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

**Subject:** Soils – Geophysical Field Assistance **Date:** 28 May 2009

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**Purpose:**
The purpose of this visit was to report to Mark Krupinski and the soil staff in Wisconsin on recent technological advancements in ground-penetrating radar (GPR) and electromagnetic induction (EMI).

**Participants:**
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**Activities:**
All activities were completed during the period of 27 to 29 April, and on 18 May 2009.

**Recommendations:**

1. While ground-penetrating radar is well suited to large areas of Wisconsin, this geophysical tool is considered to have only moderate to low potential in many areas of southern Wisconsin. The relatively higher clay contents of soils in this region of the state (see Figure 2) are responsible for these ratings. While GPR can be used in southern Wisconsin, results will be more depth restrictive and interpretations more ambiguous and challenging than in other areas of the state. It is recommended, that soil scientists explore the potentials of using electromagnetic induction (EMI) as an alternative geophysical tool in areas of more electrically conductive soils. Electromagnetic induction is widely used in the Midwest for site specific management and to support high-intensive soil surveys.

2. An EM38 RT meter (Geonics serial number 9728005; USDA-NRCS-SSL # 269) and an Allegro CE/DOS field computer (Juniper System's serial number 11492) with cables and battery charger have been loaned by the National Soil Survey Center to Jesse Turk and the Wisconsin Soil Staff for use and evaluation.

3. A recent technical innovation provides for the integration of GPR and global positioning system (GPS) receivers. The synergism of these technologies permits the collection of large, tabular, georeferenced GPR data sets, which can be stored, manipulated, analyzed, and displayed in geographic information systems (GIS). These collection, analysis, and display formats should greatly improve the utility of GPR. However, the combined use of these technologies will require an investment in a more sophisticated GPS receiver than the outdated Garmin Map76 receivers that most field offices have access to.

4. New software is available for EMI. The RTmap38 program (see Figure 1) has a colored display, which allows soil scientists to immediately track, observe, and interpret the results of EMI surveys. Following an EMI survey, soil scientists can move directly to sampling locations based on the color-scaled, pseudo-grid image displayed on the screen of a hand-held field computer. With this software, soil scientists can visually correlate EMI data with soil and landscape patterns, and move directly and accurately to soils with different $EC_a$ for sampling and verifications of the factors influencing the $EC_a$. In the future, the availability of this software should foster greater enthusiasm and use of EMI by field soil scientists.

It was my pleasure to work in Wisconsin and with members of your fine staff. The National Soil Survey Center will continue to provide whatever GPR and/or EMI training and assistance that is requested by the Wisconsin staff.

With kind regards,

James A. Doolittle
Research Soil Scientist
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**Equipment:**
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[1] The SIR-3000 consists of a DC-3000 digital control unit with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. The antenna used in this study has a center frequency of 200 MHz. With an antenna, the SIR-3000 requires two people to operate. Daniels (2004) and Jol (2008) discuss the use and operation of GPR.

The RADAN for Windows (version 6.6) software program (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, range gain adjustments, signal stacking, and migration (see Daniels (2004) or Jol (2008) for discussions of these techniques).

Recent technical developments allow the integration of GPR and GPS data (Doolittle et al., 2009). This integration effectively geo-references each scan on a radar record. Using the *Interactive 3D Module* of the RADAN for Windows (version 6.6) software program, depths to subsurface interfaces can be interpreted, automatically picked and outputted to a layer file (X, Y, Z format; containing latitude, longitude, and depth). The synergism of these technologies permits the collection of large, tabular, georeferenced GPR data sets, which can be stored, manipulated, analyzed, and displayed in GIS. These collection, analysis, and display formats should greatly improve the utility of GPR

The EM38 meter is manufactured by Geonics limited (Mississauga, Ontario).[1] This meter weighs about 1.4 kg (3.1 lbs) and needs only one person to operate. No ground contact is required with this instrument. The EM38 meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998).

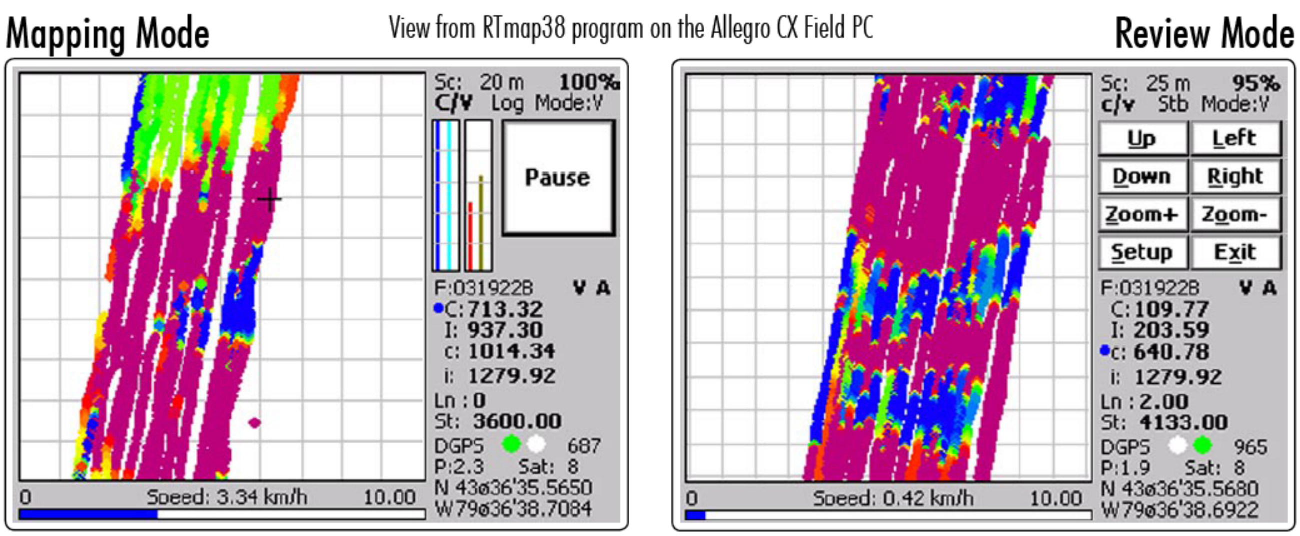


*Figure 1. The RTmap38 program provides an instaneous track of each traverse and $EC_a$ measurements are displayed as a colored points on the Allegro field computer (courtesy of Geomar Software, Inc.).*

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced EMI data.[1] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both EMI and position data.[1] Using the recently marketed RTmap38 software program (Geomar Software, Inc., Mississauga, Ontario), both GPS and apparent conductivity ($EC_a$) data were simultaneously

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

recorded and displayed on the Allegro CX field computer.[1] The color display for the RTmap38 program (see Figure 1) allows soil scientists to immediately track, observe, and interpret the results of EMI surveys while still in the field. With this software program, soil scientists can visually correlate EMI data with soil and landscape patterns, and move directly to sites with different $EC_a$ for sampling and verifications of the factors influencing $EC_a$. In Figure 1, the left-hand plot shows the display as data are being recorded on the hand-held Allegro field computer; the right-hand plot shows the screen when data collection is paused and the *hidden menu* appears.

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct simulations of $EC_a$ data.[2] Grids of $EC_a$ data shown in this report were created using kriging methods with an octant search.

**Field Techniques:**
Electromagnetic induction (EMI) surveys were conducted with the EM38 meter at two sites in Calumet County. The EM38 meter was operated in the deeper-sensing (0 to 1.5 m) vertical dipole orientation. Only quadrature phase data were collected and expressed as values of $EC_a$ in milliSiemens/meter (mS/m). Both pedestrian and mobile surveys were completed with the EM38 meter. For the pedestrian survey (Site 1), the meter was held about 3-cm (about 1 inch) above the ground surface and orientated with its long axis parallel to the direction of traverse. The mobile EMI survey (Site 2) was completed by towing the EM38 meter behind an ATV in a plastic sled at speeds of 2 to 4 m/sec. Surveys were completed by traversing each study site in a random or back and forth pattern.

Random, pedestrian surveys were conducted with the SIR-3000 and the 200 MHz antenna across Sites 2 and 3. The 200 MHz antenna provided good resolution of subsurface features and adequate penetration depths. All radar records were reviewed in the field. At Site 2, the GPR was operated with the "GPS option" activated.

**GPR Calibration:**
Ground-penetrating radar is a time-scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, bedrock, stratigraphic layer) 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 the following equation (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 the equation:

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

Where C is the velocity of propagation in a vacuum (0.298 m/ns). Velocity is normally 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 $v$.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (a 25-cm diameter, metal plate), the velocity of propagation and the relative dielectric permittivity through the upper part of a Hochheim soil profile at Site 2 was estimated using equations [1] and [2]. Based on the plate being buried at a depth of 56 cm, the estimated $E_r$ was 10.7 and the estimated $v$ was 0.0911 m/ns through the upper part of the soil profile.

**Study Sites:**
The three study sites are located in Calumet County. Site 1 (44.038967 N. Latitude, 88.075727 W. Longitude) is located in an area of CRP off of Aeblischer Road, about 2.3 miles northeast of Hoyton. Site 1 is composed of polygons of Kewaunee loam, 2 to 6 % slopes (KnB), and Manawa silt loam, 0 to 3 % slopes (MbA). The very deep, well drained Kewaunee and the somewhat poorly drained Manawa soils formed in a thin mantle of loess and

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

underlying clayey tills on glacial moraines. Also observed at this site were included areas of Channahon soils. The shallow, well drained Channahon soils formed in loamy material overlying limestone or dolostone bedrock on uplands.

Site 2 (44.0055 N. Latitude, 88.1295 W. Longitude) is in pasture. The site is located off of Quarry Road, about 2.3 miles southeast of Chilton. Site 2 is composed of polygons of Channahon loam, 2 to 12 % slopes (CnC); Dodge silt loam, 2 to 6 % slopes (DoB); and Whalan silt loam, 2 to 6 % slopes (WpB). The very deep, well-drained Dodge soils formed in loess and the underlying till on moraines and drumlins. The moderately deep, well drained Whalan soils formed in a mantle of loamy glacial drift which overlies a thin layer of clayey residuum weathered from the underlying limestone bedrock on uplands.

Site 3 (44.0079 N. Latitude, 88.1366 W. Longitude) is a road cut along Quarry Road about 2.2 miles southeast of Chilton. The road cut is located in an area of Whalan silt loam, 2 to 6 % slopes (WpB).

The taxonomic classifications of the soils identified at the three sites are listed in Table 1. Soils identified in three cores extracted from Site 2 were Hochheim. The well drained Hochheim soils formed in loamy till and are shallow or moderately deep to a densic contact.

**Table 1. Taxonomic classifications of the soils identified in the Calumet County sites.**

| Soil Series | Taxonomic classification |
|---|---|
| Channahon | Loamy, mixed, superactive, mesic Lithic Argiudolls |
| Dodge | Fine-silty, mixed, superactive, mesic Typic Hapludalfs |
| Hochheim | Fine-loamy, mixed, active, mesic Typic Argiudolls |
| Kewaunee | Fine, mixed, active, mesic Typic Hapludalfs |
| Manawa | Fine, mixed, active, mesic Aquollic Hapludalfs |
| Whalan | Fine-loamy, mixed, superactive, mesic Typic Hapludalfs |

**Results:**

GPR:

In general, while many Wisconsin soils are considered favorable to GPR, soils in southern Wisconsin have mostly moderate to low potential for GPR (Figure 2). Because of these soils's moderate to high clay contents, signal attenuation rates are comparatively high, penetration depths are limited, and interpretations are often more challenging. Because of these limitations, the evaluation and possible use of EMI as an alternative or supplementary geophysical tool in southern Wisconsin for soil survey investigations and quality control efforts is recommended.

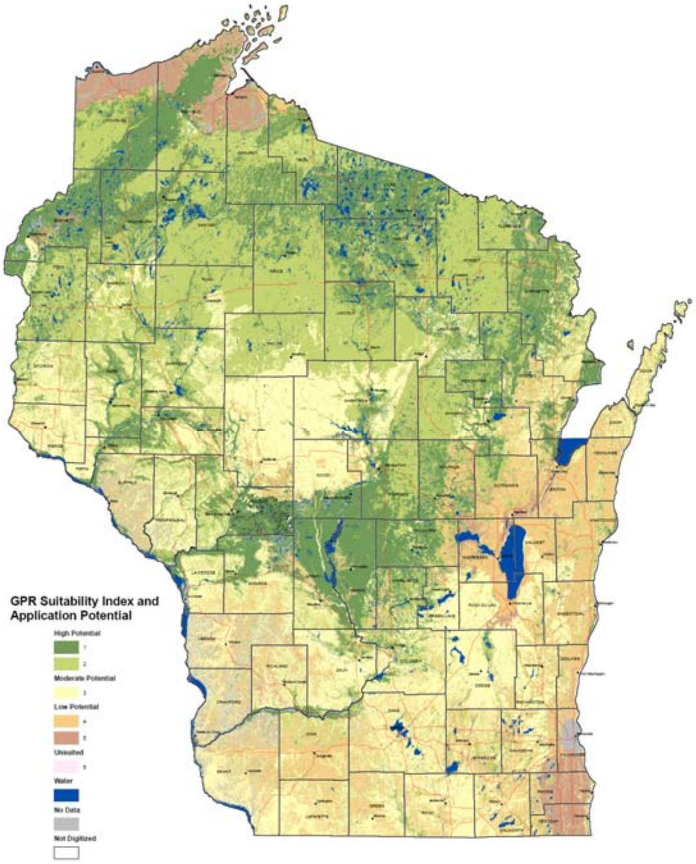


Figure 2. The GPR Soil Suitability Map of Wisconsin (from the http://soils.usda.gov/survey/geography/maps/GPR/index.html) shows the general suitability of soils for GPR. While many soils in northern and central Wisconsin are well suited to GPR, most soils in southern and eastern Wisconsin have a lower potential for GPR applications.

*Figure 3. Site 3 consists of a road cut, which provided an exposure of the underlying dolostone bedrock.*

Ground-penetrating radar surveys were conducted at Sites 2 and 3. Site 3 consists of a road cut, which provides an exposure of the underlying bedrock. A portion of this road cut is shown in Figure 3. Figure 4 is the radar record that was collected at Site 3 and in an area of moderately deep Whalan soils. In Figure 4, the vertical and horizontal scales are expressed in centimeters and meters, respectively. Whalan soils are considered well suited to GPR. Although the clays in soil mantle do attenuate the radar energy, the underlying dolostone bedrock is relatively resistive and transparent to GPR. In areas of Whalan soils, processing can be used to help improve interpretations, but is not necessary. In Figure 4, a green-colored line has been used to indicate the interpreted depth to bedrock. On this radar record, the interpreted depth to bedrock averages 64 cm with ranges from 49.8 to 85.4 cm. Along this traverse line, soils are overwhelmingly (98 %) moderately deep (50 to 100 cm) to bedrock. Shallow (< 50 cm) soils are a minor (2 %) inclusion.

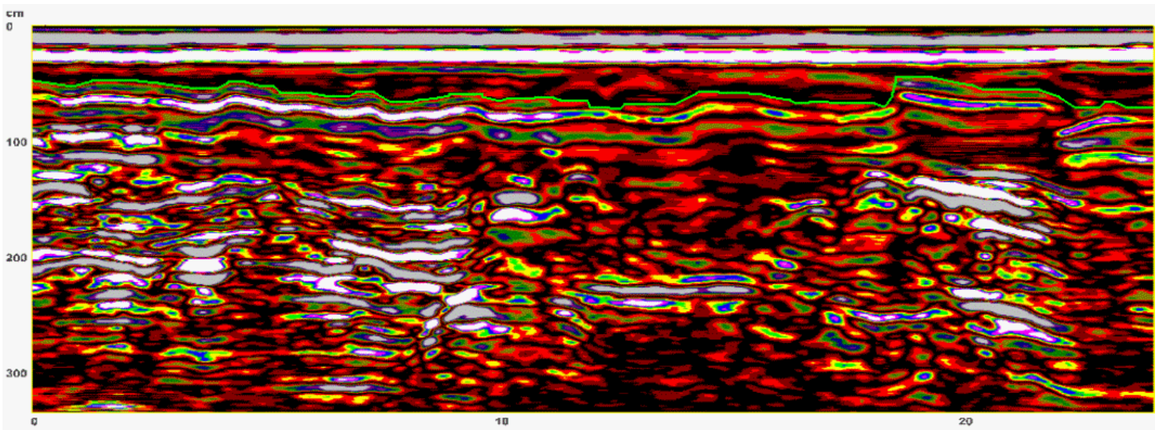


*Figure 4. This two-dimensional radar record was collected in an area of Whalan soils. A green-colored line has been used to identify the soil-bedrock interface. Bedding and fracture planes are evident in the underlying bedrock.*

In bedrock, variations in dielectric properties are principally associated with changes in water content (Davis and Annan, 1989). Differences in the geometry, separation, and contents of fractures and bedding planes will affect their detection with GPR. Abrupt changes in water content produce strong radar reflections. Saturated fractures and bedding planes will produce reflections with higher-amplitude than similar air-filled or unsaturated features (Lane et al., 2000). Because of scattering losses, signal attenuation, wave-length scale heterogeneities, and geometric constraints, the number of bedding planes and fractures interpreted on radar records are considered to be an order of magnitude less than the number observed in outcrops (Lane et al., 2000). This is apparent when one compares the photograph of the bedrock exposure (Figure 3) with the radar record from this exposure (Figure 4). Closely spaced bedding and fracture planes can produce reverberations that can masked other reflections. Lane et al. (2000) observed that fractures spaced closer than ¼ of the transmitted wave length were obscured by constructive interference. Larger dip-angles and/or more irregular surfaces will also increase scattering of the reflected wave front away from the antenna. Vertical interfaces reflect very little energy towards the antenna. Fractures and bedding planes with dip-angles greater than about 45 degrees are affected by spatial aliasing distortion and are not be accurately imaged (Buursink and Lane 1999).

Site 2 is mapped as being dominantly Channahon, Dodge, and Whalan soils. It is often difficult to extract cores in these soils using hand tools (e.g., soil augers) as coarse fragments restrict penetration. Soil scientists are uncertain whether auger refusal was the result of a large rock fragment or bedrock. It is therefore difficult for soil scientists to accurately predict the depth to bedrock in these soils. At Site 2, using the mechanized *Geoprobe*, soil scientists from the University of Wisconsin had identified very deep soils in the three extracted soil cores. A layer of dense till was identified in each of these cores and the soils were described as Hochheim. Hochheim soils are considered to be moderately suited to GPR. Hochheim soils are moderately-fine textured and belong to the active cation exchange activity class. These properties will limit penetration depths and the effectiveness of GPR for soil investigations.

Figure 5 is a represented radar record from Site 2. Site 2 is located on the crest of a drumlin and is underlain by very deep deposits of glacial drift. On all radar records collected at this site, a high-amplitude (colored white, grey, pink and blue in Figure 5) subsurface interface was identified. Though not adequately verified in the field, the cores extracted from this site suggest that this interface represents a densic contact within the till.

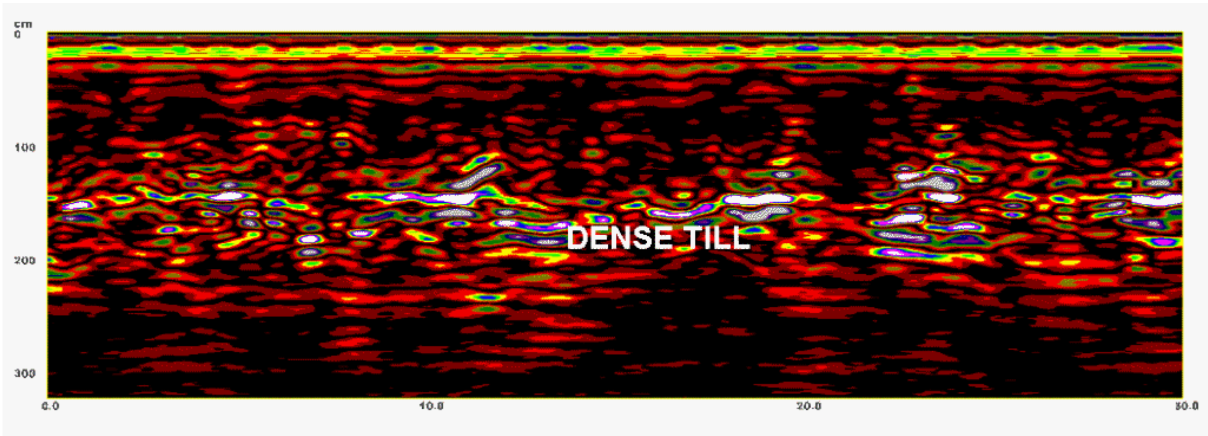


*Figure 5. This radar record was collected at Site 2 in an area of Hochheim soils. Though not confirmed, cores extracted near this traverse line suggest that the high amplitude subsurface reflector evident in this radar record is a densic contact within the till.*

Three radar traverses were conducted across Site 2. Using the *Interactive 3D Module* of RADAN, depths to a prominent subsurface reflector, which is believed to be the densic contact, were quickly and effortlessly picked and recorded in a layer file. Based on 22,070 interpreted measurements made along the three traverse lines, the average depth to the densic contact is about 131 cm with a range of about 72 to 184 cm. Over one-half of these measurements were between depths of about 122 and 142 cm.

Figure 6 is a Google Earth image of the area that was traversed with GPR at Site 2. The locations and the interpreted depths to the densic contact along the three traverse lines are shown in this image. In the areas traversed with GPR, the densic contact is moderately deep (2 %), deep (88 %), and very deep (10 %) (depth classes are colored orange, yellow, and green, respectively).

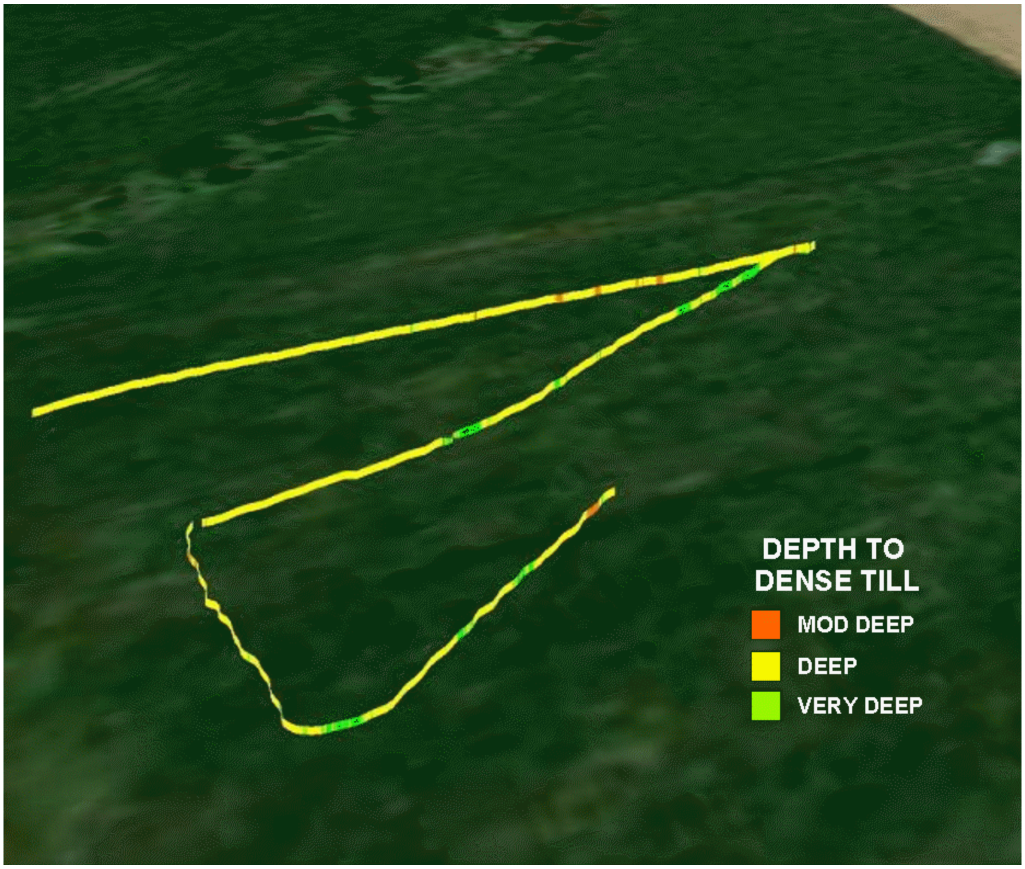


*Figure 6. In this Google Earth image of Site 2, the locations of the georeferenced GPR traverse lines are shown. Colors indicate the depths to a densic contact within the till according to soil depth classes. This contact is predominantly deep (100 to 150 cm) and very deep (> 150 cm) in areas traversed by GPR.*

**EMI Surveys:**
Electromagnetic induction (EMI) is an accepted tool for the refinement and improvement of soil maps. Because EMI data can be rapidly and effortlessly gathered, with apparent conductivity ($EC_a$) measured on a second-by-second basis, data sets are typically large and sites are more comprehensibly covered in shorter periods of time than with conventional soil survey tools and methods. As such, $EC_a$ data provide an additional, detailed layer of soil information that can be useful in making soil mapping decisions.

Areas with different $EC_a$ have been associated with different soils, soil properties, and management zones. Electromagnetic induction has potential for identifying dissimilar inclusions in soil delineations (Fenton and Lauterbach, 1999) and general soil patterns within fields (King et al., 2005). Anderson-Cook et al. (2002) used crop yields and $EC_a$ data, to classify four different soils with an accuracy of over 85 percent. In precision agriculture, field-scale $EC_a$ mapping is used to identify management zones and to direct soil sampling (Johnson et al., 2001). However, $EC_a$ is not in itself diagnostic of soils or soil properties. Spatial $EC_a$ patterns often reflect variations in more than one soil property and do not always correspond to changes is soil types. Relationships between $EC_a$ and soil properties vary at different spatial scales and can change over surprisingly short distances. As more than one soil property can influence $EC_a$, spatial variations in different soil properties can confound interpretations and foster inconsistent and ambiguous interpretations (Carroll and Oliver, 2005). The effectiveness of EMI as a soil mapping tool greatly depends on the degree to which differences in soil properties correspond to measurable differences in $EC_a$.

<u>Results</u>

Table 2 summarizes the basic $EC_a$ statistics for the two survey areas (Sites 1 and 2) in Calumet County. Within these sites, $EC_a$ ranged from about -56.0 to 132 mS/m. Negative and exceptionally high positive values are attributed principally to metallic artifacts, which are either buried or scattered across each site. At Sites 1 and 2, the measured $EC_a$ was relatively low. At Site 1, $EC_a$ averaged 13.7 mS/m and ranged from -55.8 to 132.1 mS/m. However, one-half of the observations were between 9.5 and 17.0 mS/m. At Site 2, $EC_a$ averaged only 5.6 mS/m and ranged from -13.6 to 15.7 mS/m. One-half of the observations were between 3.8 and 7.6 mS/m. The lower range in $EC_a$ at Site 2 suggests that the soils are more uniform than at Site 1.

**Table 2**
**Basic statistics for the $EC_a$ data that was collected with the EM38 meter at sites located in Calumet County.**
($EC_a$ measurements are expressed in mS/m)

| Site | Observations | Minimum | 25%-tile | 75%-tile | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Calumet County Site 1 | 4942 | -55.75 | 9.5 | 17.0 | 132.13 | 13.73 | 8.41 |
| Calumet County Site 2 | 4631 | -13.63 | 3.75 | 7.63 | 15.75 | 5.62 | 2.81 |

At both sites, differences in $EC_a$ are attributed to differences in clay and moisture contents and/or the depth to bedrock. The spatial distributions of $EC_a$ within the two sites are shown in Figures 7 and 8. In these plots, the same color scale and isoline interval (5 mS/m) are used.

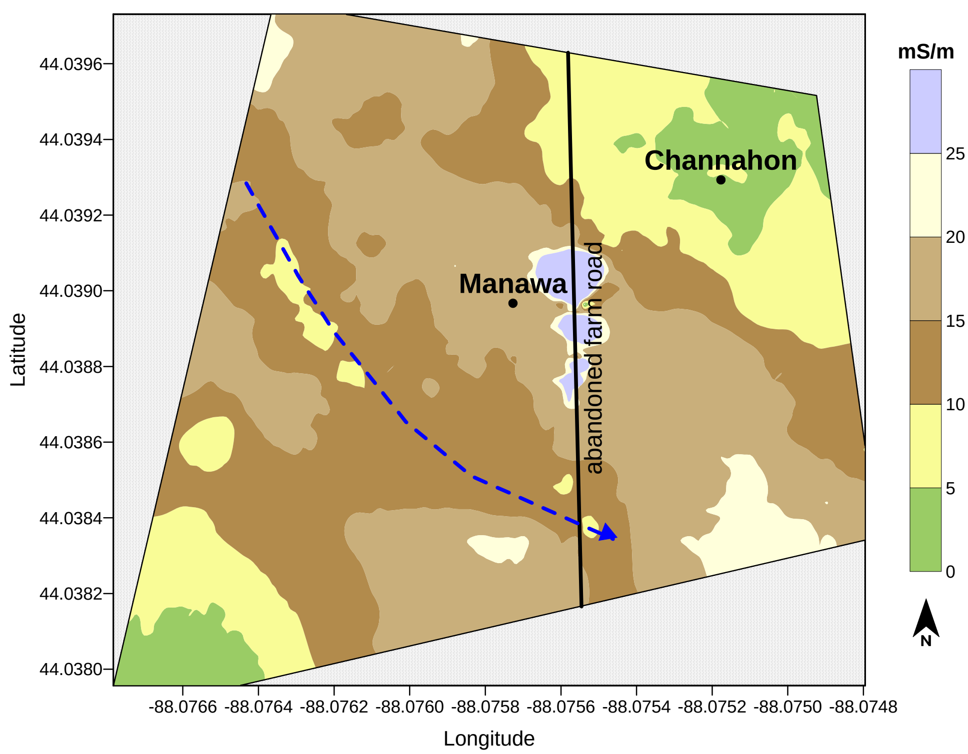


*Figure 7. Map of soil $EC_a$ collected with the EM38 meter operated in the vertical dipole orientation (VDO) Site 1*

Figure 7 is a plot of the $EC_a$ data collected at Site 1. The names and locations of the soils identified at two core sites are shown in Figure 7. The core extracted in an area of lower $EC_a$ (>5 mS/m in VDO) was identified as Channahon soil. A core extracted in an area of higher $EC_a$ (20 mS/m in VDO) was identified as Manawa soil.

At Site 1, areas of low (<5 mS/m) $EC_a$ are presumed to be shallower to bedrock and represent areas of Channahon soil. Areas of higher $EC_a$ were initially suspected to be deep or very deep and wetter soils. In Figure 7, the location of a drainage line with visibly wetter soil conditions has been drawn. Along this drainage line, $EC_a$ was moderate to low in value. As a consequence, at this site, the affect of water content on $EC_a$ is considered less significant than differences in soil depth and clay content. In Figure 7, the zone of anomalously higher $EC_a$ (> 25 mS/m) along the abandoned farm road is suspected to reflect the presence of buried artifacts. At Site 1, EMI provides an effective tool for showing general soil patterns and the relative depths to bedrock.

Figure 8 is a plot of the $EC_a$ data collected with EM38 meter at Site 2. The names and locations of the soils identified at three core sites are shown in Figure 8. Only Hochheim soils were indentified in the three cores. However, with increasing soil wetness, the drainage class went from well to moderately well drained. Areas of moderately well drained Hochheim soils occur on a higher-lying bench and have $EC_a$ greater than 10 mS/m. Compared with Site 1, the lower and less variable $EC_a$ at Site 2 reflect the dominance of a single soil with comparatively consistent soil properties.

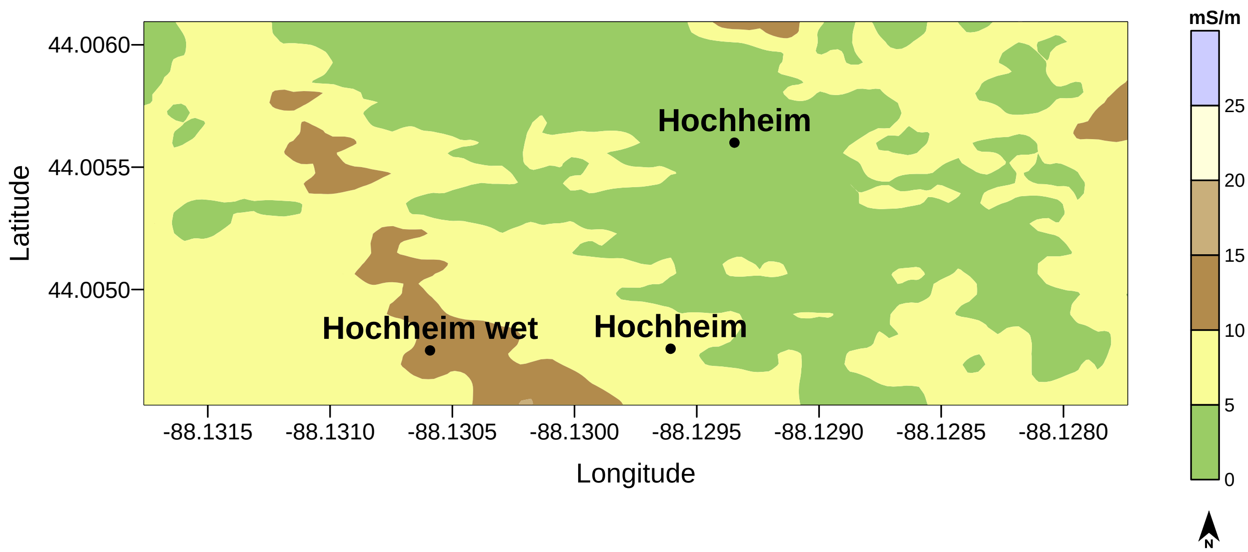


*Figure 8. Map of soil $EC_a$ collected with the EM38 meter operated in the VDO at Site 2*

At each site, soil scientists were guided to core sites by the $EC_a$ data displayed on the screen of a field computer, which used the RTmapEM38 program. With this program, $EC_a$ data are color-coded and displayed on the field computer. This display allows soil scientists to immediately observe the results of EMI surveys and to move directly to sites of different $EC_a$ for sampling and verifications of factors influencing the $EC_a$. The soils identified at the core sites did displayed differing clay and/or moisture contents (Sites 1 and 2), or contrasting depths to bedrock (Site 1).

**References**:

Anderson-Cook, C. M., M. M. Alley, J. K. F Roygard, R. Khosla, R. B. Noble, and J. A. Doolittle, 2002. Differentiating soil types using electromagnetic conductivity and crop yield maps. Soil Sci. Soc. Am. J 66(5): 1562-1570.

Buursink, M.L., and J. W. Lane, 1999. Characterizing fractures in a bedrock outcrop using ground-penetrating radar at Mirror Lake, Grafton County, New Hampshire. 769-776 pp. IN: Morganwalp, D.W., and Buxton, H.T. (eds.), U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999--Volume 3 of 3--Subsurface Contamination from Point Sources: U.S. Geological Survey Water-Resources Investigations Report 99-4018C.

Carroll, Z. L., and M. A. Oliver, 2005. Exploring the spatial relations between soil physical properties and apparent electrical conductivity. Geoderma 128: 354-374.

Daniels, D. J., 2004. Ground Penetrating Radar; 2nd Edition. The Institute of Electrical Engineers, London, United Kingdom.

Davis, J. L., and A. P. Annan, 1989. Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophysical Prospecting, 37: 531-551.

Doolittle, J., D. Surabian, S. McVey, and D. Parizek. 2009. Three "G's" for Soil-Bedrock Depth Interpretations. Soil Survey Horizons 50(1): 25-29.

Fenton, T. E., and M. A. Lauterbach, 1999. Soil map unit composition and scale of mapping related to interpretations for precision soil and crop management in Iowa. 239-251 pp. IN: Proceeding of the 4th International Conference on Precision Agriculture. ASA-CSSA-SSSA., Madison, WI.

Geonics Limited. 1998. EM38 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario.

Johnson, C. K., J. W. Doran, H. R. Duke, B. J. Weinhold, K. M. Eskridge, and J. F. Shanahan, 2001. Field-scale conductivity mapping for delineating soil condition. Soil Sci. Soc. Am. J. 65: 1829-1837.

Jol, H., 2008. Ground Penetrating Radar: Theory and Applications. Elsevier Science, Amsterdam, The Netherlands.

King, J. A., P. M. R. Dampney, R. M. Lark, H. C. Wheeler, R. I. Bradley, and T. R. Mayr, 2005. Mapping potential crop management zones within fields: Use of yield-map series and patterns of soil physical properties identified by electromagnetic induction sensing. Precision Agriculture 6: 167-181.

Lane, J. W., M. L. Buursink, F. P. Haeni, and R. J. Versteeg, 2000. Evaluation of ground-penetrating radar to detect free-phase hydrocarbons in fractured rocks – results of numerical modeling and physical experiments. Ground Water, 38(6): 929-938.