United States Department of Agriculture

NRCS

Natural Resources Conservation Service
National Soil Survey Center
Federal Building, Room 152
100 Centennial Mall North
Lincoln, NE 68508-3866

Phone: (402) 437-5499
FAX: (402) 437-5336

SUBJECT: SOI – Geophysical Assistance

November 1, 2011

TO: Denise C. Coleman
State Conservationist
NRCS, Harrisburg, Pennsylvania

File Code: 330-7

Purpose:
The purpose of these investigations is to use electromagnetic induction (EMI) to infer spatial and temporal variations in soil moisture in an expanded area that surrounds four Odyssey well sites located in Crawford, Mercer, and Lackawanna Counties, Pennsylvania. Each well is equipped with an *Odyssey* soil moisture probe, which measures soil moisture content to a data logger. This information is periodically downloaded to a computer for documentation. This state-wide NRCS project is designed to collect data on seasonal soil moisture contents, duration of saturation, and depths to water table in Pennsylvania soils. The objective of this project is to improve the *soil moisture status data* in NASIS. This project will collect data on soil moisture contents, fluctuations, and movement across different soil-landscapes.

Participants:
John Chibirka, Resource Soil Scientist, USDA-NRCS, Leesport, PA
Alex Dado, MLRA Soil Survey Office Leader, USDA-NRCS, Mercer, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Michael Swaldek, Soil Scientist, USDA-NRCS, Mercer, PA

Activities:
Field activities were completed during the period of 21 to 27 April 2011.

Summary:

1. Electromagnetic induction data were collected at two sites in Lackawanna County, and one site in both Mercer and Crawford Counties. This data will be used to evaluate temporal and spatial variations in soil moisture contents and movement across different soil-landscapes in Pennsylvania. The present surveys were conducted in the spring, when soil moisture contents are at their highest levels. To assess temporal variations in soil moisture, these sites will be return to in the fall, when soil moisture contents are at lower levels. Differences in apparent conductivity (EC_a) will be used to infer spatial differences in soil moisture contents.

2. During these investigations, a Profiler EMP-4000 sensor was used for the first time by USDA personnel. The Profiler is a newly developed, multifrequency EMI instrument. The Profiler comes with Bluetooth communications, a personal data assistant (PDA), and an integral 12-channel WAAS (Wide Area Augmentation System) GPS. Comparative studies were completed with a Profiler EMP-400 sensor and an EM38-MK2 meter at the Lackawanna and Crawford County sites. Broad spatial EC_a patterns were similar in the plots developed from

data collected with each instrument. Differences in specific details were attributed to differences in the number and track of the instrument's traverses across the sites, and to differences in depths of exploration. At each site, the averaged EC_a measured with the Profiler EMP-400 sensor was lower than that measured with the EM38-MK2 meter.

3. Based on the findings of the comparative field investigations, the Profiler is accepted as being a *geometry limited* instrument like the EM38-MK2 meter. In the vertical and horizontal dipole orientations, the depths of exploration for the Profiler are accepted as being approximately 1.8 and 0.9 m, respectively.

4. Temporal differences in the expression of fragipans on ground-penetrating radar (GPR) records are not well documented. During this study, soils with fragipans were profiled. Water was observed perched above the fragipan of the three different soils (Morris, Wellsboro, and Venango). The radar records collected over these soils will be compared with radar records collected when these sites are returned to during drier fall conditions.

5. The presence of perch water favors the detection of fragipan with GPR. Fragipans are often difficult to recognize on raw, unprocessed radar records. Signal processing and careful selection of color and transform settings are vital for the correct identification of fragipans.

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

/s/ Jonathan W. Hempel

JONATHAN W. HEMPEL

Director

National Soil Survey Center

cc: See attached list

cc:

John Chibirka, Resource Soil Scientist, USDA-NRCS, Suite 220, 1238 County Welfare Road, Leesport, PA 19533-9710

Alex Dado, MLRA Soil Survey Office Leader, USDA-NRCS, 751 Greenville Road, Mercer, PA 16137

Jim Doolittle, Research Soil Scientist, NSSC, USDA-NRCS, 11 Campus Blvd., Suite 200, Newtown Square, PA

Michael Golden, Director of Soils Survey Division, USDA-NRCS, Washington, DC 20250

Dave Kingsbury, MLRA Office Leader, USDA-NRCS, 1550 Earl Core Road, Suite 200, Morgantown, WV 26505

Wes Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 60, 207 West Main Street, Rm. G-08, Federal Building, Wilkesboro, NC 28697

Larry West, National Leader for Soil Survey Research and Laboratory Staff, USDA-NRCS-NSSC, Lincoln, NE

Edgar White, State Soil Scientist, USDA-NRCS, One Credit Union Place, Suite 340, Harrisburg, PA 17110-2993

Mike Wilson, Research Soil Scientist & Liaison for MO13, Soil Survey Research and Laboratory Staff, USDA-NRCS-NSSC, Lincoln, NE

Technical Report on the Use of Geophysical Methods for the Evaluation of Soil Water and Moisture Status at selected Sites in Lackawanna, Mercer, and Crawford Counties, Pennsylvania, 21 to 27 April 2011.

James A. Doolittle

Background:
There is a recognized need for additional and better data on seasonal soil moisture contents, duration of saturation, and depths to *high* water table in Pennsylvania soils. Data on *soil water status* are used for soil interpretations, conservation practices, risk management, and identifying hydric soils. In addition, hydrological models require accurate information on temporal and spatial variations in soil moisture and flow patterns. To accommodate these needs, a study, entitled *Evaluating Soil Water and Moisture Status,* has been implemented to improve the *soil water status* data in NASIS. This study is designed to collect data on soil moisture contents, fluctuations, and movement within different soils and across different landscapes in Pennsylvania. This project will revise and update *soil moisture status* data in NASIS using graphs from data loggers on water table depths, analysis of Pennsylvania's Soil Climate Analysis Network (SCAN) data, and geophysical methods.

Equipment:
An EM38-MK2 meter (Geonics Limited; Mississauga, Ontario) was used in this study.[1] Operating procedures for the EM38-MK2 meter are described by Geonics Limited (2007). The EM38-MK2 meter operates at a frequency of 14.5 kHz and weighs about 5.4 kg (11.9 lbs). The meter has one transmitter coil and two receiver coils, which are separated from the transmitter coil at distances of 1.0 and 0.5 m. This configuration provides two nominal exploration depths of 1.5 and 0.75 m when the meter is held in the vertical dipole orientation (VDO), and 0.75 and 0.40 m when the meter is held in the horizontal dipole orientation (HDO). In either dipole orientation, the EM38-MK2 meter provides simultaneous measurements of both apparent conductivity (EC_a) and magnetic permeability over two depth intervals. Apparent conductivity is expressed in milliSiemens/meter (mS/m). Magnetic permeability is the ratio of the secondary to primary magnetic fields and is expressed in parts per thousand (ppt).

A Trimble AG114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced EC_a data collected with the EM38-MK2 meter.[1] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both GPS and EC_a data[1]. The RTM38MK2 program (Geomar Software, Inc., Mississauga, Ontario) was used with the EM38-MK2 meter to display and record both GPS and EC_a data on the Allegro CX field computer.[1]

A Profiler EMP-400 sensor (here after referred to as the Profiler) was also used in this study (see Figure 1). The Profiler, which is manufactured by Geophysical Survey Systems, Inc. (GSSI) has a 1.22 m intercoil spacing and operated at frequencies ranging from 1 to 16 kHz. The Profiler EMP-400 sensor is a multifrequency EMI meter that can simultaneously collect data at three discrete frequencies. For each frequency, data are recorded in the in-phase and the quadrature phase components. The calibration of the Profiler is optimized for 15 kHz and, as a consequence, EC_a is most accurately measured at this frequency (Dan Delea, GSSI, personal communication). A rechargeable Li-ion battery pack powers the sensor. Surveys can be conducted with this sensor in either the VDO or HDO. The sensors electronics are controlled via Bluetooth communications with a TDS RECON-400 Personal Data Assistant (PDA). To collect geo-referenced data, the PDA is configured with an integral 12-channel WAAS (Wide Area Augmentation System) GPS.

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

Figure 1 Alex Dado, MLRA 139 Soil Survey Office Leader completes an EMI survey with a Profiler in an expanded area that surrounds an Odyssey well (white-colored access tube) located in Crawford County, Pennsylvania.

To help summarize the results of the EMI surveys, the SURFER for Windows (version 9.0) software (Golden Software, Inc., Golden, CO) was used to construct the simulations shown in this report. [1]

Depth of Exploration for the EM38-MK2 meter and the Profiler sensor:
McNeill (1980) describes how the measured apparent conductivity is a function of instruments calibration, coil separation, coil orientation, and frequency. McNeill also noted that the depth of exploration is dependent on coil separation, coil orientation, and frequency. Larger coil separations and lower frequencies are used to achieve greater depths of exploration.

Won et al. (1996) observed that changing the transmitter frequency will change the depth of exploration. Won (1980 and 1983) argues that the exploration depths of multi-frequency EMI instrument are governed by the *skin-depth effect*: lower frequency signals travel farther through conductive mediums than higher frequency signal.

The EM38-MK2 meter operates at a frequency of 14.5 kHz; the Profiler can operate at multiple frequencies ranging from 1 to 16 kHz. With the EM38-MK2 meter and all meters developed by Geonics Limited, the depth of exploration is considered *geometry limited* (intercoil spacing) rather than *skin depth limited* (McNeill, 1980). Under conditions of low induction number, the depth-response functions of these meters are assumed to be independent of soil conductivity. Conditions of low induction numbers are usually satisfied in soils having low (<100 mS/m) EC_a (McNeill, 1980). Greenhouse et al. (1998) noted that the electrical conductivity of soils plays a critical role in the depth of exploration obtained with

all EMI instruments. Slavich (1990) and de Jong et al. (1979) reported that the depth of exploration varies depending on the bulk electrical conductivity of the profiled material(s).

With the Profiler, the depth of exploration is considered *skin depth limited* rather than *geometry limited* (Won, 1980 and 1983, Won et al., 1996). The *skin effect* is the tendency for electrical current density to be greatest at the surface and decreases exponentially with depth. *Skin depth* represents the maximum depth of exploration for the Profiler operating at a specific frequency and sounding a medium of known conductivity. The *skin depth* is defined as the depth below the surface at which the current density has fallen to 1/e (about 0.37) of surface current density. The maximum exploration depth or *skin depth* is inversely proportional to frequency (Won et al., 1996). Low frequency signals have longer periods of oscillation and loose energy less rapidly than high frequency signals and supposedly achieve greater depths of exploration. In addition, for a given frequency, the depth of exploration is greater in low than in high conductivity soils.

Brosten et al. (2011) note how multifrequency EMI sensors continue to challenge practitioners. While Huang and Won (2000) argue that data recorded by multifrequency sensors provide useful information, McNeill (1996) contends that the data recorded is redundant because the sensitivity of these instruments is strongly controlled by their low frequency range and coil spacings. Greenhouse et al. (1998) also observed that, because of other factors, such as coil spacings, the actual depth of observation is less than the *skin depth*. Brosten et al. (2011) used synthetic modeling methods and determined that with a GEM-2 multifrequency sensor (similar to Profiler), in a medium that has an estimated skin depth of 23.4 m, the actual depth of exploration ranged from only 1.8 to 2.7 m.

Based on the findings of Brosten et al. (2011), I accept the Profiler as being a *geometry limited* instrument like the EM38-MK2 meter. The EM38-MK2 meter has coil separations of 50 and 100 cm; the Profiler has a larger coil separation of 121 cm. Compared to the EM38-MK2 meter, because of its larger intercoil spacing, the Profiler will profile the soil to slightly greater depths in both dipole orientations. In the VDO and HDO, the depths of exploration for the Profiler are accepted as being approximately 1.8 and 0.9 m, respectively.

Field Sites:

Lackawanna County:

The two Odyssey well sites are located in areas of idle land about 1.8 kilometers southeast of Factoryville, Pennsylvania. Site 1 (about 75.769 N. latitude and 41.551 W. longitude) is located on a higher-lying, convex slides slope in a delineation of Wellsboro channery loam on 8 to 15 % slopes (WcC). The very deep, moderately well drained and somewhat poorly drained Wellsboro soils formed in till derived from red sandstone, siltstone, and shale. Depth to the fragipan ranges from about 30 to 76 cm.

Table 1 - Taxonomic Classification Of The Soils Recognized At The Odyssey Well Sites.

Soil Series	Taxonomic Classification
Canfield	Fine-loamy, mixed, active, mesic Aquic Fragiudalfs
Chippewa	Fine-loamy, mixed, active, mesic Typic Fragiaquepts
Morris	Coarse-loamy, mixed, active, mesic Aeric Fragiaquepts
Norwich	Fine-loamy, mixed, active, mesic Typic Fragiaquepts
Venango	Fine-loamy, mixed, active, mesic Aeric Fragiaqualfs
Wellsboro	Coarse-loamy, mixed, active, mesic Typic Fragiudepts

Site 2 (about 75.773 N. latitude and 41.515 W. longitude) is located on a lower-lying, concave foot slope and includes delineations of Morris channery loam on 3 to 8 % slopes (MrB), Morris channery loam on 8 to 18 % slopes (MrC), and Norwich and Chippewa channery silt loams on 0 to 3 % slopes (NcA). These very deep soils formed in till derived from red sandstone, siltstone, and shale. Morris soils are somewhat poorly drained and have a fragipan at depths ranging from about 25 to 55 cm. The Norwich and Chippewa soils are poorly drained and very poorly drained and have a fragipan at depths ranging from about 25 to 60 cm and 20 to 50 cm, respectively. The taxonomic classifications of the named soils at both sites are listed in Table 1.

Mercer County:
The Odyssey well site (about 80.2038 N. latitude and 41.2400 W. longitude) is located in a wooded area about 3.4 kilometers northeast of Mercer, Pennsylvania. The site is located in a delineation of Canfield silt loam on 3 to 8 percent slopes, moderately eroded (CdB2). The very deep, moderately well drained Canfield soils formed in till on till plains. The depth to the fragipan ranges from about 38 to 76 cm. The taxonomic classification of Canfield soil is listed in Table 1.

Crawford County:
The Odyssey well site (about 80.1604 N. latitude and 41.8315 W. longitude) is located in pasture about 7.6 kilometers northeast of Venango, Pennsylvania. The site is located in a delineation of Venango silt loam on 0 to 3 percent slopes (VnA). The very deep, somewhat poorly drained Venango soils formed in low-lime till on till plains. The depth to the fragipan ranges from about 35 to 70 cm. The taxonomic classification of Venango soil is listed in Table 1.

Field Methods:
Pedestrian surveys were completed with both the EM38-MK2 meter and the Profiler across each site in Lackawanna and Crawford Counties. A pedestrian survey was completed with only the EM38-MK2 meter at the Mercer County site. Both devices were operated in the deeper-sensing, vertical dipole orientation. Both instruments were operated in the continuous mode with measurements recorded at a rate of 1/sec. The long axes of each device were orientated parallel to the direction of traverse, and held, where possible, about 5 cm above the ground surface. For the EM38-MK2 meter, EC_a data were recorded for both the 50 and 100 cm intercoil spacings. For the Profiler, EC_a data were recorded at 15 kHz. All EC_a data discussed in this report were temperature corrected to a standard temperature of 75° F.

Results:
Lackawanna County:
Site 1-Wellsboro Soil:
At the time of this survey, soils were moist in the surface layers, wet above the fragipan, and moist below suggesting episaturation conditions (requires saturated layers that overlie unsaturated layers within the upper 2 m)[2]. Episaturation is attributed to the perching of water from through-flow and overland flow above the fragipan. Table 2 provides basic statistics for the EC_a data that were collected at this site with the EM38-MK2 meter and the Profiler. With both instruments, EC_a was low and relatively invariable in this area of Wellsboro soils. With the EM38-MK2 meter, EC_a increased slightly with depth (comparison of measurements obtained in the deeper-sensing, 100-cm intercoil spacing with measurements obtained in the shallower-sensing, 50-cm intercoil spacing). When the EM38-MK2 meter is operated in the VDO, the maximum sensitivity of the 50 cm and 100 cm intercoil spacings are at depths of about 20 and 40 cm, respectively. As the depth to the fragipan and the perched water was about 30 to 40 cm, the higher values recorded with the 100 cm intercoil spacing are attributed to the higher water contents above the fragipan,

[2] Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson, 2002. Field book for describing and sampling soils, Version 2.0. USDA-Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

and the increased density of the fragipan. For measurements obtained in the shallower-sensing (0 to 75 cm exploration depth), 50-cm intercoil spacing, EC_a averaged about 5.7 mS/m, and ranged from about -17 to 31 mS/m. However, one-half of these measurements were between only about 5 and 7 mS/m. For the deeper-sensing (0 to 150 cm exploration depth), 100-cm intercoil spacing, EC_a averaged about 8.6 mS/m and ranged from about -3 to 13 mS/m. One-half of these measurements were between only about 8 and 9 mS/m. Atypically elevated positive and negative measurements are attributed to metallic artifacts scattered across the site.

In Table 2, the data obtained at two different frequencies with the Profiler are presented and can be compared with the data collected with the EM38-MK2 meter. The data set collected with the Profiler at 9 and 15 kHz are, for all intents and purposes, identical and suggest similar exploration depths. These data sets imply that the use of only one frequency (15 kHz) will sufficed for soil investigations.

Table 2. Apparent Conductivity Data from Site 1 – Wellsboro Soils

	EM38-MK2 50 cm	EM38-MK2 100 cm	Profiler 15000 Hz	Profiler 9000 Hz
Number	1877	1877	1465	1465
Minimum	-17.14	-2.63	1.67	-1.69
25%-tile	4.85	8.13	3.63	3.72
75%-tile	6.66	9.18	5.07	5.15
Maximum	30.58	12.86	11.89	11.97
Average	5.73	8.62	4.4	4.46
St. Dev.	1.8	0.92	1.16	1.22

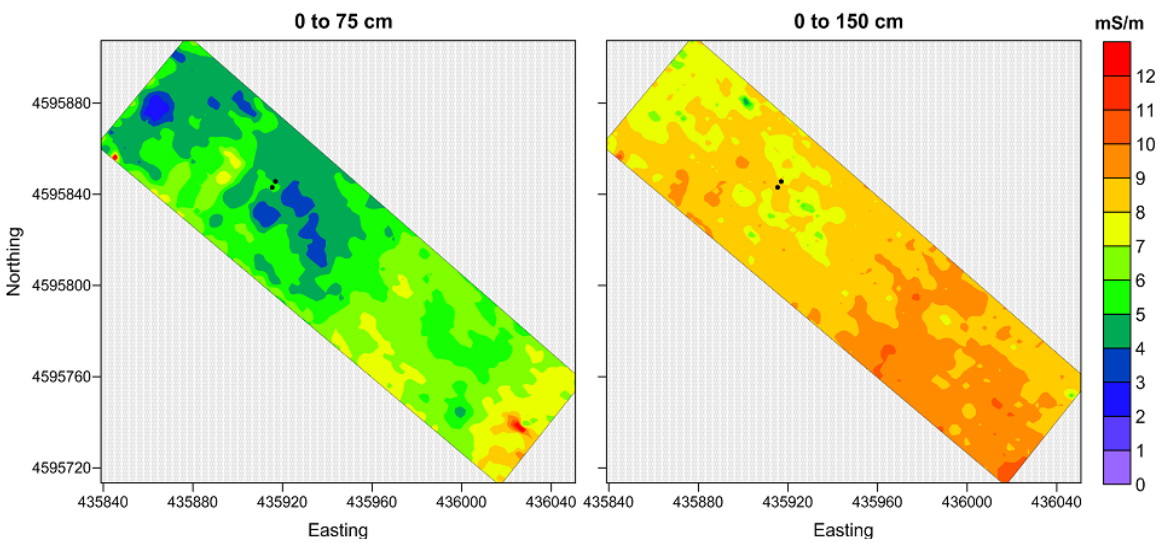

Figure 2. These plots of spatial EC_a patterns were generated from data collected with the EM38-MK2 meter at the Wellsboro soil site. The depth of effective exploration is shown above each plot. The two black dots in each plot represent the locations of the paired Odyssey wells.

Figure 2 shows the spatial EC_a patterns that were measured across the Wellsboro soil site with the shallower-sensing (0 to 75 cm) 50-cm (left-hand plot) and deeper-sensing (0 to 150 cm) 100-cm (right-hand plot) intercoil spacings of the EM38-MK2 meter. A comparison of these two plots shows that EC_a

is extremely low across the site with values increasing with increasing depth of exploration. Apparent conductivity is higher in the southeast corner of the site (lower corner in each plot) and decreases towards the northwest corner of the site (upper corner). The southeast corner consists of a higher-lying, included area of Morris soils. In each plot, intermediate values of EC_a are measured near the paired well sites.

Figure 3 contains a three-dimensional (3D) wireframe simulation of the Wellsboro soil site with a superimposed contour plot of the EC_a data measured with the deeper-sensing 100-cm intercoil spacing. In this simulation, the locations of the two paired well sites are identified by the black dots located on the lower side slope. Higher EC_a values occur on the higher-lying, convex summit area. This landscape component is occupied by the somewhat poorly drained Morris soils. The higher EC_a is associated with the higher moisture contents of the Morris soils. The moister to wetter soil conditions of Morris soils can be attributed to the accumulation of water above a more strongly developed fragipan or the lack of a horizontal component to water movement (through flow) in the soil. On the more sloping areas of Wellsboro soil, water is more likely to move diagonally down slope. Lower EC_a values occur on the lower-lying, more steeply-sloping side slopes that appeared better drained.

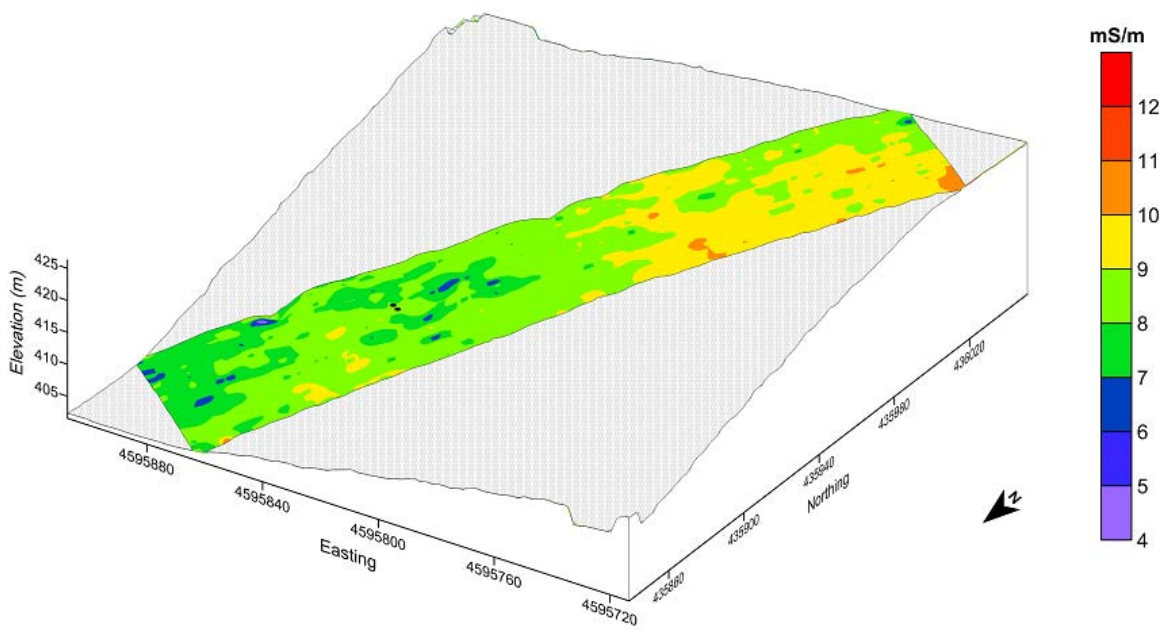

Figure 3. This three-dimensional representation of the Wellsboro soil site in Lackawanna County, Pennsylvania, shows the spatial distribution of EC_a across the surveyed area as measured with the 100-cm intercoil spacing of the EM38-MK2 meter. The two black dots represent the locations of the paired Odyssey wells.

Figure 4 compares spatial EC_a patterns that were measured across the Wellsboro soil site with the Profiler (left-hand plot) and the EM38-MK2 meter (right-hand plot). Only data collected with the Profiler at a frequency of 15 kHz and with the deeper-sensing 100-cm intercoil spacing of the EM38-MK2 meter are shown in this figure. The data in these plots appears similar as both EMI instruments have similar intercoil spacing (1.22 and 1.0 m) and operate at similar frequencies (15 and 14.5 kHz). As evident in Table 2 and Figure 4, the average EC_a measured with the Profiler is lower than measured with the EM38-MK2 meter. While the relative spatial distribution of EC_a is similar in both plots, differences in the

details are evident. These differences are attributed to differences in the number and track of traverses across the site, and to slight differences in depths of exploration. For both instruments, EC_a is higher in the southwest corner of the site (lower right portion of each plot) and decreases towards the northeast corner of the site (upper left-hand corner).

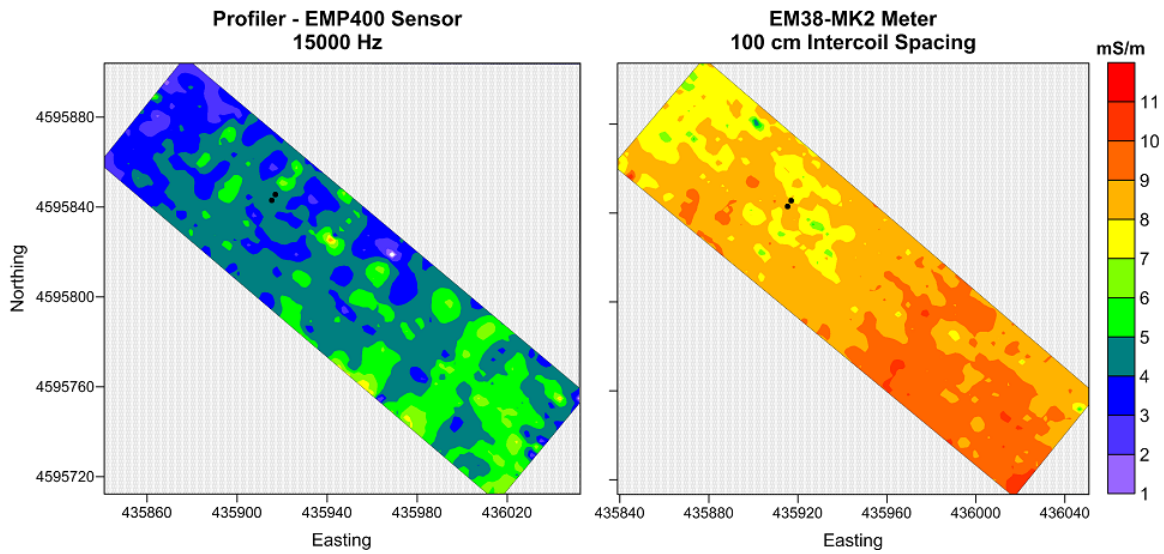

Figure 4. These plots compare spatial EC_a patterns and values measured with the Profiler (left) and the EM38-MK2 meter (right). The two black dots represent the locations of the paired Odyssey wells.

Site 2 – Morris soils

At the time of the EMI survey, soils were moist in the surface layers, wet above the fragipan, and wet below suggesting both episaturation and endosaturation conditions. Episaturation is attributed to the perching of water from through-flow and overland flow above the fragipan. Endosaturation is attributed to the water table.

Table 3. Apparent Conductivity Data from Site 2 – Morris Soils

	EM38-MK2 50 cm	EM38-MK2 100 cm	Profiler 15000 Hz	Profiler 9000 Hz
Number	559	559	551	551
Minimum	-15.2	4.42	-3.32	0.98
25%-tile	0.81	11.19	2.18	2.88
75%-tile	2.64	13.15	4.99	5.52
Maximum	21.8	17.85	11.59	9.31
Average	1.73	12.2	3.71	4.22
St. Dev.	2.07	1.47	2.09	1.77

Table 3 provides basic statistics for the EC_a data that were collected at this site with the EM38-MK2 meter and the Profiler. For the EM38-MK2 meter, EC_a increases with increasing depth (comparison of measurements obtained in the deeper-sensing 100-cm intercoil spacing with measurements obtained in the shallower-sensing 50-cm intercoil spacing). The higher values recorded with the 100 cm intercoil spacing are principally associated with higher water contents at and below the fragipan and differences in soil

density. For measurements obtained in the shallower-sensing 50-cm intercoil spacing, EC_a averaged only about 2 mS/m with a range of about -15 to 22 mS/m. Negative values are attributed to metallic artifacts scattered across the site and improper calibration of the meter. One-half of the measurements recorded with the 50-cm intercoil spacing were between only about 1 and 3 mS/m. The low values and restricted range can be attributed, in part, to the dense grass cover and the need to carry the meter at a slightly higher height during surveying (resulting in a larger column of air being measured). For the deeper-sensing 100-cm intercoil spacing, EC_a averaged about 12 mS/m and ranged from about 4 to 18 mS/m. One-half of these measurements were between about 11 and 13 mS/m. Compared with the higher-lying Wellsboro soil site, the deeper EC_a measurements are higher and more variable at the Morris soil site. However, the shallower EC_a measurements are generally lower at the Morris soil site. These differences may reflect the denser ground cover (and need to carry the meter at a higher height) and presence of more saturated conditions in the lower part of soil profiles at the Morris site.

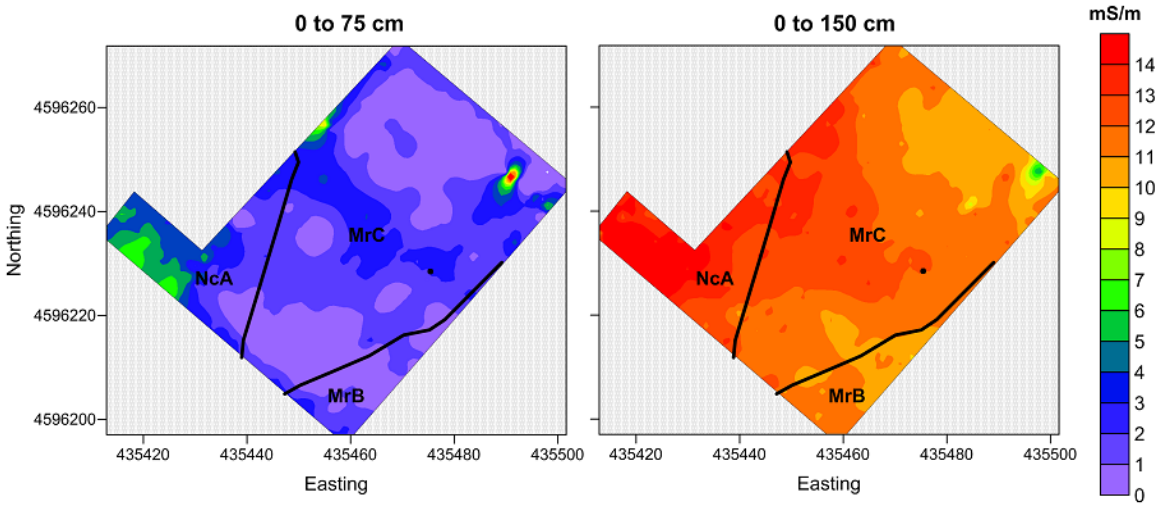

Figure 5. These plots of apparent conductivity were generated from data collected with the EM38-MK2 meter in a lower-lying area of dominantly Morris soils. The depth of effective exploration is shown above each plot. The black dot in each plot identifies the location of an Odyssey well.

Figure 5 contains plots of the EC_a data that were collected with the EM38-MK2 meter at the Morris site. The same color scales and ramps have been used in both of the plots. Soil boundary lines have been digitized from Web Soil Survey data.[3] In both plots, the general trend is for EC_a to increase towards the northwest portion of the survey area. This is the lowest-lying portion of the sites and includes areas of poorly drained and very poorly drained Norwich and Chippewa soils. As a consequence, this spatial trend is believed to reflect changes in soil moisture contents. As evident in these plots, a broad zone of slightly higher EC_a extends eastward (towards the right) and upslope from the Norwich and Chippewa unit (NcA) into the better drained unit of Morris channery loam on 8 to 18 % slopes (MrC).

The spatial trend across this landscape is perhaps more apparent in the plot shown in Figure 6. Figure 6 contains a three-dimensional (3D) wireframe simulation of the Morris soil site with a superimposed contour plot of the EC_a data measured with the deeper-sensing 100-cm intercoil spacing of the EM38-MK2 meter. The location of the Odyssey well site is identified with a black dot on the upper side slope. Surprisingly, this well is located at the apex of the zone of higher EC_a that extends downwards into the

[3] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [3/17/2011].

Norwich and Chippewa unit (NcA). This zone may represent a wetter area of preferential groundwater flow.

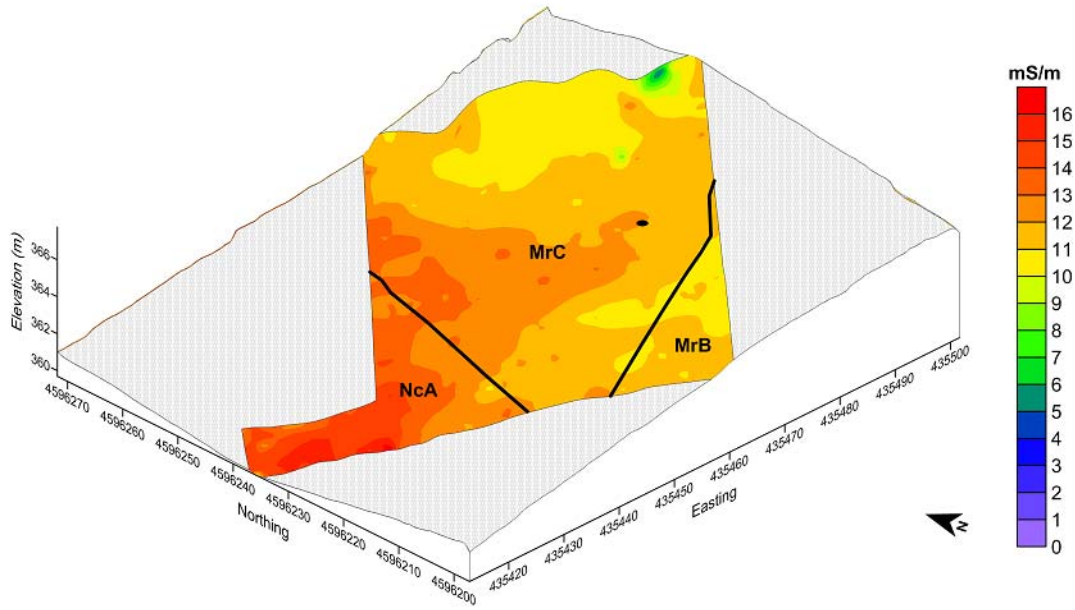

Figure 6. This three-dimensional representation of the Morris soil site in Lackawanna County, Pennsylvania, shows the spatial distribution of EC_a across the surveyed area. The two black dots represent the locations of the two, paired Odyssey wells.

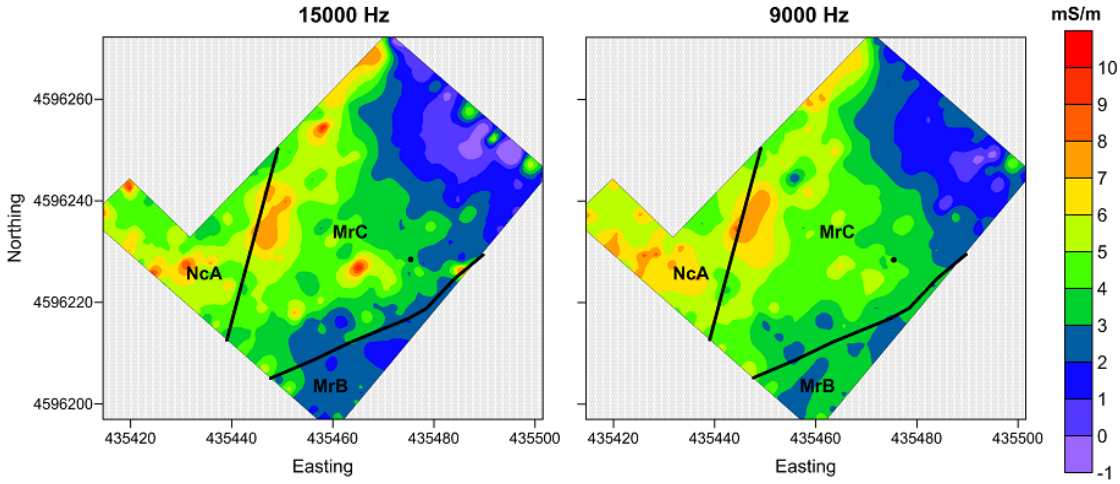

Figure 7. These plots of apparent conductivity were generated from data collected with the Profiler at the Morris soil site. The depth of effective exploration is shown above each plot. The black dot in each plot identifies the location of an Odyssey well

Figure7 contains plots of EC_a data collected with the Profiler at frequencies of 15 (left-hand plot) and 9 (right-hand plot) kHz. These frequencies most closely approximates the frequencies of the EM38 MK2

(14.6 kHz) and the EM31 (9.8 kHz) meters manufactured by Geonics Limited. As EC_a values and spatial patterns are closely similar in each plot, these frequencies appear to provide similar depths of exploration. As a consequence, no added benefit was achieved by conducting surveys with the Profiler at these two different frequencies; one frequency would suffice. Compared with the EC_a data measured with the EM38-MK2 meter, data collected with the Profiler produced similar spatial patterns, but slightly lower EC_a across the Morris soil site. The average EC_a measured with the EM38-MK2 meter is about 2 and 12 mS/m for the 50- and 100-cm intercoil spacings respectively (Table 3). The average EC_a measured with the Profiler is only about 4 mS/m at both frequencies (15 and 9 kHz) (Table 3).

Mercer County:

Canfield Soil:

At the time of the EMI survey, soils were moist in the surface layers, wet above the fragipan, and moist below suggesting episaturation conditions. The Odyssey well at this site had been vandalized and was inoperative at the time of this survey.

Table 4. Apparent Conductivity Data from Mercer County Site- Canfield Soils

	EM38-MK2 50 cm	EM38-MK2 100 cm
Number	919	919
Minimum	6.60	5.80
25%-tile	8.87	8.76
75%-tile	10.21	10.26
Maximum	13.20	12.50
Average	9.59	9.56
Std. Dev.	0.94	1.04

In this area of Canfield soil, the measured EC_a is considered low for medium-textured Alfisols. Table 4 provides basic statistics for the EC_a data that were collected at this site with the EM38-MK2 meter. Apparent conductivity remained constant with soil depth (measured about 9.6 mS/m for both intercoil spacings). Consistent values and ranges suggest fairly homogeneous soil conditions both spatially and vertically. For measurements obtained in the shallower-sensing 50-cm intercoil spacing, EC_a ranged from about 7 to 13 mS/m. One-half of these measurements were between about 9 and 10 mS/m. For the deeper-sensing 100-cm intercoil spacing, EC_a ranged from about 6 to 12 mS/m. One-half of these measurements were also between about 9 and 10 mS/m.

Figure 8 contains plots of the EC_a data that were collected with the EM38-MK2 meter at the Canfield soil site. The same color scales and ramps have been used in both of the plots shown in Figure 8. The general trend across this site is for EC_a to decrease towards northwest. Though the survey area is located within a delineation of Canfield silt loam on 3 to 8 percent slopes, moderately eroded (CdB2), a unit of Ravenna silt loam on 3 to 8 % slopes, moderately eroded (RaB2) has been mapped a short distance away in this direction (northwest). The very deep, somewhat poorly drained Ravenna (fine-loamy, mixed, active, mesic Aeric Fragiaqualfs) soils also formed in till on till plains. Compared with Canfield soils, Ravenna soils occur on lower-lying positions in the landscape and are more imperfectly drained. Assuming higher soil moisture content, if all other factors are equal, the Ravenna soils should display a higher EC_a (which is not the case suggested in Figure 8) than Canfield soils. The occurrence of lower EC_a in this portion of the survey area suggests the possibilities of soils with slightly lower clay contents, deeper depths to argillic horizon, less perched water above the fragipan, and/or less dense fragipans.

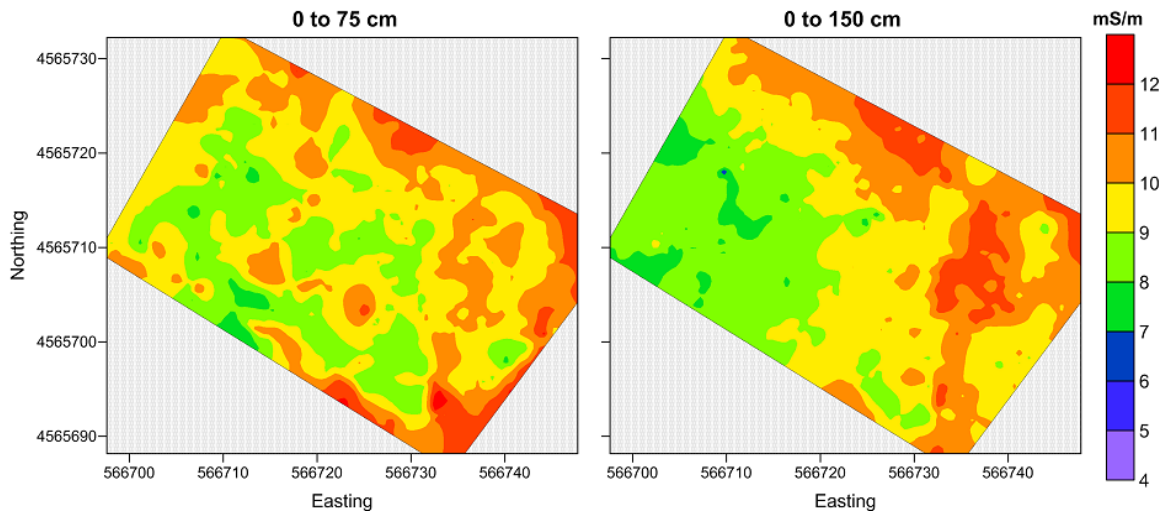

Figure 8. These plots of apparent conductivity were generated from data collected with the EM38-MK2 meter in a wooded area of Canfield silt loam on 3 to 8 percent slopes, moderately eroded (CdB2). The depth of effective exploration is shown above each plot.

<u>Crawford County:</u>

Venango Soil

Table 5 provides basic statistics for the EC_a data that were collected at the Venango soil site in Crawford County with the EM38-MK2 meter and the Profiler. For the EM38-MK2 meter, EC_a increases with increasing depth (comparison of measurements obtained in the deeper-sensing 100-cm intercoil spacing with measurements obtained in the shallower-sensing 50-cm intercoil spacing). Higher values recorded with the 100-cm intercoil spacing can be associated with higher water contents at and below the fragipan.

Table 5. Apparent Conductivity Data from Crawford County Site- Venango Soils

	EM38-MK2 50 cm	EM38-MK2 100 cm	Profiler 15000 Hz
Number	580	580	659
Minimum	-73.42	-85.13	-14.74
25%-tile	-0.59	10.00	3.89
75%-tile	1.18	11.72	7.27
Maximum	84.54	191.96	67.56
Average	1.36	12.50	6.01
Std. Dev.	9.09	16.12	5.53

In Table 5, for measurements obtained in the shallower-sensing 50-cm intercoil spacing, EC_a averaged only about 1 mS/m with a range of about -73 to 84 mS/m. Negative values are attributed to the presence of a large metallic artifact(s) buried at this site. One-half of the measurements collected with the 50-cm intercoil spacing were between only about -1 and 1 mS/m. These very low values reflect, in part, the inability to properly calibrate the more sensitive 50-cm intercoil spacing. Measurements taken with the 50-cm intercoil spacing are therefore suspected of errors. For the deeper-sensing 100-cm intercoil spacing, EC_a averaged about 12 mS/m and ranged from about -85 to 192 mS/m. This large range is attributed to the presence of large buried metallic artifact(s) within the site. One-half of the measurements collected with the 100-cm intercoil spacing were between only about 10 and 12 mS/m. The very narrow interquartile range suggests relatively homogenous soil conditions across at least 50 %

of the site. Apparent conductivity averaged only about 6 mS/m for measurements obtained with the Profiler operating at 15 kHz. These measurements ranged from about -15 to 68 mS/m. One-half of the measurements collected with the Profiler were between only about 4 and 7 mS/m. Compared with the EC_a measured with the EM38-MK2 meter, the narrower range of the Profiler's measurements suggests that it is less sensitive to the artifacts buried.

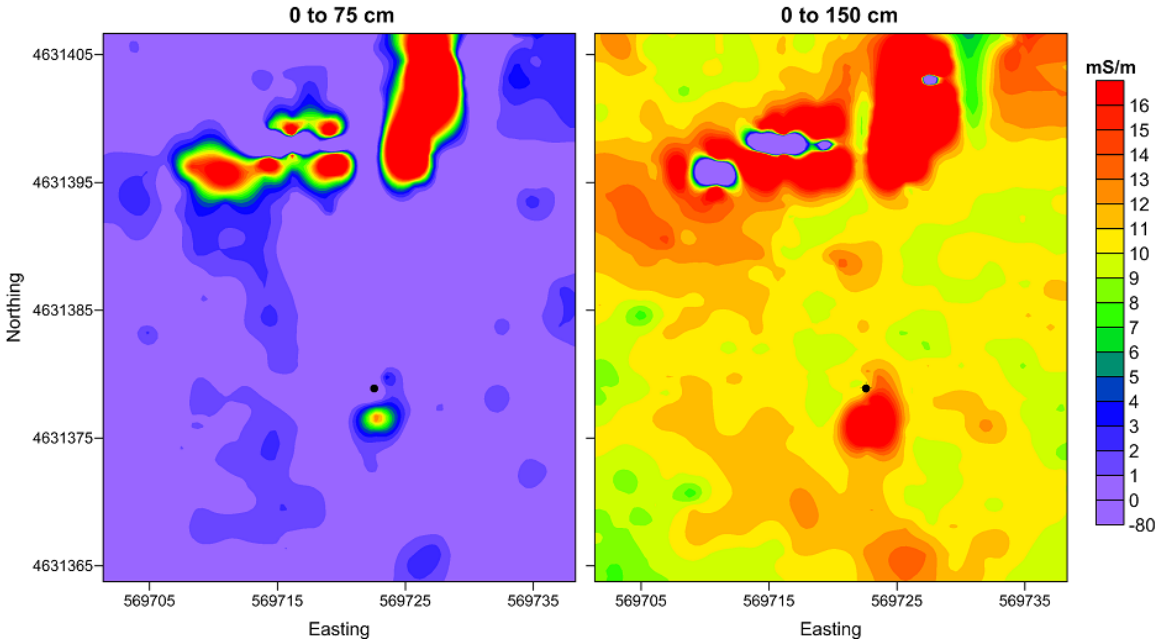

Figure 9. These plots of EC_a were generated from data collected with the EM38-MK2 meter at the Venango soil site in Crawford County. The depth of effective exploration is shown above each plot. The black dot in each plot identifies the location of an Odyssey well.

Figure 9 shows the spatial distribution of EC_a across the Venango soil site as measured with the EM38-MK2 meter operating in the shallower-sensing 50-cm (left-hand plot) and deeper-sensing 100-cm (right-hand plot) intercoil spacing. A comparison of the two plots reveals that EC_a increases with increasing soil depth. The Venango soil has a Btx horizon that has greater clay content than surface layers, which, along with the perched water, may explain, in part, this observed depth relationship.

In each plot shown in Figure 9, a black dot signifies the location of the Odyssey well. A large, subsurface, anomalous feature(s) is evident in the northern portion of each plot. This feature(s) was not investigate and identified. In the plot of the deeper-sensing, 100 cm intercoil spacing, the feature appears to form a broad, linear pattern with a long axis that parallels the slope. This pattern brings to mind the possibility of an eroded gully that has been filled with buried cultural debris. The anomalous feature near the well is an equipment bag that had been placed on the ground while the data from the well were transferred to a PC. With the exception of these features, EC_a appears relatively invariable across the site, suggesting fairly homogeneous soil properties.

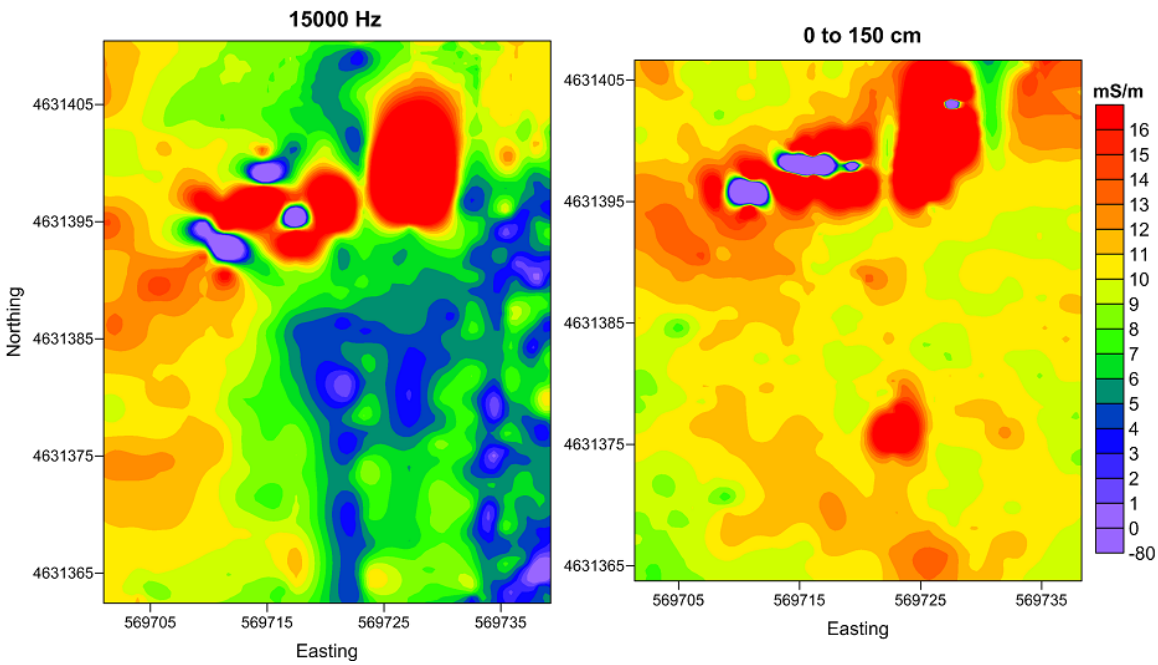

Figure 10. These plots compare spatial EC_a patterns and values measured with the Profiler (left) and the EM38-MK2 meter (right). For these two instruments the operating frequencies and intercoil spacings are similar.

Figure 10 compares spatial EC_a patterns that were measured across the Venango soil site with the Profiler (left-hand plot) and the EM38-MK2 meter (right-hand plot). As evident in Figure 10, slightly different areas were surveyed with each instrument. Only data collected with the Profiler at a frequency of 15 kHz and with the deeper-sensing 100-cm intercoil spacing of the EM38-MK2 meter are shown in this figure. Assuming that the depth of exploration is *geometry limited* with these instruments, these sets of data represent similar measured soil depths and volumes, and should therefore be the closely similar (exploration depths of about 180 cm and 150 cm for the Profiler and the EM38-MK2, respectively). As evident in Table 5 and Figure 10, the average EC_a measured with the Profiler is lower than the average EC_a measured with the EM38-MK2 meter. This is attributed to differences in intercoil spacing, frequency, and instrument calibration. The anomalous zone in the northern portion of the survey areas have been picked up with both meters. Differences in spatial patterns are attributed to differences in the number and track of traverses across the site, instrument calibration, and to differences in depths of exploration.

Figure 11 contains a three-dimensional (3D) wireframe simulation of the Venango soil site with a superimposed contour plot of the EC_a data measured with the deeper-sensing 100-cm intercoil spacing of the EM38-MK2 meter. In this simulation, the location of the Odyssey well is identified with a black dot. Elevations are based on imprecise GPS measurements. The north-south trending ripple mark in the elevation data corresponds to the location of a fence line, which evidently caused multipathing of the signal that lead to this discrepancy in the elevation data. In this plot, the axis of the anomalous zone can be seen to parallels the slope gradient.

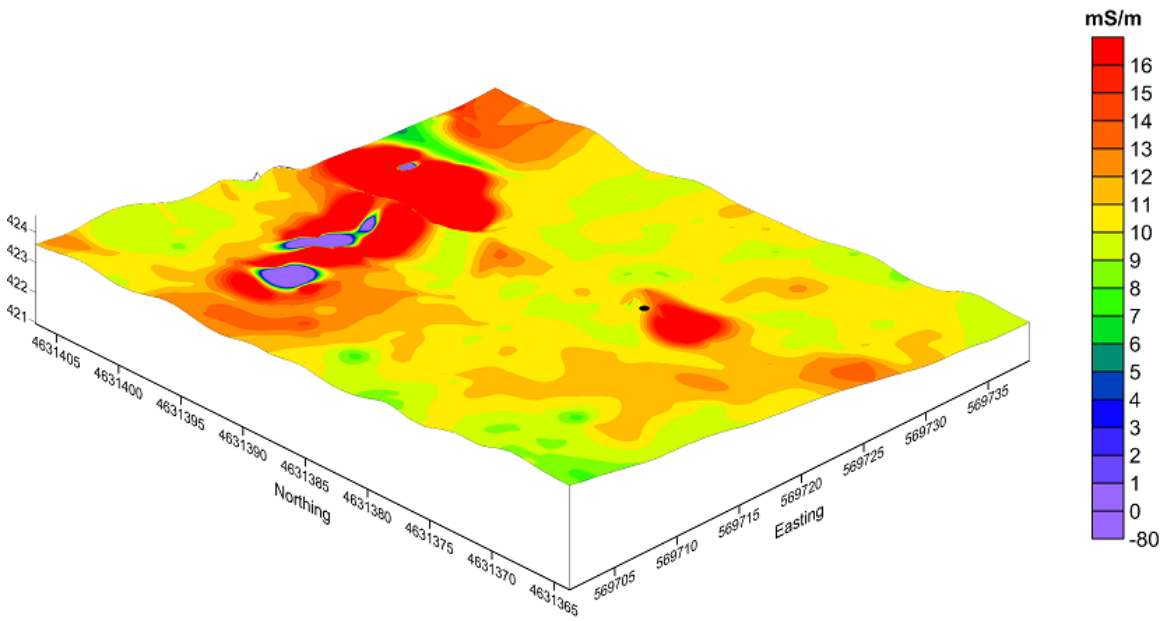

Figure 11. This three-dimensional representation of the Venango soil site in Crawford County, Pennsylvania, shows the spatial distribution of apparent conductivity collected with the 100 cm intercoil spacing of the EM38-MK2 meter across the surveyed area. The black dot represents the location of the Odyssey well.

Technical Report on Ground-Penetrating Radar (GPR) Investigations of Fragipans in Lackawanna, Mercer, and Crawford Counties, Pennsylvania, 21 to 27 April 2011.

The presence, spatial continuity and expression of fragipans are difficult to characterize with conventional soil survey tools. As fragipans form a depth restrictive layer to water and tree roots, they play an important role in near-surface hydrological processes. For nearly thirty years, ground-penetrating radar (GPR) has been used to chart the depth, lateral extent, and continuity of fragipans (Doolittle et al., 2000; Lyons et al., 1988; Olson and Doolittle, 1985). Results have had varied degrees of success, with the effectiveness of GPR being highly site and parent material specific. Temporal differences in the expression of fragipans on radar records are not well documented. The plan of this study is to profile soils with fragipans at different times of the year (under both wet (spring) and Dry (fall) conditions) and evaluate the performance of GPR.

GPR System:

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[4] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 4.1 kg (9 lbs)

[4] Trade names are used for specific references and do not constitute endorsement.

and is backpack portable. With an antenna, the SIR-3000 requires two people to operate. Jol (2009) and Daniels (2004) discuss the use and operation of GPR. A 200 MHz antenna was used in this investigation.

The RADAN for Windows (version 6.6) software program; developed by GSSI) was used to process the radar records shown in this report.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, signal stacking, and range gain adjustments (refer to Jol (2009) and Daniels (2004) for discussions of these techniques).

Calibration of GPR:

Ground-penetrating radar is a time scaled system. The system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, bedrock) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in equation [1] (after Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to equation [2] (after Daniels, 2004):

$$E_r = (C/v)^2 \qquad [2]$$

Where C is the velocity of propagation in a vacuum (0.298 m/ns). Typically, velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v. The dielectric permittivity ranges from 1 for air, to 78 to 88 for water (Cassidy, 2009). Small increments in soil moisture can result in substantial increases in the relative permittivity of soils (Daniels, 2004). Using a 100 MHz antenna, Daniels (2004) observed that the relative permittivity of most dry mineral soil materials is between 2 and 10, while for most wet mineral soil materials, it is between 10 and 30.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (buried metal plate), the velocity of propagation and the relative dielectric permittivity through the upper part of the soil profiles were estimated using equations [1] and [2]. At the Lackawanna County sites (Morris and Wellsboro soils), the estimated E_r and v were 14.4 and 0.0785 m/ns, respectively. At the Crawford County site (Venango soils), the estimated E_r and v were 25.2 and 0.0594 m/ns, respectively. At the time of these studies, soils were moist and water was observed to be perched above the fragipan. The Venango soil was noticeably wetter than the Morris or Wellsboro soils.

Detecting Fragipans with GPR:

The amount of energy reflected back to an antenna is a function of the dielectric gradient that exists across a soil interface or boundary. The greater and/or more abrupt the contrast in the dielectric properties of adjoining soil materials, the greater the amount of energy reflected back to the antenna, and the more intense and conspicuous the amplitude of the reflected signal appearing on radar records. Soil horizons, layers, and features that have similar relative permittivity are poor reflectors of electromagnetic energy and are difficult to identify on radar records.

The E_r of soil materials is therefore strongly dependent upon moisture content. As a consequence, the amount of energy reflected back to the radar's antenna is greatly influenced by the abruptness and difference in moisture contents that exist between soil horizons, layers or features. The perching of water above a relatively denser and drier fragipan is expected to increase the difference in relative dielectric permittivity across the upper boundary of the fragipan making this interface more easily detected and

traced on radar records. In this investigation, this hypothesis was tested when these conditions were most ideal; during a wetter spring month

Results:
Figures 12, 13, and 14 are representative radar records that were collected over areas of the moderately well drained Wellsboro (coarse-loamy, mixed, active, mesic Typic Fragiudepts), somewhat poorly drained Morris (coarse-loamy, mixed, active, mesic Aeric Fragiaquepts), and somewhat poorly drained Venango (fine-loamy, mixed, active, mesic Aeric Fragiaqualfs) soils, respectively. Signal processing and careful selection of signal color and transform settings are imperative to correctly identify fragipan. Fragipans are often difficult to recognize on raw, unprocessed radar records.

On each radar record, the upper boundary of the fragipan has been identified with a green-colored, segmented line. With the broader wavelength of the 200 MHz antenna, it is generally difficult to resolve features occurring within depths of 40 cm of the soil surface. Vertical resolution is dependent on the wavelength. In general vertical resolution (Rv) is theoretically about ¼ of the wavelength (λ). If two events are separated in time by less than this length, they will be indistinguishable and interpreted as one event. The wavelength is determined by dividing the propagation velocity (v) by the antenna frequency (f).

$$\lambda = v/f \qquad [3]$$

At the Wellsboro and Morris soil sites, the estimated v was 0.0785 m/ns. With a 200 MHz antenna, according to equation [3], λ is about 40 cm. Theoretically, the vertical resolution should be about 10 cm in areas of Wellsboro and Morris soils. However, as evident in Figure 13, the strong surface pulse obscured reflections from the fragipan where it occurs within depths of 40 cm. On the radar record of Wellsboro soil (Figure 12), the fragipan occurs at a deeper depth and is therefore more easily (and confidently) traced laterally.

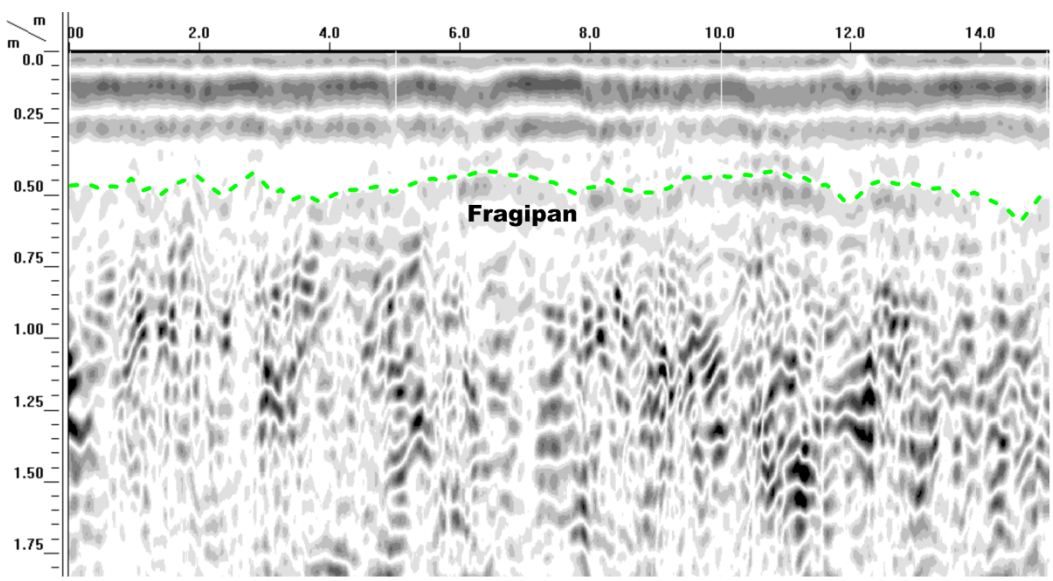

Figure 12. Representative radar record of an area of Wellsboro soil with the upper boundary of the fragipan identified with a segmented, green-colored line.

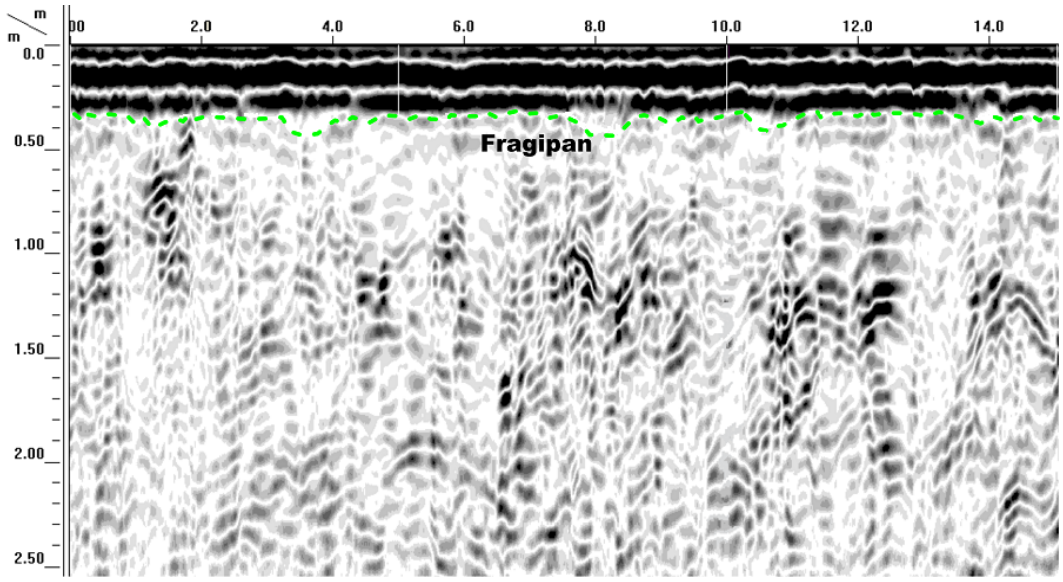

Figure 13. Representative radar record of an area of Morris soil with the upper boundary of the fragipan identified with a segmented, green-colored line.

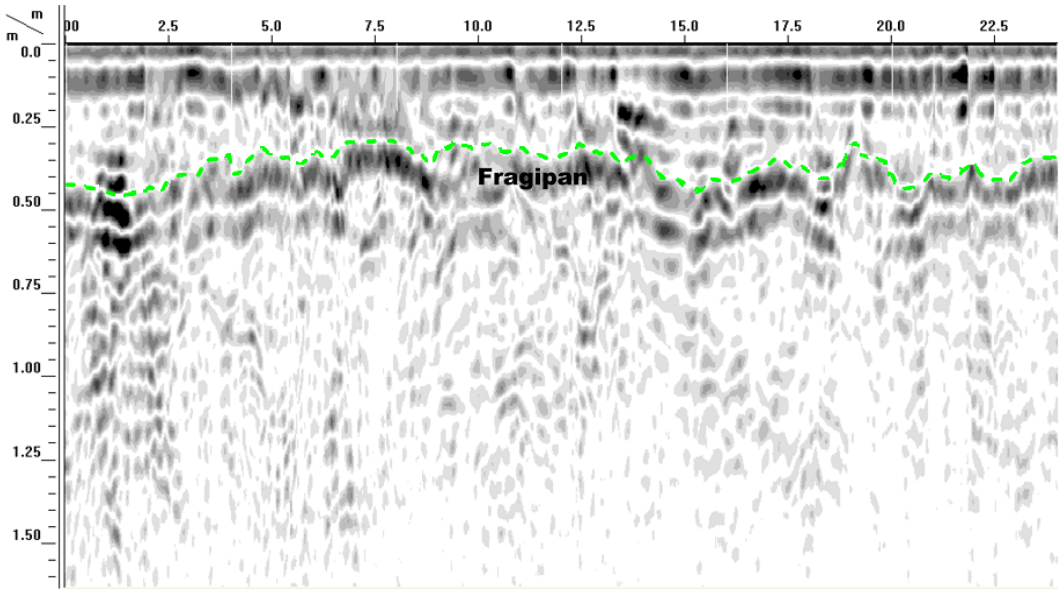

Figure 14. Representative radar record of an area of Venango soil with the upper boundary of the fragipan identified with a segmented, green-colored line.

On the radar records collected over the Wellsboro and Morris soils (Figures 12 and 13), the fragipan appears laterally discontinuous with noticeable variations in signal amplitudes. Signal amplitudes increase (become darker in our representations) where an interface boundary is more abrupt and contrasting. These properties evidently vary along the Bw/Bx boundaries of both Wellsboro and Morris soils. Comparing the representative radar records from Wellsboro and Morris soils (Figures 12 and 13) with the radar record from Venango soils (Figure 14), the contrast in signal amplitudes and expression of the fragipan is evident. The Venango soil is finer textured and has a Bw/Btx horizon that provides greater contrast and expression on radar records (collected under relatively wet conditions with a perched water

table) that the Bw/Bx boundaries of the Wellsboro and Morris soils. In addition, at the time of these GPR surveys, the Venango soil was noticeably wetter.

As previously observed in an area of Erie (fine-loamy, mixed, active, mesic Aeric Fragiaquepts) soils, the absence of a Bt horizon overlying a Btx horizon enabled the resolution of the fragipan (my trip report to Edgar White dated 5 September 2007). However, the argillic horizon of Venango soils occurs at a shallow depth and its reflection is part of and has been masked by the strong surface pulse.

Soil moisture conditions under which these investigations were conducted appear favorable for the detection of fragipan with GPR. The presence of perch water favors the detection of fragipan. Returning to these sites during drier fall conditions will help to verify this observation.

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