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

Subject: -- Soils: EMI & High Intensity Soil Surveys **Date:** 26 February 2007

To: Robert L. McLeese
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Purpose:
The purpose of this investigation was to evaluate the efficiency of using electromagnetic induction (EMI) as an ancillary mapping tool to assist high-intensity soils surveys. The focus of this investigation was to obtain soil information needed to verify the accuracy of two, order-one soil surveys, which were sequentially conducted on sites located in Stephenson and Warren Counties.

Participants:
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Activities:
All field activities were completed during the period of 28 to 30 November 2006.

Summary:

1. Nearly 100 soil cores were described in two study sites located in Warren and Stephenson Counties. The Warren County site consists of poorly drained to moderately well drained Mollisols that have formed in thick loess deposits. Other than differences in soil moisture contents, soils at this site are relatively homogenous. Differences in EC_a did exist among the soil map units. For measurements collected with the Veris system (deep), the average EC_a was significantly different at core sites located in each of the five soil map units. Although the sample population was small, results indicate significant differences in EC_a measurements among the soil consociations.

2. At the Warren County site, based on data from the 50 core sites, the second order-one soil survey, which had access to the EC_a data, provided a slight, but not substantial improvement in reducing the variability of soils within polygons.

3. Soils within the Stephenson County site are more variable and heterogeneous. The Stephenson County site is located on loess covered till plain. Compared with the Warren County site, the loess mantle is thinner and contrasting layers of till, outwash, lacustrine sediments, and residual soils were observed at the Stephenson County site. In addition, the Stephenson County site is underlain at relatively shallow depths by dolomite of the Galena formation. Soils vary from poorly drained Albolls and Aquolls to well drained Argiudolls and Hapludalfs. Within this site, variations in EC_a are principally attributed to differences in

moisture content and depth to more resistive dolomite parent rock.

4. At the Stephenson County site, spatial EC_a patterns approximate some soil polygons. Typically, lower-lying, wetter areas had higher EC_a, while higher-lying, drier and shallower to bedrock areas had lower EC_a. However, soil polygon boundary lines and EC_a isoline appear to be either offset or to cross one another and to define slightly different areas in portions of the site. For both the EM38 and EM31 meters, the average EC_a was higher in areas of Blackberry, Durand, and Mona, soils. These soils are Argiudolls. The average EC_a was lower in areas of Dubuque and Frankville soils. These soils are Hapludalfs. Though not measured, differences in EC_a among these map units suggest that EMI is sensitive not only to the thickness of the soil column (depth to bedrock), but possibly, differences in base saturation as well.

5. At the Stephenson County site, the second order-one soil survey, which had access to EC_a data, produced a greater number of soil polygons and recognized more soils. However, core observations provided no evidence that the second order-one soil survey greatly reduced the number of inclusions in soil map units. At this site, EC_a did partition the landscape into meaningful groups that reflect differences in taxonomic classification, soil depth, and drainage class.

6. EC_a maps provide additional layers of soil information, which can improve the recognition and delineation of soil polygons on high-intensity soil maps. In this study, EC_a maps were used to help delineate soil bodies that contain less variable soil conditions and to improve the placement of soil boundary lines. At each site, EC_a maps and soil pits lead soil scientists to revise the high-intensity soil maps. However, at both sites, based on a modest number of soil core observations, spatial EC_a data seemingly did not significantly reduce the variability of soils within soil polygons. However, at both sites, interpretation of the EC_a maps did result in some adjustment to the names and boundaries of soil polygons, which were seen as improvements by soil scientists.

7. All EMI devices used in this study (EM31 meter, EM38DD meter, Veris 3100 soil EC mapping system) produced similar results and interpretations. As such, any one of these tools can be used to produce high-intensity soil maps. In general, at the investigated sites, the spatial EC_a data collected with the EM31 meter produced maps that were most pleasing and acceptable to soil scientists.

It was my pleasure to work once again in Illinois. My gratitude is extended to all the soil scientists who contributed to this study under very adverse weather conditions. In addition, special thanks are extended to Roger Windhorn for the organization of this study and Dan Withers for his preparation of the ArcView GIS images shown in this report.

With kind regards,

James A. Doolittle
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Background:
Electromagnetic induction (EMI) is an accepted tool for the refinement and improvement of soil maps. Because EMI data are rapidly and effortlessly gathered on mobile platforms, with apparent conductivity (EC_a) measured on a second-by-second basis, data populations are relatively large and sites can be more comprehensibly covered in shorter periods of time than with conventional soil survey tools and methods. As such, EC_a data provide an additional, more 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 demonstrated potential for identifying dissimilar inclusions in some 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 diagnostic of soils or soil properties in itself, and 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 results (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.

Fenton and Lauterbach (1999) noted that "one of the objectives of soil mapping is to delineate soil bodies that contain less variable soil conditions than the population of soils as a whole." In high-intensity soil surveys, map units are fairly homogenous and the size and number of contrasting or dissimilar inclusions are limited. A major contribution of high-intensity soil surveys is the identification and delineation of small areas of dissimilar soils (Fenton and Lauterbach, 1999).

Previous studies in Illinois have indicated that high-intensity or order-one soil surveys satisfactorily capture soil patterns across landscapes. These studies have confirmed the difficulty in obtaining repeatable placement of soil boundary lines and consistent identification of some soil polygons when fields are resurveyed using traditional soil survey methods. In these studies, spatial EC_a data provided an additional layer of information, which improved knowledge of soils and directed soil sampling. The information provided by EC_a maps and additional soil sampling often lead soil scientists to recognize different soils and modify mapping concepts. Apparent conductivity maps did aid the identification and delineation of some soil polygons. The objective of this investigation was to collect soil core data to confirm the accuracy of high intensity soil maps and to verify improvements made with EMI.

Equipment:
Soil probe data were collected at each site with truck-mounted Giddings probes. Three geophysical tools were used in this study: the Veris 3100 soil EC mapping system (here after referred to as the Veris system) and the EM31 and EM38DD meters. The Veris system is a towed-array, multi-electrode resistivity unit manufactured by Veris Technologies (Salina, Kansas).[1] Operating procedures are described by Veris Technologies (1998). The Veris system measures apparent resistivity (expressed in ohm-m), but is programmed to convert these measurements into apparent conductivity (expressed in mS/m). The Veris system provides two soil measurement depths: one for the upper 0 to 30 cm (shallow) and one for the upper 0 to 90 cm (deep). The Veris system, under suitable field conditions, can be pulled behind a tractor or 4WD vehicle at speeds of about 5 to 10 m/hr. A Trimble 132 GPS (Global Positioning System) receiver (Sunnyvale, CA) is used with the Veris system to geo-reference the collected EC_a data.[1]

The EM31 and EM38DD meters are manufactured by Geonics Limited (Mississauga, Ontario).[1] These meters are portable and need only one person to operate. For both meters, lateral resolution is approximately equal to the intercoil spacing. No ground contact is required with these meters. These meters measure the EC_a of earthen materials. McNeill (1980) described the operation of the EM31 meter. The EM31 meter has a 3.66-m intercoil

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

(transmitter and receiving coils) spacing and operates at a frequency of 9,810 Hz. When placed on the soil surface, the EM31 meter provides theoretical penetration depths of about 3 and 6 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

Operating procedures for the EM38DD meter are described by Geonics Limited (2000). The EM38DD meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, the EM38DD meter provides theoretical penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively.

Geonics' DAS70 Data Acquisition System was used with the EMI meters to record and store both EC_a and position data.[1] The acquisition system consisted of an EMI meter, an Allegro CE field computer (Juniper Systems, North Logan, UT), and a Garmin Map 76 GPS receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack)(Olathe, KS).[1] When attached to the acquisition system, the EMI meter is keypad operated and measurements are automatically triggered. The NAV38, NAV31, Trackmaker38, and Trackmaker31 software programs developed by Geomar Software Inc. (Mississauga, Ontario) were used to record, store, and process EC_a and GPS data.[1]

Soil maps included in this report were scanned and digitized using Arc/Info and imported into ArcView 3.3.[1] Using ArcView 3.3, soil polygons were overlain (at a display scale of 1:7,920) on recent aerial photographs of both sites. Layers of EC_a data were subsequently overlain on these images.

Field Procedures:
Two order-one soil surveys had been completed at each site. At each site, the first order-one survey was completed without the aid of EC_a or soil pit data. The second order-one soil survey of each site was completed using both EC_a and pit data to supplement the survey data and to improve interpretations.

In order to verify the accuracy of the two order-one soil surveys at each site, a grid sampling scheme was completed during this investigation. Because of time limitations, a relatively coarse (100-m interval) grid was established at each site. This provided a total of 50 and 49 observation points at the Warren County and Stephenson County sites, respectively. At each observation point, cores were obtained with Giddings probes and soils were observed and described to a depth of 2.0 m or to bedrock. The location of each observation point was recorded with GPS. Brief profile descriptions were prepared and soils were identified at each observation point.

The coordinates of the soil observation points were overlaid onto the order-one soil maps for interpretation and analysis. Observation points that fell on soil polygon lines were included in the polygon that most closely identified the observed soil. At some observation points, soils were identified as intergrades between soil series. For the purpose of this investigation, intergrades were considered to be the series that they most closely resembled.

<u>Warren County Site:</u>
The site is located within Major Land Resource Area 108B – *Illinois and Iowa Deep Loess and Drift* (USDA-NRCS, 2006) in Pleasant Township, Warren County, Illinois. The site is located in the E ½ of the SE ¼ of Section 24, T. 8 N., R. 3 W. This 80-acre site was in bean stubble at the time of this investigation. The field is drained by subsurface drainage tiles. Figure 1 shows images of the two order-one soil surveys that were completed at this site. The left-hand plot shows the first order-one soil survey, which was completed in 2005. The right-hand plot shows the second order-one soil survey, which was completed in 2006. Also shown in each plot are the locations and identifying symbols for the fifty soil cores collected in this study. As evident in these images, the two order-one soil surveys resulted in changes to some map unit names and readjustments of some polygon boundaries.

Within the Warren County site, soils are comparatively homogeneous. Soils recognized within site are Mollisols and belong to the fine-silty and fine particle-size and the superactive cation-exchange activity classes (Table 1). These soils form in thick loess deposits. Though belonging to different particle-size classes, differences in clay contents among these soils are considered slight. The soils listed in Table 1 share a common clay limit (35 % clay) and, within the study site, do not vary appreciably in clay contents. Soils vary from poorly drained Aquolls to somewhat poorly drained and moderately well drained Argiudolls.

Table 1.
Names, symbols and taxonomic classifications of the soils recognized at the Warren County Site.

Symbol	Soil Series	Taxonomic Classification
41	Muscatine	Fine-silty, mixed, superactive, mesic Aquic Hapludolls
43	Ipava	Fine, smectitic, mesic Aquic Argiudolls
51	Mascatune	Fine-silty, mixed, superactive, mesic Aquic Argiudolls
68	Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
249	Edinburg	Fine, smectitic, mesic Vertic Argiaquolls
257	Assumption	Fine-silty, mixed, superactive, mesic Mollic Oxyaquic Hapludalfs
330	Peotone	Fine, smectitic, mesic Cumulic Vertic Endoaquolls
705	Buckhart	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls

All soils recognized at the Warren County site are very deep. The poorly drained Sable (68) and Peotone (330) soils are on slightly lower-lying, more concave areas. Because both Peotone and Sable soils are wetter and subject to ponding, these soils are considered dissimilar or more limiting than the other soils recognized within the study site. The somewhat poorly drained Ipava (43), Muscatine (41), and Muscatune (51), and the moderately well drained Buckhart (705) soils are on slightly higher-lying and more sloping areas. For the purpose of this investigation, Buckhart, Ipava, Muscatine, and Muscatune soils are considered closely similar.

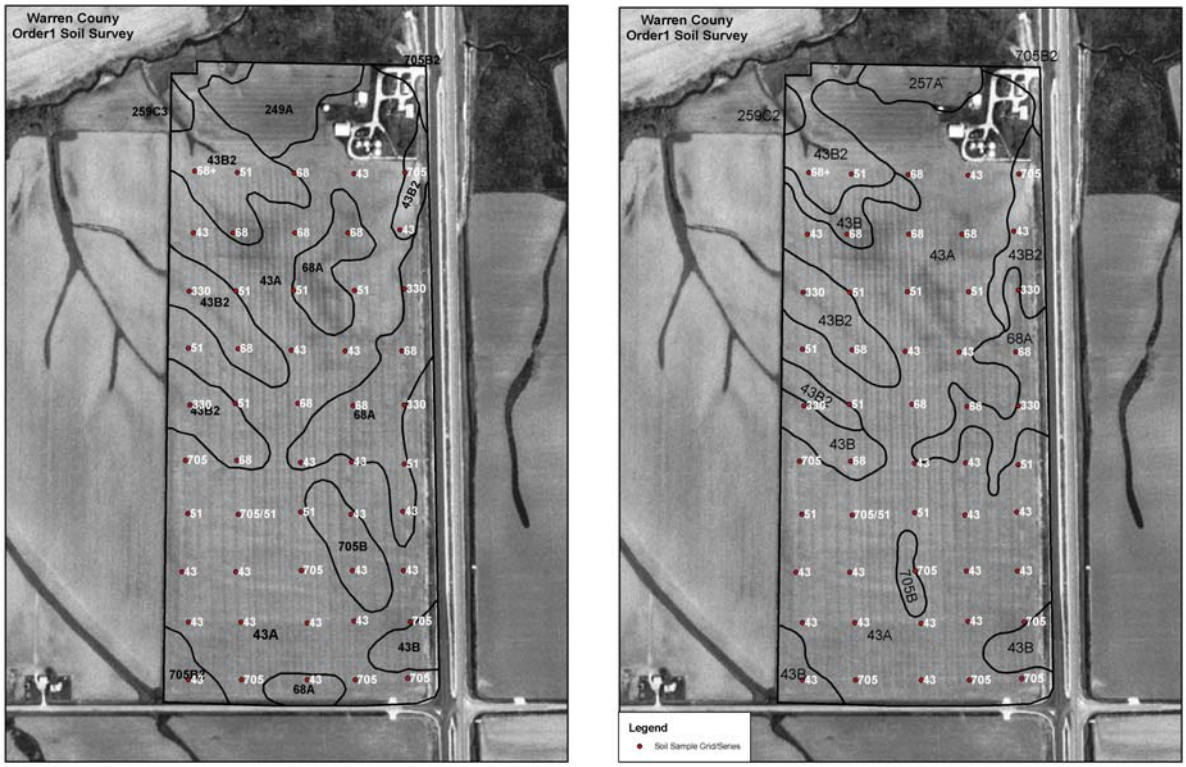

Figure 1. These images of the first (left-hand) and second (right-hand) order-one soil surveys of the Warren County Site were prepared in GIS. The locations and identities (corresponds to consociation symbol) of the fifty soil cores are shown in these plots.

Figure 2 contains plots of EC_a measured with the Veris system in the shallow (left-hand plot) and deep (right-hand plot) measurement modes. In both plots, the isoline interval is 5 mS/m. Different color scales were used in each plot. Also shown in these plots are the soil polygons and map unit symbols from the second order-one soil survey

map. Within this site, variations in EC_a are principally attributed to differences in moisture content. In general, areas of higher EC_a are associated with wetter areas of Sable and Peotone soils. Areas with lower EC_a represent better drained and more higher-lying areas of Ipava and Buckhart soils.

EC_a data were available and influenced the preparation of the second order-one soil map. Based on relative EC_a values and spatial patterns, a polygon of Sable soil (68A), which had been mapped on a slightly higher-lying area in the northern part of the site during the first survey, was removed in the second order-one soil survey (see Figure 1). In addition, polygon boundaries of Ipava (43B2) and Sable soils were adjusted to more closely approximate the spatial EC_a patterns along the eastern border of the site (see Figure 2).

Basic statistics for the EC_a data collected at the 50 core sites are listed by soil map units in Table 2. Data were interpolated from the EC_a measurements collected with the Veris system. In general, the average EC_a is higher in areas of Sable (68) and Peotone (330) soils. These soils are Aquolls and have higher soil moisture contents.

The data shown in Table 2 suggest that differences in EC_a exist among the soil map units. An analysis of variance was used to test for significant differences in EC_a among the soil cores that were collected in the five soil map units. The null hypothesis was that the average EC_a for all map units is the same. The mean sample EC_a for the deep and shallow measurements was 32.98 and 18.32 mS/m, respectively. The standard deviation was 6.78 and 3.62 mS/m for the deep and shallow measurements, respectively. For measurements collected with the Veris system (deep), the average EC_a was significantly different (F-value = 3.78; P = 0.009) for the five soil map units. Although the sample population was small, results indicate differences in EC_a measurements for the 0 to 90 cm depth interval among these soil map units.

Table 2.
Basic Statistics for the EMI survey of the Warren County Site that was conducted with the Veris 3100 Soil EC_a Mapping System

		Veris Deep			Veris Shallow		
Soil Map Unit	**Number of observations**	**Mean**	**Standard Deviation**	**Standard Error**	**Mean**	**Standard Deviation**	**Standard Error**
43	19	31.42	4.30	1.40	17.37	1.80	0.77
51	9	29.67	5.59	2.04	16.67	3.12	1.12
68	10	36.00	10.21	1.94	20.00	5.98	1.07
330	4	42.00	5.42	3.06	22.50	2.63	1.19
705	8	32.12	3.36	2.17	18.38	2.13	1.19

Tables 3 and 4 summarize the composition of the four soil map units based on observations obtained from the fifty soil cores. Results are summarized based on soil delineations mapped during the first (Table 3) and second (Table 4) order-one soil surveys. In both tables, rows identify the named soil component of each consociation; columns identify the individual soil components that were observed in the cores.

In Tables 3 and 4, the frequency of the soil for which each map unit is named is shown in red. Based on the first order-one soil map, the named soil components comprised 0 to 48 % and averaged 20.2 % of the soils observed in cores extracted from delineations of the four soil map units. Based on the second order-one soil map, the named soil components comprised 0 to 52 % and averaged 29.8 % of the soils observed in cores from delineations of the four soil map units. Compared with the first order-one soil survey, the second order-one soil survey has, on average, a higher percentage of soils recognized in the names of the map units at the core sites.

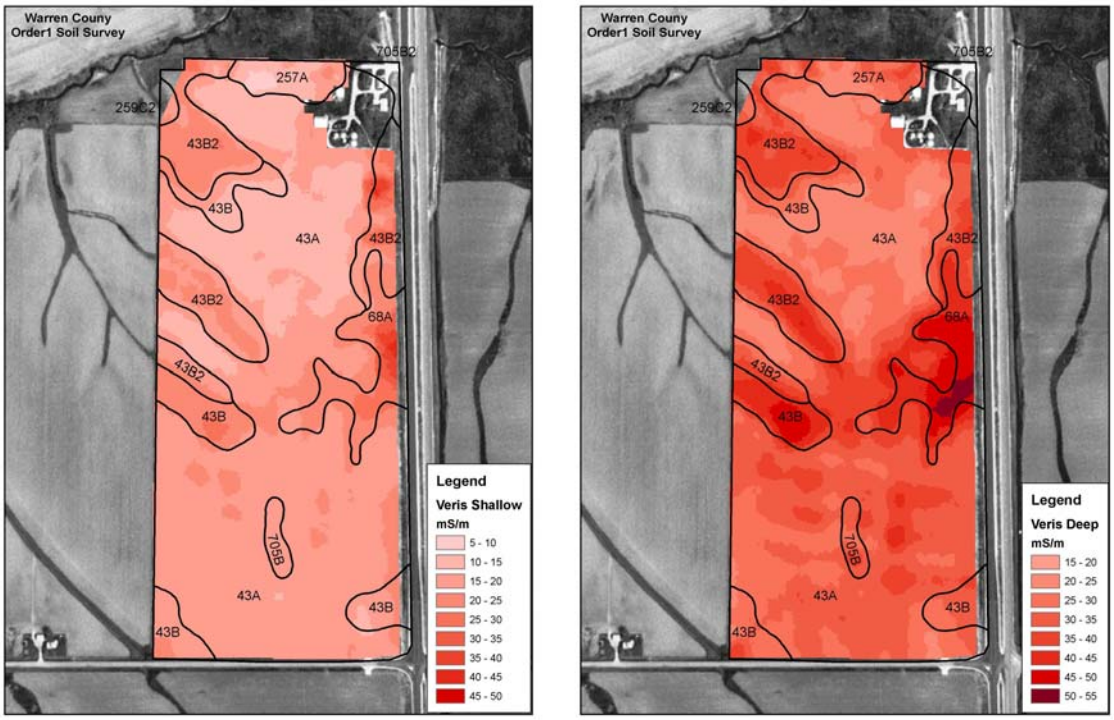

Figure 2. Spatial patterns of EC_a obtained with the Veris system at the Warren Count site.

In Tables 3 and 4, the frequency of dissimilar or more limiting soil inclusions in each map unit is shown in green. For both surveys, poorly drained and more limiting Sable (68) and Peotone (330) soils were observed in cores extracted from the somewhat poorly drained Ipava (43) map units. Based on the first order-one soil map, the more limiting Sable and Peotone soils comprised 4 to 59 %, and averaged 31.5 % of the soils observed in cores extracted from delineations of Ipava map units. Based on the second order-one soil map, the more limiting Sable and Peotone soils comprised 12 to 50 %, and averaged 31.0 % of the soils observed in cores extracted from delineations of Ipava map units.

For both surveys, the frequency of unnamed, similar inclusions (shown in black in Tables 3 and 4) ranged from 33 to 100%. Based on the first order-one soil map, similar soil components averaged 64.2 % of the soils observed in the cores. Based on the second order-one soil map, similar soil components averaged 54.8 % of the soils observed in the cores. Based on data from the 50 core sites, the second order-one soil survey, which had access to the EC_a data, provided a slight, but not substantial improvement in delineating soil polygons that contain a greater percentage of the named soil and lower percentages of dissimilar and similar inclusions.

Table 3.
Warren County Site.
Composition (%) of soil map units recognized in the first order-one soil survey based on soils identified at each of the fifty transect.

	Soils				
Soil Map Unit	**43**	**51**	**68**	**330**	**705**
43A	0.48	0.20	0.04	0.00	0.28
43B	0.08	0.25	0.42	0.17	0.08
68A	0.38	0.13	0.25	0.25	0.00
705B	1.00	0.00	0.00	0.00	0.00

Table 4.
Warren County Site.
Composition (%) of soil map units recognized in the second order-one soil survey based on soils identified at each of the fifty transect.

	Soils				
Soil Map Unit	**43**	**51**	**68**	**330**	**705**
43A	0.52	0.18	0.12	0.00	0.18
43B	0.17	0.25	0.33	0.17	0.08
68A	0.00	0.00	0.50	0.50	0.00
705B	1.00	0.00	0.00	0.00	0.00

Stephenson County Site:

The site is located within Major Land Resource Area 95B—*Southern Wisconsin and Northern Illinois Drift Plain* (USDA-NRCS, 2006) in Lancaster Township, Stephenson County, Illinois. The site is located just north of Freeport on Illinois Route 26, in the western half of Section 7, T. 27 N., and R. 8 E. At the time of the survey, the site was in corn and soybean stubble. Two small intermittent drainages cross the western part of site from south to north. A larger and wetter intermittent drainage area crosses the eastern part of site from south to north.

The Stephenson County site is located on a loess covered till plain. Compared with the Warren County site, the loess mantle is noticeably thinner. Contrasting layers of till, outwash, lacustrine sediments, and residual soil materials, as well as dolomite parent rock were observed in cores extracted from the Stephenson County site. Compared with the Warren County site, the Stephenson County site contains a greater number and diversity of soils. In addition, at the Stephenson County site, the soil consociations are more variable in composition and display more intricate and obscure spatial patterns.

Soils recognized within the Stephenson County site are classified as Mollisols and Alfisols (Table 5). Although surface layer thickness and colors vary slightly, soil scientists consider the distinction between Mollisols and Alfisols ambiguous and unclear across this site. Soils belong to the superactive cation-exchange activity and the fine-silty and fine-loamy particle-size classes (Table 5). Within the study site, soils are highly stratified and composed of different parent materials. As summarized by Roger Windhorn, some soils were described with substrata of red residuum, till, and/or paleosols. In addition, soil scientists described layers of loamy outwash and silty/clayey lacustrine sediments. Though descriptively distinct, in reality these different parent materials blend into one another, and were difficult to distinguish and separate in the field. While having variable thickness and slightly different clay contents, these parent materials do not appear to contrast sufficiently to noticeably affect the EMI response. Within the site, soils vary in drainage classes from poorly drained Albolls and Aquolls to well drained Argiudolls and Hapludalfs. Within this site, variations in EC_a are principally attributed to differences in moisture content and depth to more resistive dolomite parent rock.

Figure 3 shows the two order-one soil surveys that were conducted at this site. The upper plot shows the first order-one soil survey, which was completed in 2004. The lower plot shows the second order-one soil survey, which was completed in 2006. Also shown in each plot are the locations and identifying soil symbols for the 49 soil cores taken from this site during the present investigation.

The two order-one soil survey maps of the site (see Figure 3) are broadly similar and depict similar spatial patterns on landscape components. However, the second order-one soil survey map exhibits more intricate soil lines, and has smaller and more numerous soil polygons. Compared with the first survey, the resurvey resulted in the recognition of a lesser number of soils (8 versus 9), but a greater number of map units (10 versus 9) and soil polygons (14 versus 11). Variations in the two maps are attributed to the variability of soil within the study site, the availability of additional soil information, and the refined judgments of the soil scientists.

Table 5.
Names, symbols and taxonomic classifications of the soils recognized at the Stephenson County Site.

Symbol	Soil Series	Taxonomic Classification
29	Dubuque	Fine-silty, mixed, superactive, mesic Typic Hapludalfs
40	Dodgeville	Fine-silty over clayey, mixed, superactive, mesic Typic Argiudolls
68	Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
86	Osco	Fine-silty, mixed, superactive, mesic Typic Argiudolls
152	Drummer	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
191	Knight	Fine-silty, mixed, superactive, mesic Argiaquic Argialbolls
199B	Plano	Fine-silty, mixed, superactive, mesic Typic Argiudolls
219	Millbrook	Fine-silty, mixed, superactive, mesic Udollic Endoaqualfs
324	Ripon	Fine-silty, mixed, superactive, mesic Typic Argiudolls
411	Ashdale	Fine-silty, mixed, superactive, mesic Typic Argiudolls
416	Durand	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
440	Jasper	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
448	Mona	Fine-loamy, mixed, superactive, mesic Oxyaquic Argiudolls
506	Hitt	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
540	Frankville	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
663	Clare	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls
679	Blackberry	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls
731	Nasset	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
3107	Sawmill	Fine-silty, mixed, superactive, mesic Cumulic Endoaquolls

Figure 4 contains plots of EC_a measured with the EM38DD meter in the horizontal (upper plot) and vertical (center plot) dipole orientations, and the EM31 meter in the vertical dipole orientation (lower plot). In each plot, the isoline interval is 5 mS/m. Different color scales have been used in each plot. Soil polygons and map unit symbols from the second order-one soil survey map are shown in these plots. In general, EC_a patterns approximate some soil polygons with lower-lying, wetter areas having higher EC_a, and higher-lying, drier and shallower to bedrock areas having lower EC_a. Most boundary lines occur at noticeable breaks in slopes. While broad soil and EC_a spatial patterns do approximate one another, minor disparities are apparent in these plots. Many soil polygon boundary lines and EC_a isoline appear to be either slightly offset or to cross one another and to define slightly different areas in portions of these plots. These disparities are believed to be the result of differences is soil moisture, which may not mimic the map unit breaks observed in the landscape.

In general, EC_a measurements were not random, but varied systematically with landscape position and soil wetness. Higher EC_a values were measured on lower-lying, more imperfectly drained areas located in the north and eastern portions of the site. Lower EC_a values were measured on the higher-lying, better-drained areas located in the southwest portion of this site. The inverse relationship between EC_a and elevation reflects variations in soil moisture contents with landscape position. However, based on field observations, within higher-lying areas, the thickness of the soil column and depth to bedrock appear to affect EC_a. In a previous study at this site, a correlation coefficient (r) of 0.854 was obtained between EC_a and bedrock depth for measurements obtained with the EM31 meter in the vertical dipole orientation. On upland areas located in the southwest portion of this site, EC_a varies directly with bedrock depth. Apparent conductivity is higher in areas that are deeper to bedrock and have thicker columns of soil materials overlying relatively resistive dolomite bedrock.

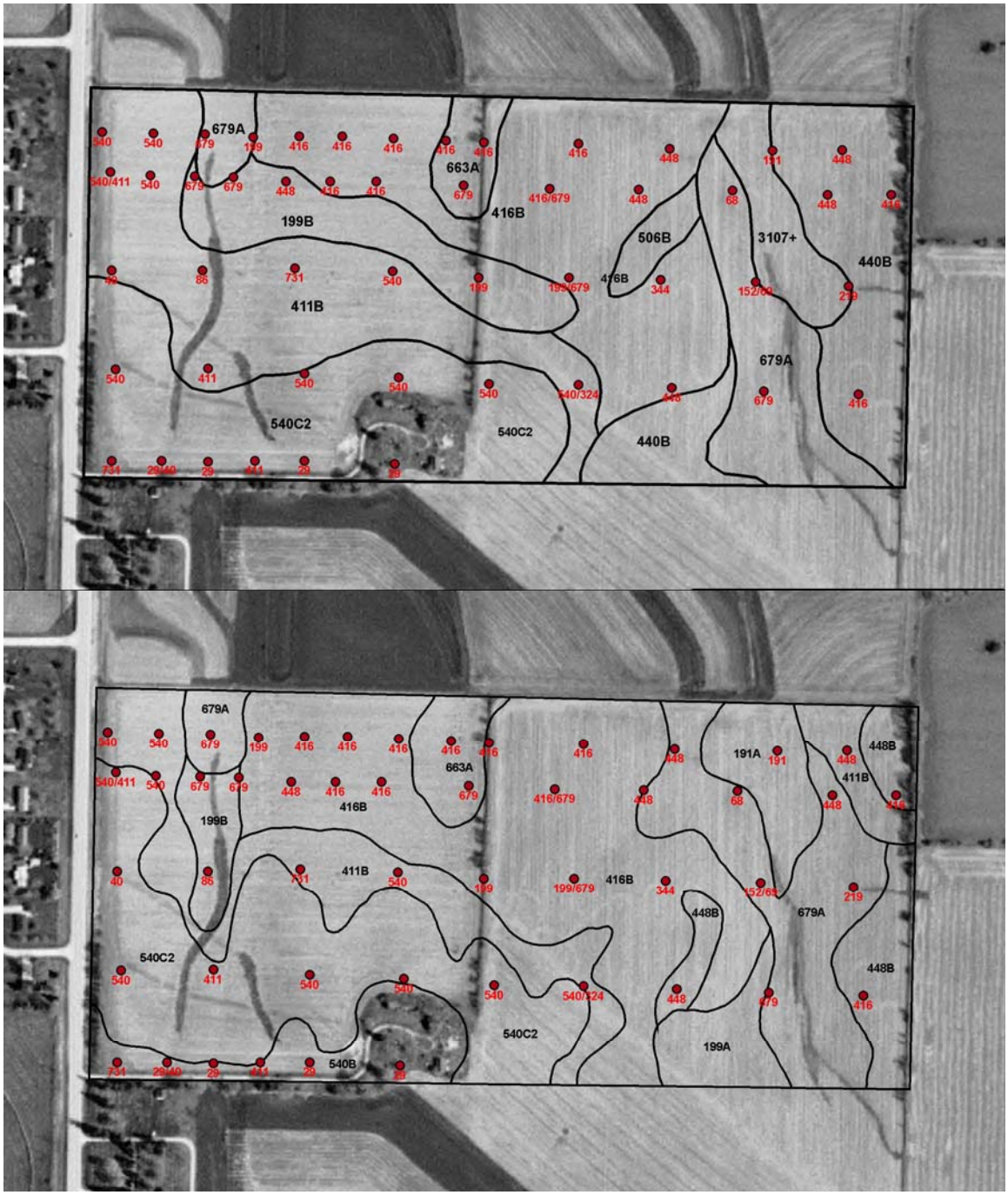

Figure 3. These images of the first (upper plot) and second (lower plot) order-one soil surveys of the Stephenson County Site were prepared in GIS. The locations and identities (corresponds to consociation symbol) of the forty-nine soil cores are shown in these plots.

Basic statistics for the EMI surveys are listed in Table 6. The average EC_a measured with the two meters is closely similar and generally decreases and became more variable with increasing depth of penetration (in Table 6, the depth of penetration increases with changes in meter and dipole orientations from top to bottom). The statistical similarity of EC_a measured with the two EMI meters suggests that either tool is suitable for mapping soils at this site.

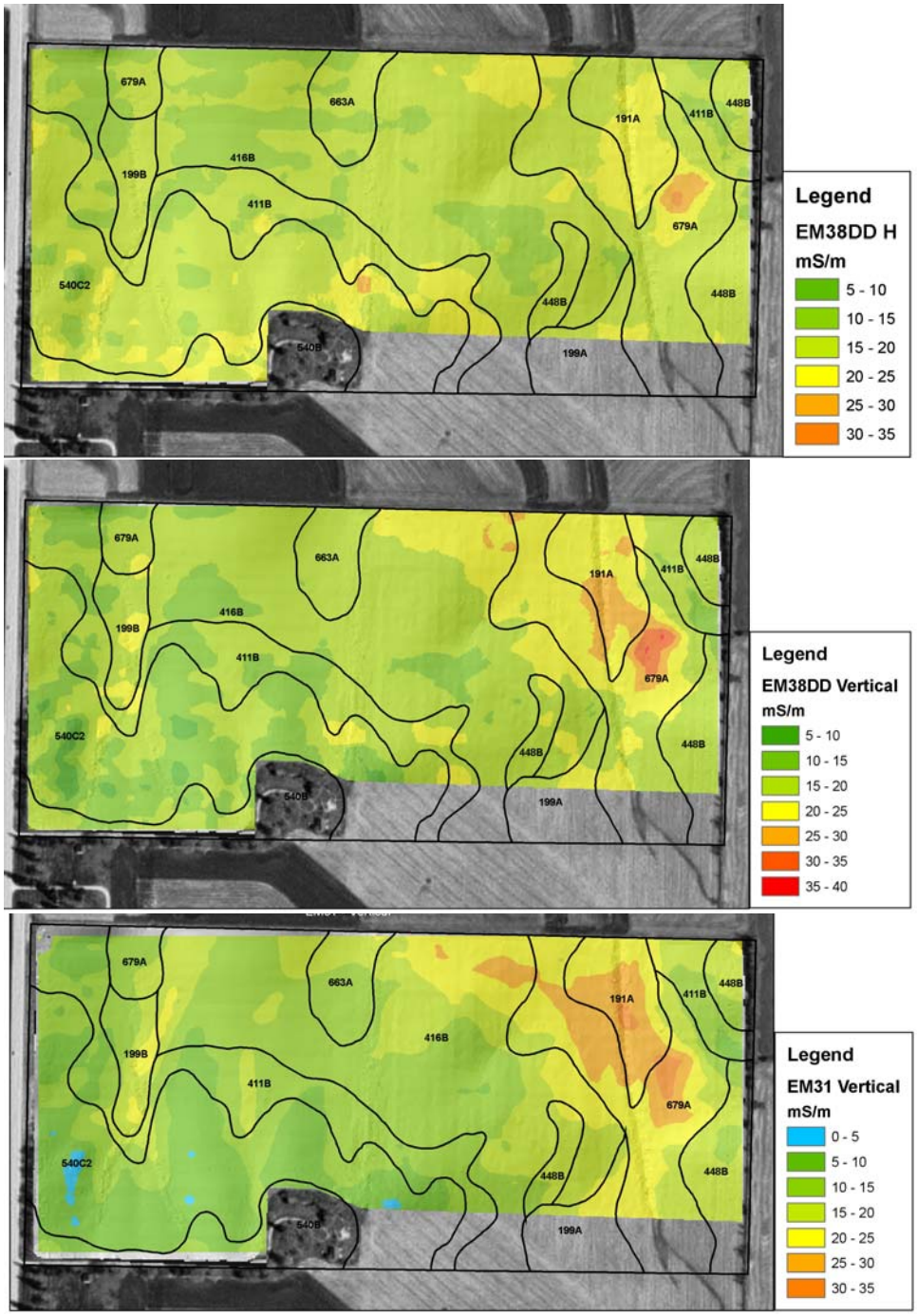

Figure 4. Spatial patterns of EC_a obtained with the EM38DD meter in the horizontal (upper plot) and vertical (center plot) dipole orientations, and the EM31 meter in the vertical dipole orientation (lower plot) at the Stephenson County site.

Basic statistics for the EC_a data collected at the 49 core sites are listed in Table 7. Data were interpolated from the EC_a measurements collected with the EM38 and the EM31 meters in the deeper-sensing, vertical dipole orientation. The EC_a data were grouped according to the soils identified at the core sites. Only five soils were observed in four or more cores. These soils are listed in Table 7. These soils are Dubuque (29), Durand (416), Mona (448), Frankville (540), and Blackberry (679). For both meters, the average EC_a was higher in areas of Durand (416), Mona (448), and Blackberry (679) soils. These soils are Argiudolls. The average EC_a was lower in areas of Dubuque (29) and Frankville (540) soils. These soils are Hapludalfs. Though not measured, these differences in

EC_a among the map units appear to reflect differences in depth to parent rock and possibly base saturation.

Table 6.
Basic Statistics for the EMI survey of the Stephenson County Site that was conducted with the EM38DD and EM31 Meters.

Sensor – Dipole Orientation	Number	Minimum	25%-tile	75%-tile	Maximum	Mean	St. Dev.
EM38DD – HDO	4926	0.00	15.25	19.25	50.88	17.31	3.23
EM38DD - VDO	4926	-7.25	14.75	19.13	38.50	17.16	4.11
EM31 - VDO	8993	3.90	11.00	19.00	41.00	15.30	5.80

Table 7.
Basic Statistics for the EMI survey of the Stephenson County Site that were conducted with the EM38 and EM31 Meters in the Vertical Dipole Orientation

		EM38 Meter			EM31 Meter		
Soil	**Number of observations**	**Mean**	**Standard Deviation**	**Standard Error**	**Mean**	**Standard Deviation**	**Standard Error**
29	4	13.50	1.73	1.14	8.00	1.43	1.51
416	11	17.23	1.75	0.69	15.64	2.84	0.91
448	6	18.50	3.51	0.93	17.50	4.55	1.24
540	10	15.40	2.17	0.72	9.45	1.98	0.96
679	5	17.40	2.07	1.02	16.10	3.85	1.35

The data shown in Table 7 suggest that differences in EC_a may exist among the five soils. An analysis of variance was used to test for significant differences in EC_a among the soil cores that were collected in the five soils. The null hypothesis was that the average EC_a for all of these soils is the same. The mean sample EC_a for the thirty-six core sites was 16.5 and 13.4 mS/m for measurements obtained with the EM38DD and EM31 meters (in the vertical dipole orientation), respectively. The standard deviation was 2.6 and 4.6 mS/m for measurements obtained with the EM38DD and EM31 meters, respectively. For measurements collected with the EM38DD meter in the vertical dipole orientation, the average EC_a was not considered significantly different (F-value = 3.948; P = 0.01) for the five soils. For measurements collected with the EM31 meter in the vertical dipole orientation, the average EC_a was significantly different (F-value = 12.666; P = 0.001) for the five soils. Although the sample population was small, results indicate significant differences in EC_a exist among these soils in measurement obtained with the deeper-sensing EM31 meter.

The EC_a measurements from the five soils were next grouped by depth to bedrock and drainage class. The moderately deep, well drained Dubuque (29) and Frankville (540) soils are considered similar (both Hapludalfs) and were grouped together. The very deep, moderately well drained Durand (416), Mona (448), and Blackberry (679) soils are considered similar (all Argiudolls) and were grouped together. An analysis of variance was used to test for significant differences in EC_a among the soil cores that were collected in these two soil groupings. The null hypothesis was that the average EC_a for both groups of soils is the same. For measurements collected with the EM38DD meter in the vertical dipole orientation, the average EC_a was significantly different (F-value = 12.439; P = 0.001) for the two groups of soils. For measurements collected with the EM31 meter in the vertical dipole orientation, the average EC_a was significantly different (F-value = 49.784; P = 0.001) for the two groups of soils. With both meters, soils appear to be distinguishable based on groupings that consider taxonomic classification, soil depth, and perhaps soil drainage class.

Tables 8 and 9 summarize the composition of map units based on the soils observed in the forty-nine cores. Results are summarized for each map unit based on the identity of cores sampled within consociations delineated on the

first (Table 8) and second (Table 9) order-one soil survey maps. In both tables, rows identify the named soil component of each consociation; columns identify the individual soil components that were observed in cores extracted from these consociations.

In each table, the frequency of the soil for which each consociation is named is shown in red. Based on the first order-one soil map, the named soil components comprised 0 to 67 % and averaged 28.12 % of the soils observed in cores from eight soil consociations. Based on the second order-one soil map, the named soil components comprised 0 to 100 % and averaged 32.78 % of the soils observed in cores from nine soil consociations. Compared with the first order-one soil survey, the second order-one soil survey has, on average, a slightly higher percentage of soils recognized in the names of the consociations at the core sites. For both surveys, in most consociations, the name soil makes up less than fifty percent of the soils observed in the cores.

Table 8.
Stephenson County Site.
Composition (%) of soil map units recognized in the first, order-one soil survey based on soils identified at each of the forty-nine core observation points.

SOILS

Soils Map unit	29	40	68	86	152	191	199	219	324	411	416	448	540	679	731
199B	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00
411B	0.00	0.10	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.60	0.00	0.10
416B	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.08	0.00	0.67	0.17	0.00	0.00	0.00
440B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.00	0.00	0.00
540C2	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.40	0.00	0.10
663	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.33	0.00
679A	0.00	0.00	0.14	0.00	0.14	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00
3107	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 9.
Stephenson County Site.
Composition (%) of soil map units recognized in the second, order-one soil survey based on the soils identified at each of the forty-nine core observation points.

SOILS

Soils Map unit	29	40	68	86	152	191	199	219	324	411	416	448	540	679	731
191	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
199B	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00
411B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.67	0.00	0.17
416B	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.08	0.00	0.62	0.08	0.00	0.00	0.00
448	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.33	0.00	0.00	0.00
540B	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.17
540C2	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.75	0.00	0.00
663	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.00
679A	0.00	0.00	0.13	0.00	0.13	0.00	0.00	0.11	0.00	0.00	0.00	0.38	0.00	0.25	0.00

In Tables 8 and 9, the frequency of dissimilar or more limiting soil inclusions in each consociation is shown in green. Dissimilar soils do not share a common soil depth or drainage class limits with the soil for which the consociation is named. For both surveys, poorly drained and more limiting Sable (29) and Drummer (152) soils were observed in cores extracted from areas mapped as moderately well drained Blackberry (679) soil. Though sampling was limited, based on the first order-one soil map, the more limiting Sable and Drummer soils comprised 28 % of the soils observed in cores extracted from the Blackberry consociation. Based on the second order-one soil map, the more limiting Sable and Drummer soils comprised 26 % of the soils observed in cores extracted from the Blackberry consociation. For both surveys, moderately deep and more limiting Ripon soils (324) were observed in cores extracted from the very deep Duran (416) consociation. For both surveys, Ripon soils made up 8 % of the observed cores in the Duran unit. Based on limited core data, the resurvey did not reduce the amount of dissimilar soils in map units.

For both surveys, the frequency of unnamed, similar inclusions (shown in black in Tables 7 and 8) ranged from 0 to 100%. Based on the first order-one soil map, similar soil components averaged 67.4 % of the soils observed in the cores. Based on the second order-one soil map, similar soil components averaged 63.4 % of the soils observed in the cores. Based on data from the 49 core sites, the second order-one soil survey, which had access to the EC_a data, provided a slight, but not substantial improvement in delineating soil polygons that contain a greater percentage of the named soil and lower percentages of dissimilar and similar soils.

The second order-one soil survey of the Stephenson County site produced a greater number of soil polygons and recognized more soils. However, soil cores provided no evidence that the second order-one soil survey greatly improved the accuracy of the soil maps. This study did show that EC_a can be used to effectively partition landscapes into groups that consider taxonomic classifications, soil depth, and drainage classes. Spatial EC_a patterns do conform to the general but not specific soil polygon patterns mapped by soil scientists.

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