter (measured with the EM38 meter in the horizontal dipole orientation) averaged 17.25 mS/m with a range of 1.0 to 55.0 mS/m. Half of the observations had values of apparent conductivity between 11.0 and 21.0 mS/m. The apparent conductivity of the upper 1.5 meters (measured with the EM38 meter in the vertical dipole orientation) averaged 22.29 mS/m with a range of 2.0 to 71.0 mS/m. Half of the observations had values of apparent conductivity between 14.0 and 28.0 mS/m.

Table 7
Basic Statistics
Geonics Limited Meters
Study Site #2
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM38H	17.25	1.0	55.0	11.0	15.0	21.0
EM38V	22.29	2.0	71.0	14.0	19.0	28.0

Figures 22 and 23 show the spatial distribution of apparent conductivity measured with the EM38 meter in the horizontal and vertical dipole orientation, respectively. In each plot, the isoline interval is 10 mS/m. In each plot, the locations of five of the six soil sampling sites are also shown. The sixth sampling site was located outside the area surveyed with the EM38 meter.

Spatial patterns in these figures are believed to principally reflect differences in clay contents and changes in soil types. Despite more limited sampling, the spatial patterns are similar to those obtained with the Veris 3100 implement and the GEM300 sensor and reflect the soils delineations that had been mapped across this site.

Soil samples were obtained at six observation points within Site 2. Brief profile descriptions of these soils are described in Appendix A. Table 8 shows the apparent conductivity values collected with the various devices at each of these observation points. With each device, soils containing higher clay contents had higher apparent conductivity. The data shown in Table 8 will be compared with textural analysis data when it becomes available from the NSSC.

Table 8
Comparison of Apparent Conductivity Data
Collected at Sample Sites with various EMI Devices
Study Site #2
(All values are in mS/m)

Sample#	EM 38H	EM 38V	2010(C)	9810(C)	14610(C)	Veris S	Veris D
1	5	6	12.0	12.8	11.7	3.0	4.4
2	12	13	21.1	20.5	22.1	11.7	17.5
3	23	28	34.2	35.2	38.2	17.7	27.8
4	58	70	98.5	78.8	97.5	34.7	85.0
5	45	57	67.2	70.5	73.1	29.6	61.2
6	34	41	49.6	51.0	44.7	27.5	53.2

Despite varying sample sizes, different geo-referenced datum, and the rubber sheeting of some data, all three tools produced similar spatial patterns of apparent conductivity (see figures 16, 18, 19, 20, 22, and 23). Data collected with the EM38 meter was the most limited (287 observations) and time-consuming to obtain. What is surprising is that even with a comparatively modest sample size, the data collected with the EM38 meter provided spatial patterns similar to those obtained with the other devices.

Site #3

The study site was located in southwest quarter of Section 31, Township 24 N, Range 14 E. The field had been was ridged for rice. The site included mapped areas of Roellen clay, Sikeston sandy clay loam, and Gideon loam (Brown, 1977). The very deep, poorly drained Gideon soil form in alluvium on slightly depressed flood plains. Gideon is a member of the fine-loamy, mixed, superactive, nonacid, thermic Mollic Fluvaquents family. The very deep, poorly drained Roellen soil form in clayey alluvium on depressed flood plains and in former braided channels. Roellen is a member of the fine, smectitic, thermic Vertic Epiaquolls family. The very deep, poorly drained Sikeston soil form in loamy alluvium in depressions, channels, and sunken lowlands on flood plains. Sikeston is a member of the fine-loamy, mixed, superactive, thermic Cumulic Endoaquolls family.

Once again, comparative studies were conducted with the Veris 3100 implement, GEM300 sensor, and EM38 meter. The observation depth, area of coverage, number of observations, and survey times varied with each method. The mobile Veris 3100 implement had the shallowest observation depth, covered the entire site in the shortest period of time, and collected the largest number of observations (2079). The hand-held GEM300 sensor provided the deepest observation depth, covered the entire site, and recorded 1230 observations in the second fastest time. The EM38 meter covered most of the site and recorded the fewest (96) observations. This method was the slowest and most labor-intensive.

Figure 24 shows the track of the Veris 3100 implement and the locations of observation points within Site 3. Multiple, parallel, low (about 15 cm) formed ridges within the field produced a rough ride that slowed the Veris 3100 implement (especially in turning areas). These ridges produced a highly irregular surface that caused the coulter-electrodes to periodically come out of the ground. Poor ground contact and erroneous measurements were observed with the Veris 3100 implement in this field. As a consequence, the Veris data is considered inaccurate at this site.

Basic statistics for the Veris data collected at Site 2 are listed in Table 9. Apparent conductivity increased with increasing soil depth. This vertical trend is attributed to increased clay and moisture contents with increasing soil depths. For the upper 0 to 30 cm of the soil, apparent conductivity averaged 34.0 mS/m with a range of 12.8 to 70.7 mS/m. Half of the observations had values of apparent conductivity between 26.4 and 41.6 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 53.4 mS/m with a range of –27.0 to 85.4 mS/m. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes. Half of the observations had values of apparent conductivity between 46.0 and 61.4 mS/m.

Table 9
Basic Statistics
Veris 3100 Survey
Site #2
(All values are in mS/m)

	Shallow	Deep
AVERAGE	33.99	53.35
MINIMUM	12.80	-27.00
MAXIMUM	70.70	85.40
FIRST	26.40	46.00
MEDIAN	33.90	53.60
THIRD	41.60	61.40

Figures 25 and 26 show the spatial distribution of apparent conductivity measured with the Veris 3100 implement for the upper 30 and 90 cm of the soil, respectively. In each plot, the isoline interval is 10 mS/m. Also shown in Figures 25 and 26 are the locations of the three soil sampling sites (see Appendix A). The spatial patterns shown in figures 25 and 26, while having a similar north to south trend, are more intricate and do not conform with the soil patterns shown in Figure 1 (bottom). In Figure 25, the spatial patterns show an increase from south to north in apparent conductivity. This trend is assumed to reflect changes in the clay content of the surface layers (0 to 30 cm).

In Figure 26, periodic, poor electrode contact has produced the conspicuous "spots" of low apparent conductivity along a mid north-south traverse line. Additional "spots" or areas of both high and low conductivity are similarly orientated and evident in Figure 26. These "spots" are presumed to reflect deeper and shallower points of electrical contact. To insure accurate measurements with the Veris 3100 implement, operations should be conducted only under proper field conditions. Care must be taken to insure that the electrodes are adequately and uniformly inserted and maintained in the ground.

Figure 27 shows the locations of the 1230 observation points recorded with the GEM300 sensor. With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 43.4, 47.6, and 41.2 mS/m at frequencies of 2010, 9810, and 14610Hz, respectively. Based on these averaged conductivities and frequencies, the estimated skin depths (observation depths) are about 1.7 m at 2010 Hz, 0.7 m at 9,810 Hz, and 0.6 m at 14,610 Hz.

Table 10
Basic Statistics
GEM300
Study Site #3
(All values are in mS/m)

	Frequency (Hz)		
	2010	9810	14610
AVERAGE	43.4	47.6	41.2
MINIMUM	25.8	29.6	-44.0
MAXIMUM	64.7	66.6	60.2
FIRST	39.0	43.2	40.0
MEDIAN	43.5	48.2	41.7
THIRD	48.2	52.6	46.9

Table 10 summarizes the results of the survey of Site 3 with the GEM300 sensor. Data obtained at each frequency are closely similar. The similarities in data attest to the restricted and equivalent skin depths in these moderately fine and fine textured, moderately conductive soils. With a frequency of 2010 Hz, apparent conductivity ranged from 25.8 to 64.7 mS/m. Half of the observation points had values of apparent conductivity between 39.0 and 48.2 mS/m. With a frequency of 9810 Hz, apparent conductivity ranged from 29.6 to 66.6 mS/m. Half of the observation points had values of apparent conductivity between 43.2

and 52.6 mS/m. With a frequency of 14610 Hz, apparent conductivity ranged from –44.0 to 60.2 mS/m. Half of the observation points had values of apparent conductivity between 40.0 and 46.9 mS/m.

Spatial patterns of apparent conductivity measured with the GEM300 sensor (figures 28, 29, and 30) appear chaotic, irregularly shaped, and do not conform to mapped soil patterns (Figure 1, bottom). In the Missouri Bootheel, at existing soil temperatures and moisture contents, areas having apparent conductivity values of less than 20 mS/m are believed to have low clay contents and are considered marginal land for rice production. No observation point within Site 2 had an apparent conductivity value less than 20 mS/m and the field is considered suited to rice production. With an isoline interval of 10 mS/m, the spatial patterns do not closely approximate those obtained with the deep measurements of Veris 3100 implement (Figure 216). Within this ridged field, the poor and variable contact with the ground of the Veris's electrodes could explain this lack of agreement between the two data sets.

Figure 31 shows the locations of the 96 observation points recorded with the EM38 meter at Site 3. The complete site was not surveyed with the EM38 meter. Measurements made with the EM31 meter at this site could not be geo-referenced and were therefore discarded.

Table 11
Basic Statistics
EM38 Meter
Study Site #3
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM38H	38.47	26.0	55.0	34.75	39.0	44.0
EM38V	40.43	23.0	54.0	36.00	41.0	45.0

Table 11 summarizes the apparent conductivity measurements collected with the EM38 meter at Site 3. The apparent conductivity of the upper 0.75 meter (measured with the EM38 meter in the horizontal dipole orientation) averaged 38.47 mS/m with a range of 26.0 to 55.0 mS/m. Half of the observations had values of apparent conductivity between 34.8 and 44.0 mS/m. The apparent conductivity of the upper 1.5 meters (measured with the EM38 meter in the vertical dipole orientation) averaged 40.43 mS/m with a range of 23.0 to 54.0 mS/m. Half of the observations had values of apparent conductivity between 36.0 and 45.0 mS/m.

Figures 32 and 33 show the spatial distribution of apparent conductivity collected with the EM38 meter in the horizontal and vertical dipole orientation, respectively. In each plot, the isoline interval is 10 mS/m. In each plot, the approximate locations of the three sampling sites are also shown. Spatial patterns in these figures are believed to principally reflect differences in clay contents and changes in soil types. As with the Veris 3100 implement and the GEM300 sensor, spatial patterns obtained with the EM38 meter fail to approximate the soil patterns shown in Figure 1 (bottom).

At Site 3, the narrow range in apparent conductivity measured with the EM38 meter and the GEM300 sensor suggest the presence of fairly uniform soil properties. Closely similar and over lapping soil properties could explain the poor definition of map soil delineations with apparent conductivity measurements. Perhaps at Site 3 there is greater variation in soil properties within than between the mapped soil delineations.

Soil samples were obtained at three observation points within Site 3. Brief profile descriptions of these soils are described in Appendix A. Table 12 shows the apparent conductivity values collected with the various devices at each of these observation points. With each device, soils containing higher clay contents had higher apparent conductivity. The data shown in Table 12 will be compared with textural analysis data when it becomes available from the NSSC.

Table 12
Comparison of Apparent Conductivity Data Collected at Sample Sites with various EMI Devices
Study Site #3

(All values are in mS/m)

Sample#	EM 38H	EM 38V	2010(C)	9810(C)	14610(C)	Veris S	Veris D
1	34	29	28.7	32.0	25.1	47.0	34.1
2	44	52	50.9	54.1	46.6	38.8	70.2
3	22	38	44.8	44.1	37.0	19.3	41.7

Appendix A

Soil Descriptions

Site #1 – Mark Baker's Field, Howardville, MO
Pedon #1 (S99MO143001)
0 to 12 inches – sandy loam
12 to 24 inches – loamy sand
22 to 34 inches – silty clay
34 to 40 inches – silty clay loam

Pedon #2 (S99MO143002)
0 to 6 inches – sandy loam
6 to 24 inches – silty clay
24 to 40 inches –clay

Pedon #3 (S99MO143003)
0 to 4 inches – sandy loam
4 to 12 inches – clay loam
12 to 20 inches – silty clay
20 to 28 inches –clay loam
28 to 40 inches –sandy loam

Pedon #4 (S99MO143004)
0 to 17 inches – fine sandy loam
17 to 38 inches – silty clay loam
38 to 40 inches – silt loam

Pedon #5 (S99MO143005)
0 to 14 inches – fine sandy loam
14 to 18 inches – loam
18 to 26 inches – loamy sand
26 to 40 inches – silty clay loam

Site #2 – Lawfield's Field, New Madrid, MO
Pedon #1 (S99MO143006)
0 to 16 inches – fine sandy loam
16 to 35 inches – sandy loam
35 to 38 inches – sandy clay loam
38 to 40 inches – sandy loam

Pedon #2 (S99MO143007)
0 to 21 inches – sandy loam
21 to 28 inches – clay loam
28 to 34 inches – sandy clay
34 to 40 inches – clay

Pedon #3 (S99MO143008)
0 to 6 inches – sandy loam
6 to 28 inches – cay loam
28 to 40 inches – clay

Pedon #4 (S99MO143009)
0 to 4 inches – silty clay loam
4 to 40 inches – silty clay

Pedon #5 (S99MO143010)
0 to 4 inches – loam
4 to 40 inches – clay

Pedon #6 (S99MO143011)
0 to 5 inches – loam
5 to 12 inches – silt loam
12 to 18 inches – silty clay loam
18 to 40 inches – silty clay

Site #3 – Riley's Field, Kewanee, MO
Pedon #1 (S99MO143012)
0 to 16 inches – silty clay loam
16 to 45 inches – silt loam
+ 40 inches – sand

Pedon #2 (S99MO143013)
0 to 7 inches – silty clay loam
7 to 20 inches – clay
20 to 36 inches – silty clay loam (saturated)
36 to 40 inches – silt loam ((buried wood material - cypress)

Pedon #3 (S99MO143014)
0 to 12 inches – clay loam
12 to 31 inches – loam
31 to 40 inches – fine sandy loam

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