United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI – Geophysical Field Assistance **Date:** 15 December 2011

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Purpose:
To explore the potentials of using electromagnetic induction (EMI) to map differences in soil mineralogy and heavy metals in areas of serpentine soils.

Participants:
John Chibirka, Soil Scientist, USDA-NRCS, Leesport, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA

Activities:
All field activities were completed during on 12 December 2011.

Summary:

1. Anomalous EMI responses were measured over soils formed in residuum weathered from serpentinite rock. Spatial patterns of apparent conductivity and in-phase data may provide a means to differentiate soils formed over different lithologies, assess mineralogical composition of soils, and detect concentrations of naturally occurring heavy metals (Cr and Ni).

2. Using the measured EMI data and a response surface sampling design model, a 12-point optimal sampling design has been identified. The study site will be returned to and small grab samples will be collected from the 0 to 30 and 30 to 60 cm soil depths using a soil auger at the 12 identified points. These samples will be sent to Richard Shaw (New Jersey State Soil Scientist) for an analysis of heavy metals using an Olympus portable XRF (X-ray fluorescence). Correlations analysis will be performed on the EMI and XRF data and a report filed.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Background

Serpentinite rock outcrops in portions of southeastern Pennsylvania and north-central Maryland. Serpentinite is an Mg-rich, sub-siliceous rock, which is formed principally through the metamorphic alteration of dunite, peridotite, or pyroxenite, which are comprised of antigorite, chrysotile, and lizardite serpentine minerals (Istok and Hayward, 1982). Soils formed over serpentinite have low Ca/Mg ratios, are low in essential nutrients, and have high concentrations of heavy metals (nickel and chromium) that are toxic to many plant species. Unique plant communities grow on these soils. These unique plant communities contain few species that are common with the species found in the surrounding forest or fields. Known as *serpentine barrens,* prairie grasses, greenbrier, and pitch pines are the dominant communities.

In Chester County, moderately deep, well-drained Chrome soil has been mapped on the *serpentine barrens* (Kunkle, 1963). Chrome is a rare and unique series, and a member of the fine, mixed, superactive, mesic Typic Hapludalfs taxonomic family. However, the taxonomic classification, in particular the mineralogy, of this series is being reexamined. The deep, moderately well to somewhat poorly drained Conowingo soils also form in materials weathered from serpentinite rock, and are members of the same catena as Chrome. The Conowingo series, however, is a member of the fine-loamy, magnesic, mesic Aquic Hapludalfs taxonomic family.

Magnetic susceptibility influences all EMI data to some extent, but, in most soils, the affects are generally small. However, in areas of serpentinite rocks and residuum, the affects of magnetic susceptibility are suspected to be high. The magnetic properties of soils principally reflect mineralogy (Magiera et al., 2006). For most soils, magnetic susceptibility is low, its affects on electromagnetic field strengths minimal, and its presence generally ignored. However, some ferromagnetic minerals, such as maghemite, magnetite, titanomagnetites magnetite, siderite, hematite, ilmenite, pyrrhotite, and chromite, exhibit noticeable levels of magnetic susceptibility (Takahashi et al., 2011; van Dam et al. 2004; Mullins, 1977). The magnitude of the magnetic susceptibility response depends on the concentration, size, and shape of these minerals and the method of measurement (Mullins, 1977). Magnetic susceptibility has been associated with several soil properties including parent material, soil age, particle size, organic matter and soil moisture contents (Maier et al., 2006; van Dam et al. 2004; Mullin, 1977).

Areas of Chrome and Conowingo soils are suspected to exhibit conspicuous levels of magnetic susceptibility. Magnetic susceptibility is commonly measured with a magnetometer. However, EMI sensors can be used as a surrogate to infer levels of magnetic susceptibility. Early EMI sensors, such as the EM38 meter, could only measure one component (in-phase phase or apparent conductivity) at a time. As a consequence, operators generally opted to measure the EC_a and therefore the in-phase component was seldom measured. This has lead to a lack of understanding of the affects of magnetic susceptibility on EMI data. The objective of this study is to use EMI in areas of Chrome and Conowingo soils to attain a better understanding of its response in areas of serpentinite rocks.

Electromagnetic Induction, Principals of Operation:

Alternating electrical currents in an EMI meter's transmitter coil generate a time-varying, primary electromagnetic field. This primary electromagnetic field induces an electromagnetic force into the ground which in turn generates eddy currents and a secondary electromagnetic field in the soil. The secondary electromagnetic field, which is sensed by the receiver coil, consists of two components: an in-phase and a quadrature component. The in-phase component is in-phase with the primary electromagnetic field. The quadrature is out of phase (leads by 90 degrees) with the primary electromagnetic field. The strength of the secondary electromagnetic field, measured in the quadrature component, is directly proportional, under condition of *low induction numbers* (LIN) to the apparent conductivity (EC_a) of the soil.

Electromagnetic induction meters are calibrated to covert quadrature component directly into measures of apparent conductivity (EC_a). Apparent conductivity is expressed in milliSiemens per meter (mS/m). Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is mostly influenced by the volumetric water content, type and concentration of ions in solution, amount and type of clays in the soil matrix, and temperature and phase of the soil water (McNeill, 1980). The apparent conductivity of soils increases with increased soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

The in-phase component of the secondary electrical field is strongly affected by the presence of ferromagnetic minerals in the soil. The magnitude of the in-phase response can therefore be used to as a surrogate to infer magnetic susceptibility. The in-phase component is assumed to be directly proportional to apparent the magnetic susceptibility (MS_a) of the soil (Simpson et al., 2009). Apparent magnetic susceptibility affects all EMI data to some extent, but, in most soils, its affects are less significant than the affects of EC_a.

During *final in-phase nulling* calibration of the EM38-MK2 meter in the field, the in-phase component is set to an arbitrary zero value. The zero-level is therefore a relative measurement depending on the location and value of the in-phase component at the point of calibration. As a consequence of this subjectivity, quantitative measurements are impracticable. In addition, meters are unstable in maintaining a zero-level (North and Simms, 2007). With EMI meters, the in-phase readings are automatically converted into parts per thousand (ppt) of the primary electromagnetic field's intensity.

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 apparent conductivity and in-phase readings over two depth intervals.

The Geonics DAS70 Data Acquisition System was used with the EM38-MK2 meter to record and store both EC_a and GPS data.[1] The acquisition system consists of the EM38-MK2 meter, an Allegro CX field computer (Juniper Systems, Logan, Utah), and Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA).[1] With the acquisition system, the EM38-MK2 meter is keypad operated and measurements are automatically triggered. 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]

To help summarize the results of the EMI surveys, SURFER for Windows (version 10.0) software (Golden Software, Inc., Golden, CO) was used to construct the simulations shown in this report.[1]

Study Sites:
The study site is located in Nottingham County Park. The park is located near the town of Nottingham in extreme southwestern Chester County near the Maryland state line. Figure 1 is a soil map of the survey area. The survey area extends further down slope towards a stream and contained a greater portion of a hay field and a lesser portion of a cultivated field than the area that was earlier surveyed in November 2011. In Figure 1, the survey area is identified by segmented lines that form its boundaries.

Relief at the site is about 19 m. The hay land is mapped as Chrome silt loam on 8 to 15 % slopes, moderately eroded (ChC2). The cultivated field is largely mapped as Glenelg silt loam on 3 to 8 % slopes (GgB), but does contain a small strip of ChC2 along its southern boundary (see Figure 1). The very deep, well drained Glenelg soils formed in residuum weathered from micaceous schist. Glenelg series is a member of the fine-loamy, mixed, semiactive, mesic Typic Hapludults family.

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

Field Methods:
A pedestrian survey was completed with the EM38-MK2 meter across the site. The EM38-MK2 meter was operated in the deeper-sensing, vertical dipole orientation (VDO). The instrument was operated in the continuous mode with measurements recorded at a rate of 1/sec. The long axes of the meter was orientated parallel to the direction of traverse, and held, where possible, about 5 cm above the ground surface. The data discussed in this report were not temperature corrected to a standard temperature of 75^{o} F. Because of the calibration difficulties and the instability of measurements collected with the 50-cm intercoil spacing, only measurements recorded with the 100 cm intercoil spacing of the EM38-MK2 meter were used.

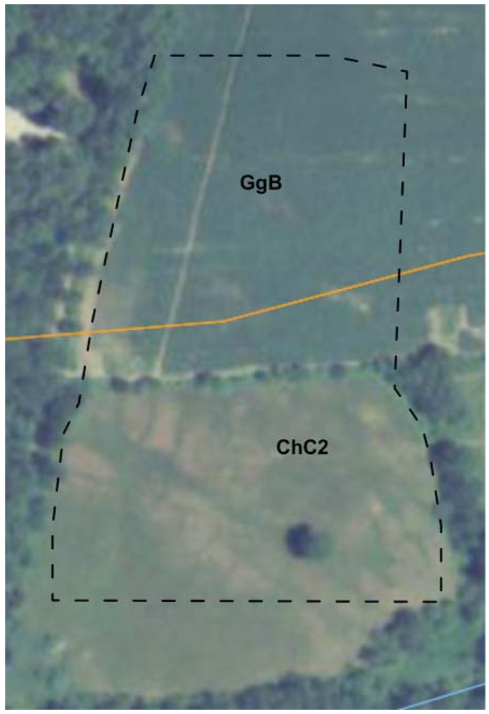

Figure 1. This soil map of the areas surveyed in Nottingham County Park is from the Web Soil Survey

Results:
Basic statistics for the EMI data are provided in Table 1. The nominal depth of penetration for the EM38-MK2 meter operated in the vertical dipole orientation is 150 cm. The bulk averaged EC_a was 14.3 mS/m and ranged from about 2.6 to 31.3 mS/m. One-half of the 4465 measurements were between about 10.9 and 17.1 mS/m. These values are considered slightly high for Glenelg soils, but may be characteristic for Chrome soils.

Table 1. Basic Statistics for the EMI Data measured with the EM38-MK2 in the Fields at Nottingham County Park.

	In-phase (ppm)	EC_a (mS/m)
Number	4465	4465
Minimum	2.58	0
25%-tile	10.86	141.64
75%-tile	17.07	188.67
Maximum	31.29	530.16
Mean	14.26	173.45
Std. Deviation	4.77	55.42

The IP data shown in Table 1 has been adjusted to reflect only positive values (lowest recorded measurement was adjusted to zero and all others measurements adjusted accordingly). The recorded values are considered anomalous, reflecting the magnetic susceptibility of the soils. The IP measurements averaged 173 ppt and ranged from 0 to about 530 ppt. One-half of the 4465 measurements were between about 142 and 189 ppt. This range of IP values is not commonly observed in undisturbed, natural settings and is believed to reflect the magnetic susceptibility of the soils.

Figure 2 contains plots showing the spatial apparent conductivity (left-hand plot) and in-phase (right-hand plot) patterns across the study site. The soil boundary line has been digitized from Web Soil Survey data[2]. Comparing the two plots, areas mapped as Chrome soils have noticeably higher EC_a than areas mapped as Glenelg soils. In general, areas mapped as Chrome have lower IP values, but are pockmarked by small isolated areas of exceedingly high IP values, which are not so evident in areas mapped as Glenelg soils. Based on the collected data, soils with suspected high magnetic susceptibility (Chrome soils) display a greater range and more irregular and unpredictable patterns of both IP and EC_a. A quick view of the spatial patterns in Figure 2, suggest a readjustment of the soil boundary line from its present east-west orientation to a more northwest to southeast orientation.

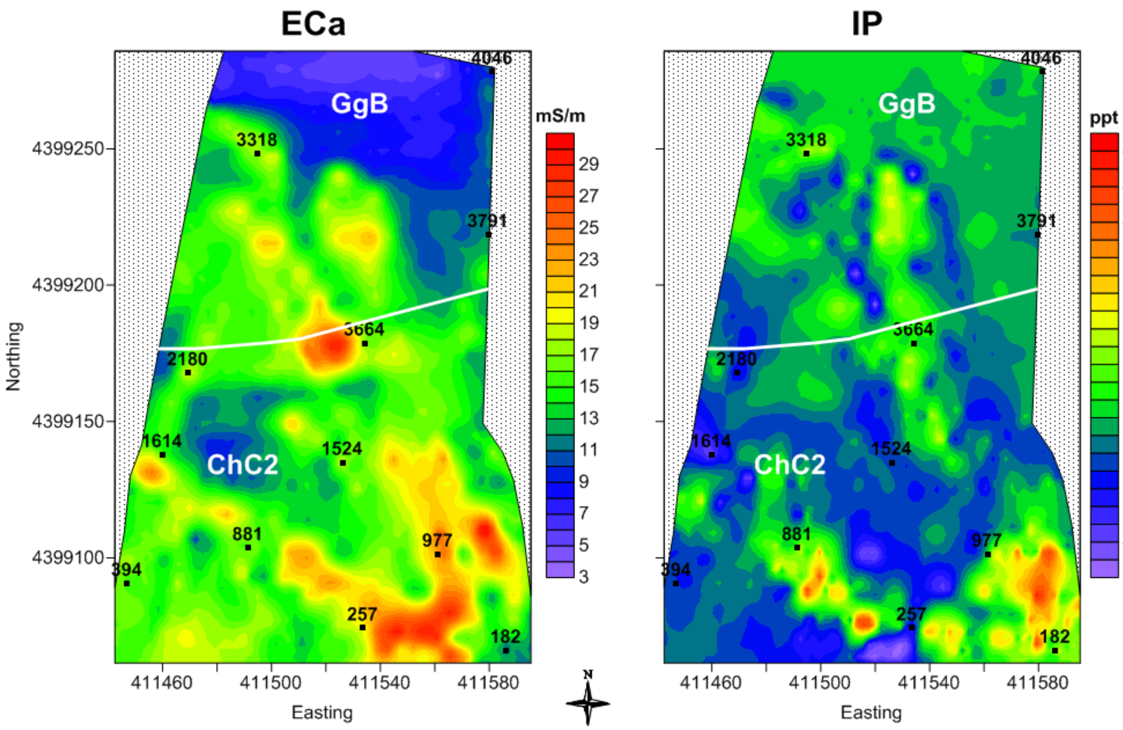

Figure 2. Spatial EC_a (left-hand) and In-phase (right-hand) data are shown in these plots of the study site at Nottingham County Park.

In Figure 2, short-range differences in lithology and mineralogy are believed to be the principal factors responsible for the spatial patterns. Linear pattern evident in the plot of EC_a, and also, but to a lesser degree, in the plot of in-phase data, are believed to reflect lithologic seams of dissimilar mineralogy. High spatial variability in soil mineralogy and underlying lithology is suggested by the intricate spatial patterns.

Figure 3 is a three-dimension wire frame image of the study area that has been simulated from elevation data collected with the Trimble AgGPS 114 L-band DGPS (differential GPS) antenna. Superimposed on this

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[2] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [11/7/2011].

wireframe is the EC_a data set. It is evident in this plot that lineations traverse rather than conform to the slope. A subsurface difference in lithology is suspected to be the causal factor for these patterns.

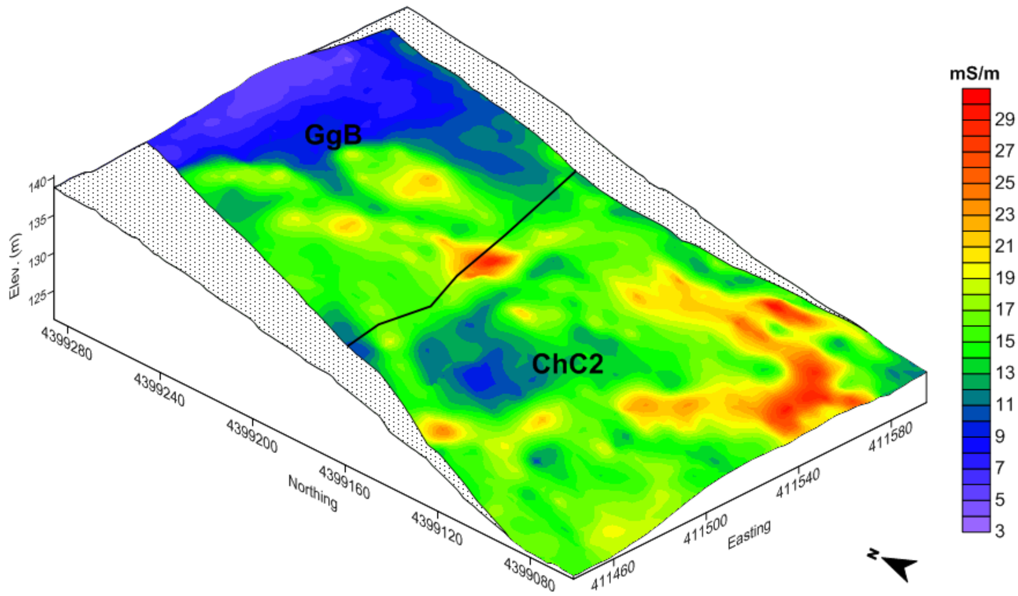

Figure 3. On this 3D wireframe image of the study area, spatial EC_a patterns appear to traverse the slope. This pattern is believed to represent subsurface lithologic seams of dissimilar mineralogy.

Response Surface Sampling Design:

A response surface sampling design model was applied to IP data collected at the site. This model was used to identify a set of optimal sampling points. The sampling points were identified using the *ESAP* (EC_e Sampling, Assessment, and Prediction) software's "*Respond Surface Sampling Design*" (RSSD) Program. The ESAP-RSSD program is a prediction-based sampling approach that is designed to reduce the number and optimize the location of sampling points (6, 12, or 20 points) based on the observed magnitudes and spatial locations of the raw IP data. The set contains 12 calibration points. Table 2 provides the georeferenced EC_a data for the twelve points, which are identified by their observation number. Each sampling point is referenced by UTM or Geodetic (decimal degrees) coordinates (WGS84).

Table 2. Twelve Point Optimal Sample Scheme for the Nottingham Site. The EC_a and in-phase (IP) data are expressed in mS/m and ppt, respectively.

Observation #	Easting	Northing	Longitude	Latitude	EC_a	IP
182	411586.2	4399066.03	-76.03182033	39.7369065	11.64	293.28
257	411533.6	4399074.2	-76.03243478	39.73697464	19.30	72.58
394	411447.0	4399090.591	-76.03344776	39.73711331	15.27	121.91
881	411491.5	4399103.647	-76.03292988	39.73723555	16.72	244.41
977	411561.3	4399101.29	-76.03211553	39.73722156	23.36	207.50
1524	411526.1	4399134.946	-76.03253067	39.73752111	17.81	134.14
1614	411459.9	4399137.762	-76.03330312	39.7375396	15.47	48.40
2180	411469.3	4399167.747	-76.03319698	39.73781072	18.28	97.62
3318	411494.9	4399248.249	-76.03290951	39.73853859	17.70	269.22
3664	411534.2	4399178.687	-76.03244131	39.73791601	17.23	219.84
3791	411579.6	4399218.524	-76.03191694	39.7382796	12.42	158.94
4046	411581.2	4399278.275	-76.03190675	39.73881804	10.00	182.97

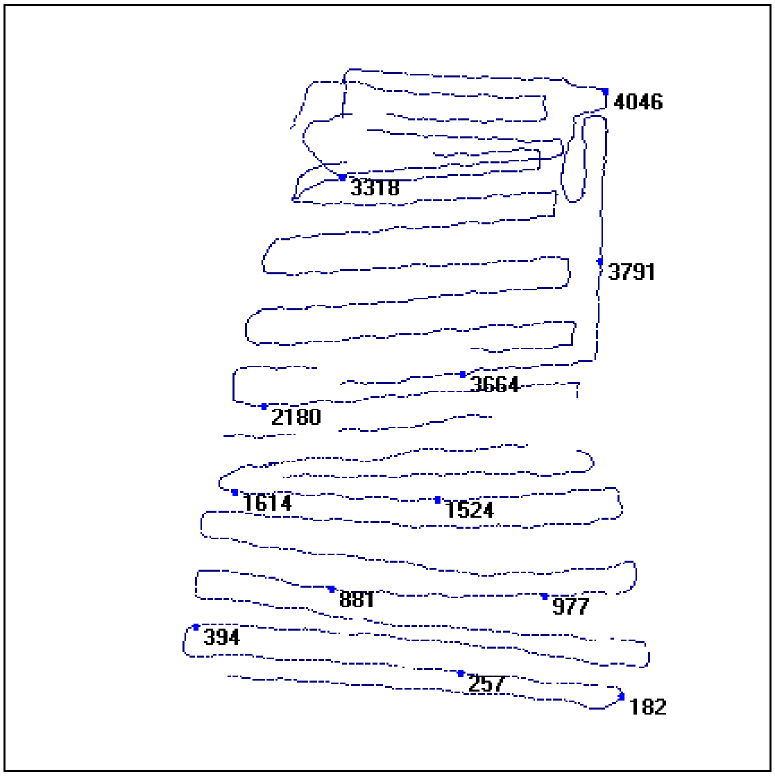

Figure 4. Location and identity of the twelve optimal sampling points selected with a response surface sampling design program.

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