THE IMPACT OF TEMPERATURE AND SHALLOW HYDROLOGIC CONDITIONS ON THE MAGNITUDE AND SPATIAL PATTERN CONSISTENCY OF ELECTROMAGNETIC INDUCTION MEASURED SOIL ELECTRICAL CONDUCTIVITY

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ABSTRACT. *In situ measurement of apparent soil electrical conductivity (EC_a) is an important precision agriculture tool for determining spatial changes in the soil properties affecting soil fertility. However, dynamic temperature and shallow hydrologic conditions also influence the measured EC_a and need to be considered. Therefore, the impact of temperature (air, soil) and shallow hydrologic conditions (soil moisture content, water table depth) on the magnitude and spatial patterns of EC_a was evaluated. Eighty-eight EC_a mapping surveys were conducted at a single test plot over an interval of two years. Soil electrical conductivity was measured by electromagnetic induction (EMI) at primary field frequencies of 8190, 14610, and 20010 Hz. Because results were similar at all three frequencies, analyses focused on the 14610 Hz data. The EC_a surveys were grouped into four time periods for analysis based upon factory recalibration of the sensor, climate changes, and a shift in instrument response. Reduced values of measured EC_a occurred with air temperatures at or below 12°C and/or soil temperatures at or below 8°C. Correlation analysis within each of the four data groups showed that the average EC_a, within the test plot, was most strongly affected by near-surface volumetric moisture content ($r_{MC-ECa:\ Grp.\ Avg.} = 0.73$), followed by water table depth ($r_{WTD-ECa:\ Grp.\ Avg.} = -0.42$), soil temperature ($r_{ST-ECa:\ Grp.\ Avg.} = 0.14$), and ambient air temperature ($r_{AT-ECa:\ Grp.\ Avg.} = -0.10$). Correlation analysis of spatial EC_a patterns between pairs of EMI surveys, conducted under a range of temperature and shallow hydrologic conditions, produced $r_{Spatial:\ ECa\ vs.\ ECa}$ values averaging 0.63 (standard deviation equaled 0.17), indicating that spatial EC_a patterns remain relatively consistent over time. These EC_a results indicate that the spatial EC_a response is governed to a large extent by the spatial changes in soil properties and less by changes in shallow hydrologic conditions.*

Keywords. *Air temperature, Apparent soil electrical conductivity (EC_a), Electromagnetic induction (EMI), Soil properties, Soil temperature, Volumetric moisture content, Water table depth.*

Precision agriculture combines geospatial datasets, state-of-the-art farm equipment technology, and global positioning system (GPS) receivers to support spatially variable field application of fertilizer, soil amendments, pesticides, herbicides, and tillage. The benefits of precision agriculture to farmers are maximized crop yields and/or reduced input costs. There is an important environmental benefit as well. Over-application of agrochemicals and soil tillage is fairly common. Since precision agriculture operations can result in optimal amounts of fertilizer, soil amendments, pesticides, herbicides, and tillage applied to different parts of the field, potentially less agrochemicals and sediment enter waterways from runoff.

Geospatial information on soil fertility aids determination of appropriate agrochemical application rates and tillage effort. The relatively stable soil profile properties influencing soil fertility include salinity, organic matter content, cation exchange capacity, grain size distribution, clay mineralogy, claypan/fragipan depth, etc. These same soil profile properties affect measured apparent soil electrical conductivity (EC_a). Consequently, spatial patterns of soil fertility can potentially be inferred from mapped EC_a. However, other more dynamic soil properties, such as temperature and shallow hydrologic conditions, can also theoretically impact EC_a geophysical measurements and, therefore, need to be carefully considered.

Soil electrical conductivity is generally electrolytic in nature, and thus depends on the concentration and mobility of dissolved ions present within the soil pore water (McNeill, 1980a). As one would expect, the EC_a effect due to the concentration of exchangeable, mobile ions in the soil environment is influenced by or related to the same previously mentioned soil profile properties that govern fertility. Ion mobility is affected by the size, shape, tortuosity, and interconnectedness of the pores; the temperature and phase state of the pore water; and the extent to which the

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pores are filled with water. Consequently, grain size distribution that governs the soil pore geometry, soil temperature, frozen ground conditions, the presence of claypans or fragipans that keep more water in the root zone by reducing drainage, surface wetness related to timing and intensity of rainfall/irrigation events, and depth to the water table can all influence ion mobility in the shallow soil environment, and hence, measured EC_a.

Near-surface geophysical methods, particularly those capable of mapping EC_a, are gaining more widespread use in agriculture. Increasing research documents possible uses and limitations for mapped EC_a. There has been substantial study of EC_a mapping as a tool for gauging the magnitude and spatial variability of soil salinity (Lesch et al., 1992; Hendrickx et al., 1992; Doolittle et al., 2001). Doolittle et al. (1994) determined a way to estimate claypan depths in a Missouri soil based on EC_a values obtained with EMI methods. Furthermore, Fraisse et al. (2001) were able to define claypan soil management zones with a combination of topographic elevation and EMI EC_a data. Kravchenko et al. (2002) likewise employed this combination of topographic elevation and EC_a (obtained from pulled electrode array resistivity methods) to map soil drainage classes. Inman et al. (2002) found that EMI EC_a and ground-penetrating radar data, when used together, can be a promising soil survey technique. Jaynes et al. (1995) estimated herbicide partition coefficients based on EMI EC_a measurements. In addition, Eigenberg and Nienaber (1998) established that EMI EC_a could be used as a way to detect field areas with high soil nutrient build-up due to manure applications. Consequently, a continually growing body of research is discovering new, potentially valuable agricultural applications for geophysical EC_a mapping.

Studies relating the effects of shallow hydrology on EC_a are relatively limited. Scanlon et al. (1999) evaluated EC_a measured with EMI methods as a reconnaissance technique to characterize unsaturated flow in an arid setting and determined that the magnitude of the impact of moisture content on EC_a was dependent on the geomorphic setting. An investigation conducted by Sheets and Hendrickx (1995) in an arid region of southern New Mexico documented a positive linear relationship between EMI EC_a and moisture content in the top 1.5 m of the soil profile. At a site in Minnesota, Khakural et al. (1998) also verified a positive linear relationship between EMI EC_a and soil profile water storage. Kachanoski et al. (1990) found that EMI EC_a explained more than 80% of the variation in soil water storage at scales larger than 40 m. Sudduth et al. (2001) concluded that soil moisture and soil temperature need to be taken into account when using EMI EC_a to estimate top soil depth. Lund et al. (1999), using resistivity methods, showed that variable soil moisture and temperature conditions did not significantly affect the EC_a spatial patterns in a Kansas wheat field. Interestingly, in a field study near Quebec City, Quebec, Canada, carried out with traditional resistivity methods, Banton et al. (1997) found that neither the EC_a mean nor the spatial pattern changed significantly between wet and dry soil conditions.

Past research has focused on the effects of soil characteristics on EC_a. Banton et al. (1997) determined that EC_a was moderately correlated with soil texture and organic matter, but not with porosity, bulk density, or hydraulic conductivity. Johnson et al. (2001) established that, for a test site located in the Colorado portion of the semiarid central Great Plains, EC_a was positively correlated with bulk density, percentage clay, laboratory measured soil electrical conductivity, and pH, but EC_a was negatively correlated with moisture content, total and particulate organic matter, total carbon, total nitrogen, extractable phosphorous, microbial biomass carbon, microbial biomass nitrogen, potentially mineralizable nitrogen, and surface residue mass.

Clearly, soil electrical conductivity can be affected by a number of different factors, some of which are more important than others depending location, climate, etc. Spatial patterns in soil fertility provide a basis for precision agriculture, and EC_a measurement can potentially be used to map the soil profile properties that affect soil fertility. However, EC_a can also be affected by transient temperature and shallow hydrologic conditions. For geophysical EC_a mapping to be useful as a soil fertility guide within a particular region, the relative impact of stable soil profile properties on spatial EC_a patterns must be greater than that of the transient soil conditions.

Above-ground air temperature does not have a direct impact on the actual soil electrical conductivity, but it may affect the internal electronics of EMI geophysics equipment, thereby causing a "drift" in the measured EC_a. Manufacturers of EMI equipment usually employ some form of temperature compensation strategy to minimize this potential problem (Geophex, Ltd., Raleigh, N.C., personal communication, 15 July 2004). The soil temperature effect is seemingly more straightforward. As soil temperature rises, pore water viscosity decreases, the mobility of dissolved ions become greater, and measured EC_a should increase (McNeill, 1980a). With regard to shallow hydrology, the more water present in near-surface soils, the greater the mobility of dissolved ions, resulting in larger EC_a values. Consequently, EC_a should be directly proportional to surface wetness as measured by soil volumetric moisture content. Conversely, EC_a should be inversely proportional to the depth of the shallow water tables that are common in glacially derived soils throughout the Midwest U.S.

Because soil conditions vary widely throughout the U.S. and the world, the potential use of EC_a for soil fertility mapping must be assessed on a region-by-region basis. The Midwest U.S. is one of the most agriculturally productive areas in the world. Fine-grained glacially derived soils and shallow, fluctuating water tables are common throughout the Midwest U.S. Accordingly, the objective of this project was to evaluate the impact of temperature (air, soil) and shallow hydrologic conditions (soil surface volumetric moisture content, water table depth) on measured EC_a in this region. Our research hypothesis was: "Given a typical Midwest U.S. setting characterized by poorly drained, glacially derived soils, temperature and shallow hydrologic conditions will affect the magnitude of the measured EC_a; however, spatial patterns in EC_a will remain relatively consistent over time, indicating that the EC_a response is largely governed by stable soil properties."

MATERIALS AND METHODS

The electromagnetic induction (EMI) method used to measure soil electrical conductivity employs an instrument called a ground conductivity meter (GCM), which contains two small wire coils spaced a set distance apart, one for transmitting a primary electromagnetic (EM) field downwards into the ground and a second for receiving a secondary EM field propagating upwards from the ground. The amplitude and phase differences between the primary and secondary fields are then used, along with the inter-coil spacing, to calculate an "apparent" or bulk value for soil electrical conductivity (EC_a). The GEM-2 (Geophex, Ltd., Raleigh, N.C.) was the GCM used exclusively in this study (fig. 1). The GEM-2 is a multi-frequency GCM, and the three primary EM field frequencies employed in this research were 8190, 14610, and 20010 Hz. These three frequencies were chosen to reflect the range of frequencies for different GCMs commonly utilized for shallow subsurface investigations. Lower frequencies were additionally tested initially but were not employed beyond this stage within the investigation because the data obtained were quite "noisy."

The GEM-2 had a separation distance of 1.66 m between the transmitting and receiving electric wire coils. For the EC_a surveys conducted in this study, the GEM-2 was operated 1 m above the ground surface with the transmitting and receiving electric wire coils oriented horizontal co-planer (vertical dipole mode). Manufacturer-provided data processing software corrected EC_a readings for instrument height above the ground surface. The GEM-2 was designed for ease of use, and as such, this GCM was not set up to allow for manual operator re-adjustment of EMI readings to compensate for "drift" in instrument response. However, it should be noted that the GEM-2 employs a temperature compensation strategy to minimize drift associated with changes in ambient air temperature (Geophex, Ltd., Raleigh, N.C., personal communication, 15 July 2004).

The actual depth of investigation is an important issue for EC_a measurement with EMI methods. Based strictly on skin depth considerations, EC_a investigation depth is a function of soil electrical conductivity and the GCM primary EM field frequency (Reynolds, 1997; Sharma, 1997). Huang (2004) developed a procedure, based on skin depth and the separation distance between the transmitting and receiving coils, to alternatively determine the depth of EMI investigation. Skin depth considerations alone or the procedure developed by Huang (2004) both imply that a multi-frequency GCM, such as the GEM-2, can provide information on vertical changes in EC_a because there is a different investigation depth for each primary EM field frequency employed.

A more commonly used approximation for the EMI investigation depth is discussed in detail by McNeill (1980b). For this method, given operation at low values of the induction number and assuming horizontal flow of electric current within the soil, the EMI depth of investigation is determined only by the spacing distance (*S*) between the transmitting and receiving coils. McNeill (1980b) showed that, in the vertical dipole mode of operation, approximately 70% of the EMI response can be attributed to the material present within a distance 1.5*S* beneath the GCM. The GEM-2 has an *S* value of 1.66 m and during operation it was held 1 m above the ground surface in the vertical dipole orientation, thereby giving it a 1.5 m investigation depth beneath the ground surface ($[1.5 \times 1.66 \text{ m}] - 1 \text{ m} \approx 1.5 \text{ m}$) based on this approach. As implied by McNeill (1980b), the 8190, 14610, and 20010 Hz frequencies used with the GEM-2 in this study should all provide the same depth of investigation.

Because this research project focused on assessing the contributions of soil temperature and hydrologic conditions to measured EC_a, it was crucial that the GCM employed had a depth of investigation beneath the ground surface of no more than 2 m. The procedures found in the literature that were previously discussed gave widely different estimates of the GEM-2 investigation depth. Consequently, electromagnetic vertical sounding techniques (Dualem, 2004) were employed in the field to determine the GEM-2 investigation depth. The vertical sounding technique involved collecting EC_a measurements (uncorrected for height) as the GEM-2 was raised in 0.2 m increments from the ground surface to a

Figure 1. The multi-frequency ground conductivity meter (GEM-2, Geophex, Ltd.) used in this study. The GEM-2, as shown, is in vertical dipole mode (transmitting and receiving coils are horizontal co-planer).

height of 2.6 m. A total of 320 EC_a measurements were averaged at each GEM-2 vertical position. As the EMI sensor is raised, more and more of the instrument response is governed by the zero electrical conductivity air layer between the sensor and ground surface. Therefore, with increasing height, measured GEM-2 EC_a should decrease. The height at which measured EC_a was reduced to a fraction of the EC_a value obtained at the ground surface corresponded to the GEM-2 depth of investigation. Electromagnetic vertical soundings were conducted at two test plot locations, once under extremely dry soil conditions and again under saturated conditions.

Test plot soil electrical conductivity surveys involved taking discrete measurements at a slow walking pace along a set of parallel transects covering a 15.2 × 19.8 m rectangular test plot (fig. 2). Soil electrical conductivity sampling was conducted at all three frequencies (8190, 14610, and 20010 Hz) simultaneously, and the distance between measurement points along transects ranged from 10 to 20 cm. The distance between EC_a sampling points was uniform along each transect, assuming a constant walking pace. The spacing distance between adjacent transects was 1.5 m (fig. 2). Apparent soil electrical conductivity was measured in milliSiemens per meter (mS/m). For each test plot survey, EC_a average and standard deviation were calculated and EC_a contour maps were generated. Surfer 8, a mapping package developed by Golden Software, Inc. (Golden, Colorado) was used to produce EC_a contour maps through geostatistical kriging techniques (Davis, 1973) in which a linear function with nugget effect model was fitted to the variogram of the data (Golden Software, 2002).

The test plot (fig. 3) was located behind the ElectroScience Laboratory on the Ohio State University campus in Columbus, Ohio. Celina series soils (fine, mixed, mesic aquic Hapludalfs) cover the site. A total of 88 EC_a mapping surveys were conducted during four separate periods over two years (8 July 2002 to 10 July 2004) at the test plot. These surveys were performed during summer, fall, winter, and spring months to assess EC_a response under a wide range of air and soil temperature conditions. Air and soil temperature data were collected prior to each EC_a survey. Ambient air temperature was measured using a Crop TRAK infrared thermometer (Spectrum Technologies, Inc., East Plainfield, Ill.). Air temperature readings were taken approximately 30 cm above the soil surface at points near the top of four wooden stakes partially inserted into the soil at the corners of the test plot. Soil temperatures were measured at depths of 15 to 20 cm with Weksler soil thermometers (Stratford, Conn.) near the southwest and northeast corners of the test plot.

The test plot was well-suited for investigating the impact of shallow hydrologic conditions on the EC_a response. As shown in figure 3, the test plot has a drainage system centered beneath it. This buried drainage system is comprised of four 10 cm diameter clay tile and corrugated plastic tubing (CPT) drainage pipes connected to two 10 cm diameter CPT main pipes. Due to land slope, the drainage pipe system was 1 m deep in its northwest corner and 0.6 m deep in its southeast corner. Two 10 cm diameter polyvinyl chloride (PVC) riser pipes (fig. 3) connected the buried drainage pipe system to the surface, thereby allowing a shallow water table to be maintained at any desired level by adjusting the water supply via a Hudson valve suspended inside one of the riser pipes. Nine shallow monitoring wells were installed at the test plot (fig. 3) to determine water table positions at the time the EC_a surveys were conducted. The monitoring wells extended approximately 1 m into the subsurface. They were constructed of 2.5 cm diameter perforated PVC pipe capped at one end and wrapped along its length with a sheet of fiberglass screen taped securely in place. Water table depths were measured in the monitoring wells using a Mini 101

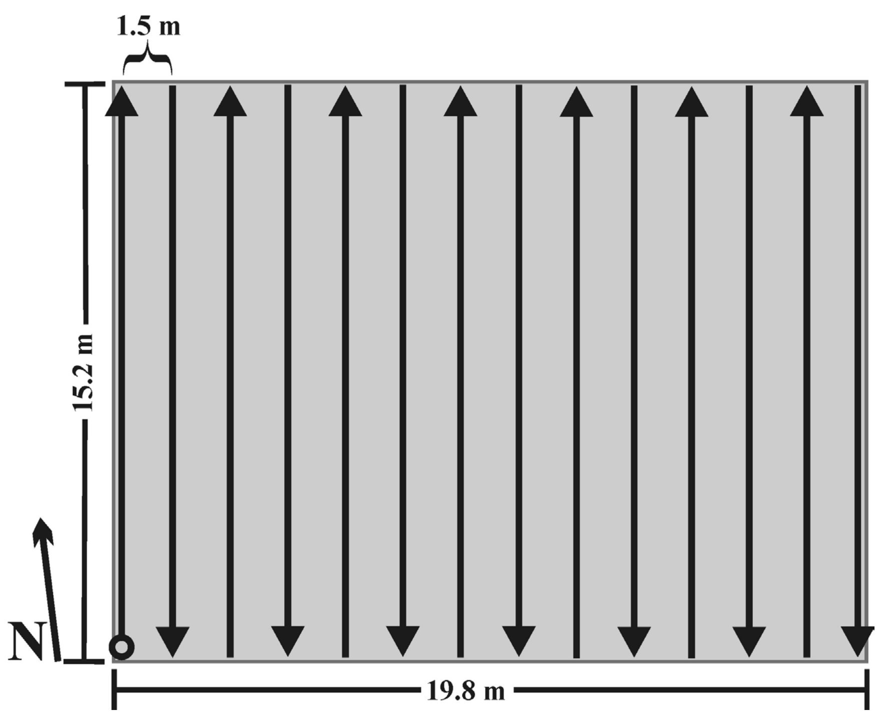

Figure 2. Vertical dipole mode electromagnetic induction surveys of the test plot all started in the southwest corner, with measurement lines that were north-south, bi-directional, and spaced 1.5 m apart.

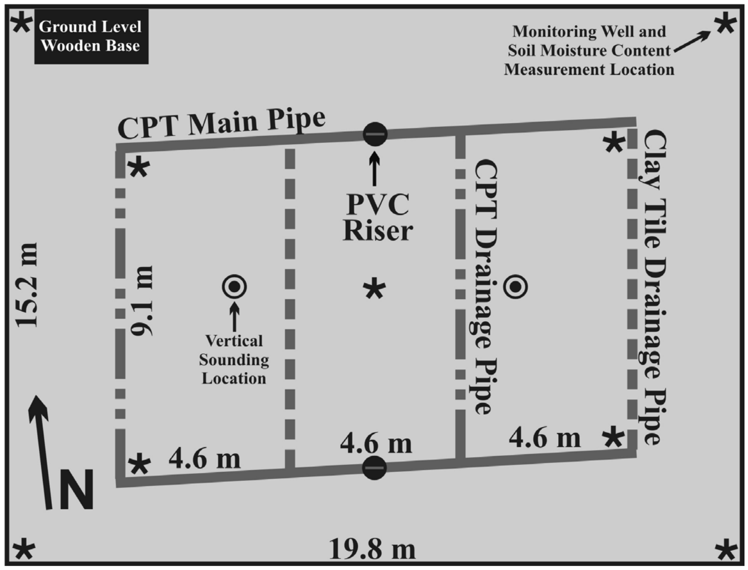

Figure 3. Schematic of the ElectroScience Laboratory test plot on which electromagnetic induction soil electrical conductivity surveys were conducted.

water level meter (Solinst Canada, Ltd., Georgetown, Ontario, Canada).

For each EC_a survey, soil surface volumetric moisture content was measured near each of the nine monitoring wells (fig. 3). A Field Scout TDR-300 soil moisture probe (Spectrum Technologies, Inc., East Plainfield, Ill.) employing time domain reflectometry (TDR) principles was used to measure the average soil volumetric moisture content between the soil surface and a depth of 20 cm. These TDR measurements averaged 70% under saturated, non-frozen soil conditions, which was somewhat higher than expected. Regardless, TDR measurements were useful for the relative assessment of near-surface soil moisture. Soil electrical conductivity surveys were conducted under wet, dry, and frozen soil surface conditions. Wet soil conditions resulted from significant rainfall or sprinkler application of water.

Fifteen soil subsamples were obtained at different test plot locations from 10 cm diameter boreholes augered to a depth of 1 m. These composited soil samples were analyzed using standard methods (ASA and SSSA, 1982; Wray, 1986) at Ohio State University laboratories for pH, concentration of the dominant exchangeable cation (Ca^{2+}), % organic matter, cation exchange capacity, % sand, % silt, % clay, and salinity as indicated by the electrical conductivity of a 1/1 by weight soil/water slurry. The soil types present at the test plot, based on the grain size analysis of the composited samples (Wray, 1986), ranged from silt loam to silty clay loam to clay loam, all of which are typical of material derived from weathering of Midwest U.S. glacial till deposits. The soil properties from composited auger samples taken at the 15 test plot locations were then compared via statistical regression with EC_a values obtained at the same test plot locations. The EC_a point values used for this comparison with soil properties were determined by calculating the average of 400 to 600 GEM-2 measurements taken at each of the 15 locations.

Data analysis of the 88 EC_a surveys was conducted in six phases for determining:

1. EMI investigation depth (from electromagnetic vertical sounding results).
2. Necessity of dividing the complete EC_a survey record into distinct data periods, based on the average EC_a test plot values (8190, 14610, and 20010 Hz) from each survey.
3. Similarity of EC_a results between the three EM frequencies employed.
4. Correlation between average test plot EC_a and average test plot temperature or shallow hydrologic conditions.
5. Temporal consistency of the test plot EC_a spatial pattern.
6. Relative effect of soil properties on the test plot EC_a spatial pattern.

Data Analysis, Results, and Discussion

Electromagnetic Induction (EMI) Investigation Depth

The electromagnetic (EM) vertical sounding results are exhibited in figure 4. The two locations where the vertical soundings were conducted, one on the east side of the test plot and the other on the west side, are shown in figure 3. As previously stated, the vertical soundings were carried out at both test plot locations once under very dry conditions (average near-surface soil volumetric moisture content equaled 12.4%, and water table depths were greater than 1 m) and once under very wet conditions (water table was at the ground surface). Each graph in figure 4 provides vertical sounding data plots for all three frequencies (8190, 14610, and 20010 Hz).

Vertical sounding electrical conductivity values under wet soil conditions averaged almost twice those under dry soil conditions. It is not clear why the electrical conductivity readings first increase and then decrease as the sensor is raised above the ground surface, but this could be due to a low electrical conductivity zone beneath a depth of 2.2 to 2.4 m. For each of the four vertical sounding graphs in figure 4, the plotted data are fairly similar for all three primary EM field frequencies. Furthermore, averaged over all three EM frequencies and calculated for both dry and wet field conditions, the electrical conductivity at a sensor height of 2.5 m was only 15% of the electrical conductivity measured by the GEM-2 at the ground surface.

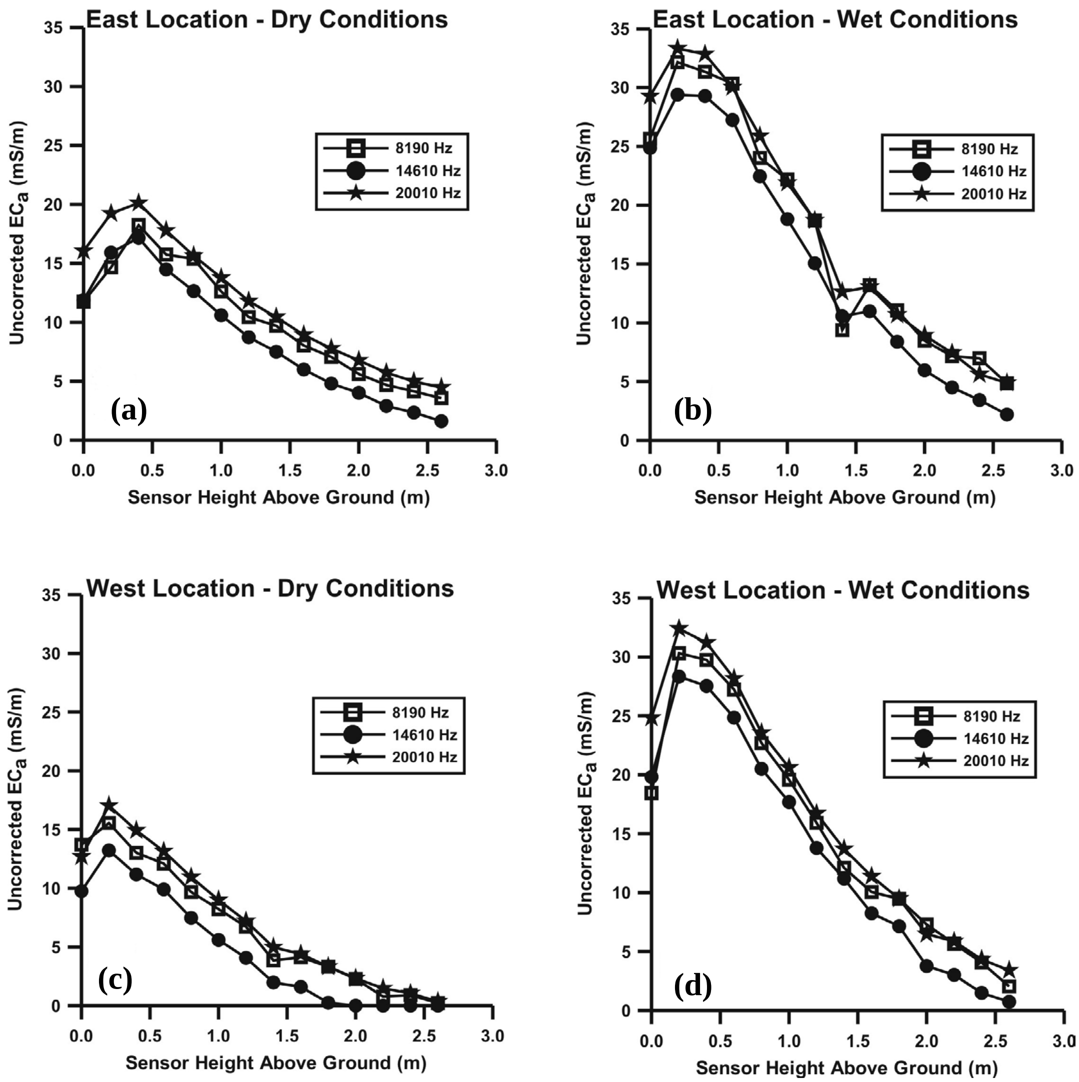

Figure 4. Electromagnetic vertical sounding results for 8190, 14610, and 20010 Hz primary EM field frequencies showing uncorrected EC_a versus above-ground sensor height: (a) east test plot location and dry field conditions, (b) east test plot location and wet field conditions, (c) west test plot location and dry field conditions, and (d) west test plot location and wet field conditions.

This result implies that the GEM-2 has an investigation depth of 2.5 m, which is independent of the three primary EM field frequencies employed and soil moisture conditions. In accordance with McNeill (1980b), the GEM-2 investigation depth of 2.5 m is greater by a factor of 1.5 than its inter-coil spacing (1.66 m) and is unaffected by the range of EM frequencies used (8190 to 20010 Hz) and field moisture conditions. Because the GEM-2 was operated 1 m above the ground surface, its actual investigation depth beneath the ground surface was approximately 1.5 m, thereby fitting with the focus of this research to assess the impact of soil temperature and hydrologic conditions on EC_a.

Necessity of Dividing the Complete EC_a Survey Record into Distinct Data Periods

A total of 88 EC_a test plot surveys were conducted during four separate periods (8 July 2002 to 28 April 2003, 29 May 2003 to 14 Aug. 2003, 2 Dec. 2003 to 10 March 2004, and 8 June 2004 to 10 July 2004) over two years. For each survey, the EC_a average and standard deviation were calculated for all three of the GEM-2 primary EM field frequencies. Corresponding to each EC_a test plot survey, measurement averages were also calculated for ambient above-ground air temperature (AT), near-surface soil temperature (ST), near-surface soil volumetric moisture content (MC), and water table depth (WTD).

Charts of test plot survey EC_a averages versus the corresponding average values for AT, ST, MC, and WTD are provided in figure 5. Only the 14610 Hz data are shown in figure 5, but the results are similar for 8190 and 20010 Hz. Different symbols are used for data points from each of the four EC_a survey periods. For simplicity, the following terms are used: group A (data from 8 July 2002 to 28 April 2003), group B (data from 29 May 2003 to 14 Aug. 2003), group C (data from 2 Dec. 2003 to 10 March 2004), and group D (data from 8 June 2004 to 10 July 2004). Comparison of the data provided the first indication that test plot EC_a averages were different among the groups, even though the ranges in temperature and shallow hydrologic conditions for the four groups overlapped (fig. 5). Data points within each group tend to form clusters (for EC_a vs. AT and EC_a vs. ST) or linear bands (for EC_a vs. MC and EC_a vs. WTD) different from those of other groups.

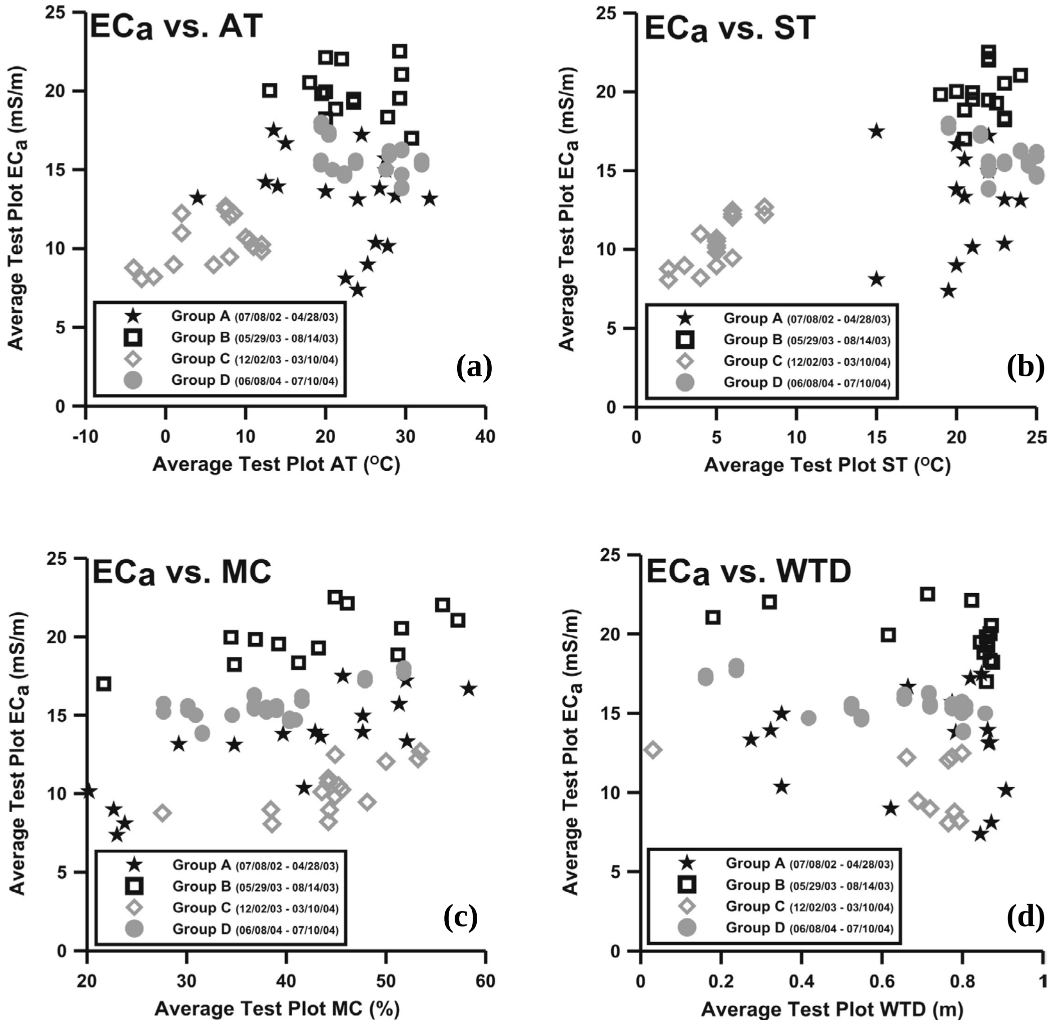

Figure 5. Charts of test plot EC_a averages with respect to average test plot temperature and shallow hydrologic conditions: (a) EC_a vs. ambient above-ground air temperature (AT), (b) EC_a vs. near-surface soil temperature (ST), (c) EC_a vs. near-surface soil volumetric moisture content (MC), and (d) EC_a vs. water table depth (WTD).

Differences in mean EC_a between the four data collection periods were confirmed through statistical analysis. These analyses were based on values provided in table 1 for the group averages of the test plot EC_a averages, the group standard deviations of the test plot EC_a averages (table 1), and the number of EC_a surveys within each group. A modified statistical t-test (Snedecor and Cochran, 1967) compared two groups (same EM frequency) to determine whether the null hypothesis that the two groups had the same mean could be rejected, given that each group had a different standard deviation and a different number of observations. Based the assumption of normality, and confirmed by skewness, kurtosis, and other calculations, all four groups (EC_a data collection periods) were statistically different ($P < 0.05$). Again, these EC_a differences occurred even though the ranges in temperature and shallow hydrologic conditions for the four periods overlapped. Because of these differences, the impacts of AT, ST, MC, and WTD averages on the test plot EC_a average were analyzed separately for each data collection period.

Table 2 highlights possible explanations for the differences in test plot EC_a averages between groups. The difference in group A is due to factory recalibration of the GEM-2 when it was sent back for repair of an internal battery

Table 1. Group statistics for EC_a surveys.

Group[a]	No. of Surveys	Average[b] (mS/m)			Standard Deviation 1[c] (2[d]) (mS/m)		
		8190 Hz	14610 Hz	20010 Hz	8190 Hz	14610 Hz	20010 Hz
A	21	15.66	12.91	15.40	3.17 (3.00)	2.38 (2.94)	2.16 (2.90)
B	16	19.39	19.81	21.45	3.69 (1.78)	2.53 (1.56)	2.19 (1.64)
C	17	10.78	10.38	11.79	2.42 (2.19)	1.73 (1.53)	1.48 (1.59)
D	34	17.34	15.67	18.08	3.11 (0.99)	2.24 (1.07)	1.68 (1.04)

[a] A = 8 July 2002 to 28 April 2003, B = 29 May 2003 to 14 Aug. 2003, C = 2 Dec. 2003 to 10 March 2004, and D = 8 June 2004 to 10 July 2004.
[b] Group average of test plot EC_a averages.
[c] Group average of the test plot EC_a standard deviations.
[d] Standard deviation of the group test plot EC_a averages.

Table 2. Group characteristics of EC_a surveys.

Group	Time Period	Timing in Regard to Recalibration	AT[a] (°C)	ST[b] (°C)	MC[c] (%)	WTD[d] (m)
A	8 July 2002 − 28 April 2003	Before	22.0	20.4	39.8	0.69
B	29 May 2003 − 14 Aug. 2003	After	23.2	21.7	42.9	0.75
C	2 Dec. 2003 − 10 March 2004	After	5.7	5.0	44.4	0.68
D	8 June 2004 − 10 July 2004	After	25.0	23.0	38.6	0.60

[a] Ambient above-ground air temperature (AT) group average.
[b] Near-surface soil temperature (ST) group average.
[c] Near-surface soil volumetric moisture content (MC) group average.
[d] Water table depth (WTD) group average.

malfunction. As indicated in table 2, average AT, ST, MC, and WTD conditions were similar for the four groups with one exception: the average AT and ST values were much lower for group C than for the other groups. Group C EC_a surveys were completed in 2003/2004 during winter and early spring when climate conditions were cold (from table 2, average AT = 5.7˚C and average ST = 5.0˚C). By inspecting the data presented in figures 5a and 5b and comparing the EC_a averages between groups in table 1, there appears to be a temperature threshold, AT $\leq$ 12˚C and/or ST $\leq$ 8˚C, below which there is a substantial reduction in the measured EC_a. Compared with the "after recalibration" groups (B and D), group C has average EC_a values for the three EM frequencies that are 5 to 10 mS/m less (table 1).

While it is possible that cold air temperatures have a direct influence on the GEM-2 response, it is more likely that the lower group C EC_a values are a result of soil temperature conditions. Soil electrical conductivity could have been reduced due to frozen soil surface conditions (even though ST values for soil at 15 to 20 cm depths were above freezing, the surface was typically frozen.) However, reduced EC_a values for group C are more likely the result of increases in the viscosity of water in the soil profile, due to the cold temperatures, which decreases electrolyte mobility. Additionally, cold climate conditions suppress the range of EC_a values measured, as indicated in table 1 where group C has the lowest average EC_a standard deviation. Finally, average temperature and shallow hydrologic conditions were similar for groups B and D (table 2), so it is puzzling why EC_a averages differed between the two groups. It is possible that an internal change in instrument performance caused a small 2 to 3 mS/m "shift" in the GEM-2 EC_a response between groups B and D.

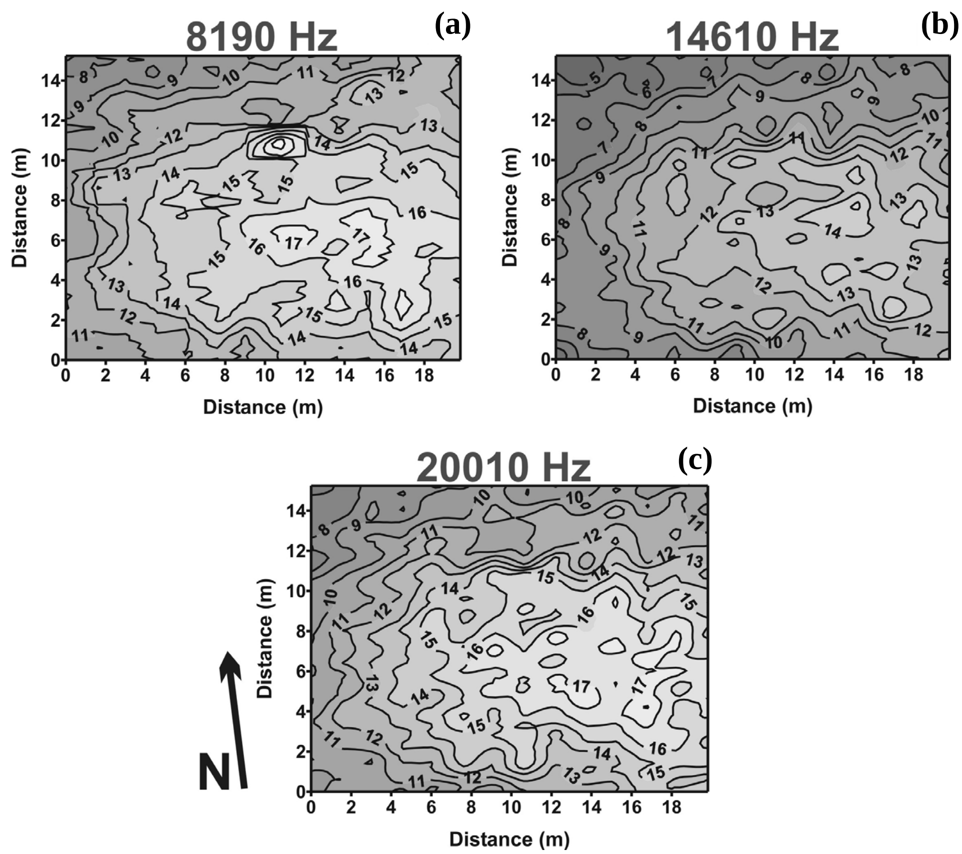

Figure 6. Results from EMI EC_a survey conducted on 18 July 2002: (a) EC_a map produced from 8190 Hz data, (b) EC_a map produced from 14610 Hz data, and (c) EC_a map produced from 20010 Hz data.

SIMILARITY OF EC_a RESULTS BETWEEN THE THREE EM FREQUENCIES.

Surveyed EC_a averages and spatial patterns were similar for 8190, 14610, 20010 Hz (table 1 and fig. 6). This result was expected because the GEM-2 investigation depth was the same for all three primary EM field frequencies. It is interesting to note that standard deviations of the group EC_a test plot averages were moderately greater at 8190 Hz than at 14610 or 20010 Hz, implying that the 8190 Hz data is somewhat "noisier." General spatial patterns shown in figure 6 are typical of the EC_a surveys conducted in this study. Specifically, low EC_a values were present along the north, west, and south test plot boundaries, while higher EC_a values could be found in a lobe that extends westward from the east boundary through the center of the plot. Because EC_a results were similar for all three GEM-2 frequencies, further analysis concentrated on EC_a data collected at 14610 Hz.

CORRELATION BETWEEN AVERAGE TEST PLOT EC_a AND AVERAGE TEST PLOT TEMPERATURE OR SHALLOW HYDROLOGIC CONDITIONS

Correlation coefficients (r) for each of the four groups, between test plot EC_a averages (14610 Hz) and corresponding temperature (AT, ST) or shallow hydrologic (MC, WTD) condition averages, are provided in table 3. Correlation analysis assumes a linear relationship, and this approach for this phase of the study seemed appropriate based on inspection of figure 5. As indicated by the averages of the group r values, $(r_A + r_B + r_C + r_D)/4$, the strongest correlation was between EC_a and MC ($r_{MC-ECa: Grp. Avg.} = 0.73$), followed by WTD ($r_{WTD-ECa: Grp. Avg.} = -0.42$). As would be expected, EC_a is inversely related to WTD (decreased water table depths lead to wetter soil conditions and increased EC_a). It is not surprising that the EC_a versus MC correlation is substantially stronger than the EC_a versus WTD correlation. A high water table close to the surface causes wet soil conditions, which produce relatively high EC_a values. However, with a low water table well beneath the root zone, EC_a values can be relatively high or relatively low based predominantly on moisture conditions in the unsaturated soil above the water table.

The average of the group r values between EC_a and AT ($r_{AT-ECa: Grp. Avg.} = -0.10$) or EC_a and ST ($r_{ST-ECa: Grp. Avg.} = 0.14$)are both relatively small. Here, a failure to separate the data into the four groups could be misleading, because while EC_a versus AT ($r_{AT-ECa: Comp. Rec.} = 0.47$) and EC_a versus ST ($r_{ST-ECa: Comp. Rec.} = 0.67$) seem large, they actually reflect spurious correlation from data clustering, as described by Haan (1977). Cold climate conditions in group C caused EC_a averages to be significantly lower than the EC_a averages of groups A, B, and D measured under warmer climate conditions (figs. 5a and 5b). Within-group correlations between EC_a and temperature conditions were relatively large and positive for group C ($r_{AT-ECa: Grp. C} = 0.46$, $r_{ST-ECa: Grp. C} = 0.80$), but for the other three groups, correlations were smaller in magnitude and/or negative. The most important result presented in table 3 is that shallow soil hydrology has a much greater impact on EC_a than air/soil temperature, assuming reasonably uniform climatic conditions.

Table 3. Correlation coefficients with respect to average test plot EC_a (14610 Hz) versus average temperature or shallow hydrologic conditions.

	Group A	Group B	Group C	Group D	Average of Groups A through D
AT	−0.26	−0.14	0.46	−0.46	−0.10
ST	0.08	0.20	0.80	−0.53	0.14
MC	0.84	0.67	0.67	0.74	0.73
WTD	−0.06	−0.51	−0.40	−0.69	−0.42

TEMPORAL CONSISTENCY OF THE TEST PLOT EC_a SPATIAL PATTERN

Spatial correlation results are presented in table 4. To test the consistency of EC_a spatial patterns over time, five EC_a (14610 Hz) surveys were chosen from each of the four survey groups (20 in all). The surveys were selected based on the criterion of greatest possible variability in average test plot temperature and shallow hydrologic conditions. Spatial correlation coefficients for EC_a ($r_{Spatial: ECa\ vs.\ ECa}$) were calculated for all 190 possible pairs of surveys. These spatial correlation coefficients indicate the degree of similarity in spatial EC_a patterns between two EC_a surveys.

These correlation coefficients were calculated by first taking the 1500 (on average) irregularly spaced EC_a measurements from each survey and using geostatistical kriging methods (Davis, 1973) to interpolate a regularly spaced grid of 7700 EC_a point estimates using Surfer 8. Each EC_a point estimate on one spatial grid was compared to a corresponding location point estimate on the second grid. Consequently, 7700 pairs of interpolated EC_a point estimates were used in the calculation of an $r_{Spatial: ECa\ vs.\ ECa}$ value. The software package employed to compute $r_{Spatial: ECa\ vs.\ ECa}$ values was MapCalc developed by Red Hen Systems, Inc. (Fort Collins, Colo.).

The average of the 190 computed $r_{Spatial: ECa\ vs.\ ECa}$ values equaled 0.63 ($P < 0.001$) with a standard deviation of 0.17. The $r_{Spatial: ECa\ vs.\ ECa}$ average value of 0.63 is large, especially considering that the walking pace for each transect was not likely to be entirely uniform and the inherent GEM-2 measurement variability at a point location. Thus, an $r_{Spatial: ECa\ vs.\ ECa}$ average value of 0.63 indicates that the spatial EC_a pattern at the test plot does indeed remain reasonably consistent over time.

Figure 7 shows the range of spatial patterns for MC and WTD, which were measured at the same time as three of the EC_a surveys used for the spatial correlation analyses. The relatively strong within-group correlation between the test plot EC_a averages and the test plot MC and WTD averages indicates that MC and WTD potentially influence EC_a spatial patterns. If this were the case, then the MC spatial correlation coefficient ($r_{Spatial: MC\ vs.\ MC}$) average and/or the WTD spatial correlation coefficient ($r_{Spatial: WTD\ vs.\ WTD}$) average might be expected to have a magnitude similar to the $r_{Spatial: ECa\ vs.\ ECa}$ average. The $r_{Spatial: MC\ vs.\ MC}$ values were calculated by correlation analysis of nine MC measurements (see fig. 3 for measurement locations) taken during one survey event versus nine MC measurements (fig. 3) taken during a second survey event. Values of $r_{Spatial: WTD\ vs.\ WTD}$ were determined in a similar manner. Twenty MC data sets and 20 WTD data sets were used to calculate 190 $r_{Spatial: MC\ vs.\ MC}$ values and 190 $r_{Spatial: WTD\ vs.\ WTD}$ values, respectively. The 20 MC data sets and 20 WTD data sets employed corresponded to the 20 EC_a surveys used to calculate $r_{Spatial: ECa\ vs.\ ECa}$ values.

Table 4 shows that $r_{Spatial: MC\ vs.\ MC}$ and $r_{Spatial: WTD\ vs.\ WTD}$ averages, 0.26 and 0.29 respectively, were substantially less than the $r_{Spatial: ECa\ vs.\ ECa}$ average of 0.63. The $r_{Spatial:MC\ vs.MC}$

Table 4. Spatial correlation results.

Group	Date	AT Average (°C)	ST Average (°C)	MC Average (%)	WTD Average (m)	EC_a Average (14610 Hz) (mS/m)	Spatial Correlation Coefficient Statistics: MC	WTD	EC_a
	15 July 2002	25.5	20.0	22.7	0.62	8.98			
	18 July 2002	26.5	23.0	41.8	0.35	10.36			
A	19 July 2002	28.8	20.5	52.1	0.27	13.33			
	21 Sept. 2002	27.5	20.5	51.3	0.77	15.70			
	28 April 2003	22.5	15.0	23.8	0.87	8.10			
	3 July 2003	30.8	20.5	21.7	0.86	17.00			
	11 July 2003	18.0	23.0	51.6	0.87	20.54			
B	31 July 2003	20.0	21.0	34.4	0.62	19.95			
	4 Aug. 2003	22.0	22.0	55.7	0.32	22.02	Average r = 0.26 (standard deviation of r = 0.38)	Average r = 0.29 (standard deviation of r = 0.43)	Average r = 0.63 (standard deviation of r = 0.17)
	7 Aug. 2003	29.5	24.0	57.2	0.18	21.05			
	5 Dec. 2003	7.5	8.0	53.4	0.03	12.69			
	10 Dec. 2003	8.5	8.0	53.2	0.66	12.21			
C	16 Dec. 2003	8.0	6.0	50.0	0.77	12.05			
	9 Jan. 2004	1.0	3.0	38.8	0.72	8.98			
	20 Jan. 2004	−4.0	2.0	27.6	0.78	8.77			
	22 June 2004	27.6	22.0	30.9	0.80	15.00			
	30 June 2004	20.4	21.5	47.9	0.16	17.20			
D	8 July 2004a	20.9	22.0	34.6	0.86	15.00			
	8 July 2004b	22.4	25.0	40.3	0.55	14.70			
	10 July 2004	32.0	24.5	39.0	0.52	15.30			

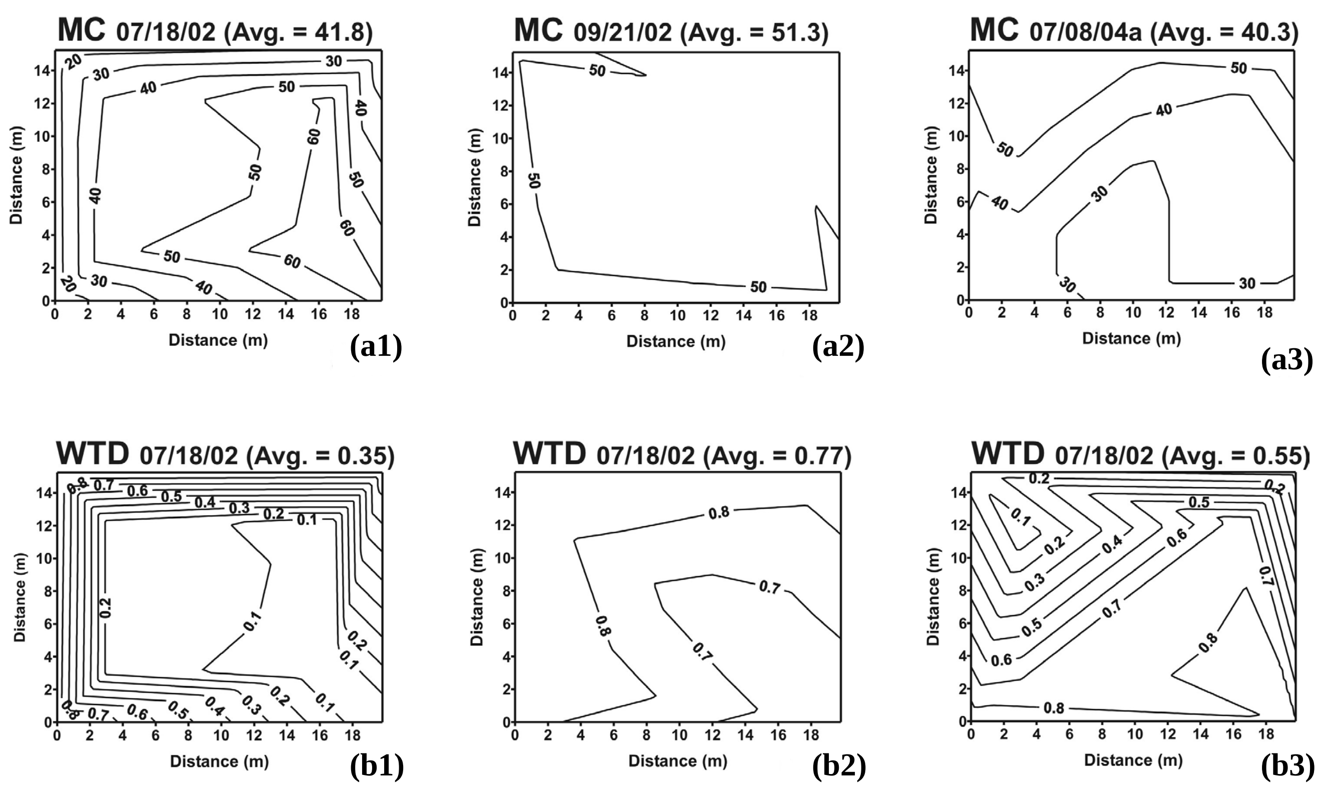

Figure 7. Examples of test plot MC and WTD spatial patterns: (a1, b1) water applied via the subsurface drainage system produced a groundwater mound that the rose to the surface, (a2, b2) a rainfall event wets the surface, but the water table remains relatively low, and (a3, b3) water was applied via sprinkler irrigation along the north boundary and northwest corner of the test plot.

and $r_{Spatial: WTD\ vs.\ WTD}$ standard deviations, 0.38 and 0.43 respectively, were much greater than the $r_{Spatial: ECa\ vs.\ ECa}$ standard deviation of 0.17. Plotting $r_{Spatial: ECa\ vs.\ ECa}$ versus $r_{Spatial: MC\ vs.\ MC}$ data points on an X-Y coordinate chart indicated that the relationship between $r_{Spatial: ECa\ vs.\ ECa}$ and $r_{Spatial: MC\ vs.\ MC}$ is linear. Likewise, plotting $r_{Spatial: ECa\ vs.\ ECa}$ versus $r_{Spatial: WTD\ vs.\ WTD}$ data points on an X-Y coordinate chart indicated that the relationship between $r_{Spatial: ECa\ vs.\ ECa}$ and $r_{Spatial: WTD\ vs.\ WTD}$ is linear. Stepwise linear regression analysis produced an equation of the form:

$$r_{\text{Spatial: ECa vs. ECa}} = 0.149(r_{\text{Spatial: MC vs. MC}}) + 0.149(r_{\text{Spatial: WTD vs. WTD}}) + 0.544 \quad (1)$$

that has a coefficient of determination (R^2) value of only 0.314. The R^2 value of 0.314 indicates that both $r_{\text{Spatial: MC vs. MC}}$ and $r_{\text{Spatial: WTD vs. WTD}}$ together account for just 31.4% of the variation in $r_{\text{Spatial: ECa vs. ECa}}$. Overall, the comparison analysis involving $r_{\text{Spatial: ECa vs. ECa}}$, $r_{\text{Spatial: MC vs. MC}}$, and $r_{\text{Spatial: WTD vs. WTD}}$ implies that factors other than MC and WTD have a substantial affect on the general EC_a pattern of the test plot. These other factors must be soil properties.

Relative Effect of Soil Properties on the Test Plot EC_a Spatial Pattern

With the spatial correlation results in table 4 indicating that the test plot EC_a spatial pattern remains fairly consistent over time, and that spatial variation in soil properties is largely responsible for this EC_a spatial pattern, the next logical step is to determine which soil properties have the greatest impact on the EC_a response. Table 5 presents regression analysis results between EMI EC_a point values obtained at 15 test plot locations and soil properties determined from laboratory analysis of composite soil samples taken at the same 15 test plot locations. Each of the EC_a point values represents an average of 400 to 600 measurements taken at that location, and soil samples from the same location were hand-augered from a 4 in. diameter borehole and composited with material from the surface down to a depth of 1 m. Again, the composited soil samples were analyzed for pH, concentration of the dominant exchangeable cation (calcium, Ca^{2+}), % by weight organic matter, cation exchange capacity (CEC), % by weight sand, % by weight silt, % by weight clay, and salinity as indicated by the electrical conductivity of a 1/1 by weight soil/water slurry. Four functions, linear ($Y = BX + A$), logarithmic ($Y = B\ln[X] + A$), exponential ($\ln[Y] = BX + A$), and power ($\ln[Y] = B\ln[X] + A$), were fitted to the data using Grapher 3 software, developed by Golden Software, Inc. (Golden, Colorado), and the functions giving the best fit are listed in table 5.

It would have been preferable for the soil sample boreholes to have extended 1.5 m beneath the surface so as to correspond with the EMI depth of investigation. However, hand-augering the boreholes to a depth much below 1 m was not possible. Based on McNeill (1980b), and taking into consideration that the GEM-2 was operated 1 m above the ground surface, it was determined that the interval from the surface to a depth of 1 m accounts for 80% of the total instrument response for the surface to the 1.5 m depth interval. Consequently, the soil samples from the surface to a depth of 1 m were obtained from the layer that contributes significantly to the overall EMI instrument response.

Based on the R^2 values in table 5, none of the soil properties proved to have a strong fit with EC_a. The largest R^2 values were found between EC_a versus Ca^{2+} ($R^2 = 0.082$) and EC_a versus CEC ($R^2 = 0.086$). These small R^2 values can be explained as follows:

- It is possible that EC_a is governed by a soil property not listed in table 5.
- EC_a may be affected by more that one soil property, thereby requiring multi-regression statistical analysis to determine a more complex EC_a versus soil properties relationship. (Because there are eight potential independent variables, a valid multi-regression analysis would have required more than 15 soil samples.)
- The EC_a measured with EMI methods is an effective value for a large soil volume, and the overall properties of this large volume might not be well represented by a relatively small soil sample, especially if there is considerable small-scale soil property spatial variability.

Table 5. Regression analysis results for EC_a compared to soil properties. Soil samples were a composite from the surface to a depth of 1 m, and electromagnetic induction measurements had a depth of investigation of 1.5 m.

Sample	X[a] Position (m)	Y[b] Position (m)	EC_a (mS/m)	pH	Ca^{2+} [c] (µg/g)	Organic Matter (% by wt.)	CEC[d] (meq/100g)	Sand (% by wt.)	Silt (% by wt.)	Clay (% by wt.)	EC_{ss}[e] (mS/m)
1	0.00	0.00	14.17	5.7	1806	2.50	12.42	16.39	58.28	25.33	43
2	19.81	0.00	17.79	7.5	3165	2.34	17.84	19.86	54.82	25.33	33
3	9.14	6.10	16.69	6.1	1539	2.06	8.98	19.86	55.64	24.50	37
4	16.76	6.10	17.05	6.2	2079	2.79	13.36	20.84	50.57	28.58	47
5	9.14	15.24	12.31	7.4	3008	2.39	17.00	17.68	56.14	26.18	46
6	0.00	15.24	13.60	7.0	2246	2.37	14.30	23.31	48.11	28.58	29
7	19.81	15.24	14.97	7.7	3172	2.05	17.61	19.86	53.96	26.18	32
8	0.00	9.14	13.72	7.4	3333	1.96	19.10	19.86	53.96	26.18	47
9	6.10	6.10	16.97	7.2	2507	2.60	15.31	19.86	50.03	30.12	31
10	6.10	12.19	15.10	7.0	2199	1.95	14.04	23.31	46.58	30.12	25
11	15.24	13.72	16.53	7.0	2028	1.53	11.84	19.86	51.56	28.58	33
12	19.81	4.57	18.21	6.9	2139	2.39	14.23	19.86	52.41	27.73	29
13	19.81	10.67	17.58	6.9	2327	2.21	14.21	23.31	48.96	27.73	46
14	9.14	0.00	14.76	6.5	2196	2.64	14.14	19.86	50.03	30.12	34
15	3.05	12.19	15.81	6.7	2523	2.26	15.99	19.86	45.32	34.83	48
Relationship (+ or −)				−	−	+	−	+	−	+	−
Coefficient of determination (R^2)				0.014	0.082	0.0013	0.086	0.077	0.040	0.0103	0.038
Function with best fit				Exp.	Exp.	Linear	Exp.	Power	Exp.	Power	Exp.

[a] East-west position within test plot referenced from the origin at the southwest corner.
[b] North-south position within test plot referenced from the origin at the southwest corner.
[c] Concentration of dominant exchangeable cation (calcium, Ca^{2+}).
[d] Cation exchange capacity.
[e] Soil salinity as indicated by electrical conductivity of 1/1 by weight soil/water slurry.

The presence of this small-scale soil property spatial variability was tested using a Field Scout Direct EC probe (Spectrum Technologies, Inc., East Plainfield, Ill.) to measure 100 point values of soil electrical conductivity at a depth of 15 cm within a 1 m^2 area. This testing was done at three 1 m^2 areas within the test plot. At one testing area, the average soil electrical conductivity was 21.16 mS/m with a standard deviation of 3.96 mS/m. At another area, the average soil electrical conductivity was 33.31 mS/m with a standard deviation of 13.62 mS/m. For the third location, the average soil electrical conductivity was 41.77 mS/m with a standard deviation of 15.42 mS/m. These results indicate that there is a significant amount of small-scale spatial variability present within the soil at the test plot. Consequently, some form of soil sampling protocol representative of a soil volume similar to the EC_a measurement volume may be needed to better determine which soil properties have the greatest influence on the EC_a response.

Summary and Conclusions

The major findings of this research project are as follows:

- Electromagnetic vertical sounding tests indicated that the depth of investigation was similar (1.5 m beneath the soil surface) for all three primary electromagnetic (EM) field frequencies (8190, 14610, and 20010 Hz) used in this study. Although the three primary EM field frequencies provided comparable results, a multi-frequency GCM is still advantageous. Interference from electromagnetic "noise" at the same frequency employed by a single-frequency GCM could interfere with EC_a measurement, while a multi-frequency GCM could be set at a frequency not coinciding with outside "noise."
- Cold climate conditions significantly reduce measured EC_a, probably due to the reduced electrolyte mobility that results from the increased viscosity and freezing of soil water. Consequently, caution is warranted when comparing EC_a magnitudes measured in cold weather to EC_a magnitudes measured during other times of the year.
- During time periods with a relatively uniform climate, shallow hydrologic conditions such as soil surface moisture content and water table depth tend to have a much greater impact on EC_a than air or soil temperature conditions. Therefore, rainfall and irrigation events, depending on duration and intensity, can substantially impact EC_a magnitudes over short time durations.
- Test plot EC_a spatial patterns remained relatively consistent over time regardless of temperature and shallow hydrologic conditions, indicating that spatial EC_a patterns are largely governed by spatial variations in soil profile properties. Consequently, under conditions similar to those tested in this study, EC_a mapping would be a useful tool in precision agriculture. In other words, spatial patterns in measured EC_a appear to be driven to a great extent by stable soil properties that are associated with fertility.
- Based on statistical regression analysis, none of the soil properties of composited samples collected from shallow boreholes had a strong fit individually with point EC_a values obtained at the borehole locations. One reasonable explanation is that a complex relationship exists between EC_a and a combination of soil properties for this test plot location. In addition, the presence of small-scale soil property spatial variability may explain this finding, thereby implying that some form of soil sampling protocol representative of a soil volume similar to the EMI EC_a measurement volume may be needed to better determine which soil properties have the greatest influence on the EC_a response.

The findings of this investigation are applicable to fine-grained soils with poor drainage having a shallow, fluctuating water table. This type of soil environment is common throughout the Midwest U.S. Soil electrical conductivity measurement results for different soil environments in different regions of the U.S. or elsewhere in the world may not be the same as those obtained in this investigation. Thus, the potential use of EC_a mapping as a fertility assessment tool for precision agriculture will undoubtedly have to be assessed on a region-by-region basis.

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