Exhibit 8a #177

Mapping Soil Electrical Conductivity

KA. SUDDUTH and NR. KITCHEN[1]

Summary

As agricultural producers seek to reduce costs and environmental impacts, they are turning to more information-intensive production methods. When coupled with geographic information system (GIS) and global positioning system (GPS) technologies, sensors can provide the spatially-dense information needed to quantify within-field variations for subsequent management decisions. Apparent soil electrical conductivity (EC_a) sensors have shown promise for delineating soil variability, and are in commercial use in many parts of the world. These commercial units either sense EC_a remotely from immediately above the soil surface or operate in contact with the soil. They respond to soil differences over a significant part of the soil profile - from 30 cm to well over 1 m, depending on the sensor. Soil EC_a is affected by, and can provide a measure of, soil properties such as salinity, texture, cation exchange capacity (CEC), and moisture content. Since ECa integrates texture and moisture availability, two soil characteristics that affect productivity, it can also aid in interpreting spatial yield variations. The relationship of EC_a to crop yield is often more pronounced in conditions of water stress, and EC_a has explained over 50 percent of the within-field yield variation in some such cases. Other uses of EC_a data have included refining the boundaries of soil survey map units, estimating herbicide leaching potential, and creating sub-field management zones. The reliability and applicability of EC_a data can be maximized through proper sensor selection and operation and through the choice of appropriate data analysis methods. Simultaneous collection and analysis of other sensor-acquired data such as elevation can also increase the utility of the EC_a information. Soil EC_a mapping is an effective and efficient data collection tool for precision agriculture.

Introduction

Numerous sensors are available to remotely measure surface characteristics of agricultural and environmental sites. As reported in this workshop and elsewhere, it is possible to remotely quantify a number of crop and soil biophysical parameters using reflected electromagnetic radiation, particularly in the optical wavelengths. Although surface characteristics are often of primary interest, at other times it is desirable to measure bulk site characteristics. For example, since crop roots explore the soil volume to a rooting depth, a sensor-based measurement of soil condition through that rooting depth could provide information important for characterizing the suitability of the soil for plant growth.

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Apparent profile soil electrical conductivity (EC_a) sensors can provide such a bulk soil measurement. Soil salinity, clay content, cation exchange capacity (CEC), clay mineralogy, soil pore size and distribution, soil moisture content, and temperature all affect EC_a (McNeill, 1992; Rhoades et al., 1999). In saline soils, most of the variation in EC_a can be related to salt concentration (Williams and Baker, 1982). In non-saline soils, conductivity variations are primarily a function of soil texture, moisture content, and CEC (Rhoades et al., 1999; Kachanoski et al., 1988; Sudduth et al., 2003). In a theoretical analysis, Rhoades et al. (1989) modeled EC_a as a function of soil water content (both the mobile and immobile fractions), the electrical conductivity of the soil water, soil bulk density, and the electrical conductivity of the soil solid phase.

Soil EC_a can be measured either by sensors in contact with the soil, or remotely through the use of electromagnetic induction (EM) sensing techniques. These two techniques yield similar, but not identical results (Sudduth et al., 2003). In this paper, we review the operating principles behind EM sensing of soil EC_a, discuss agricultural and environmental applications of EC_a sensing, and consider ways that EC_a data might be combined with other remote sensing data for information-based site-specific crop management. Although other EM-based EC_a sensors are available, we will focus on the one most often used in agriculture, the Geonics EM38[2].

Remote Sensing of Soil Electrical Conductivity by Electromagnetic Induction

Electromagnetic induction-based conductivity sensing was first applied for geophysical exploration. In the EM sensing approach, a transmitter coil at or above the ground surface is energized with an alternating current, creating a primary, time-varying magnetic field in the soil. This magnetic field induces small currents in the soil which generate a secondary magnetic field. A receiver coil responds to both the primary and secondary magnetic fields. By operating at "low induction numbers," the ratio between the primary and secondary fields is a linear function of conductivity (McNeill, 1980, 1992).

In the 1970s EM instruments were commercially available with effective measurement depths of from 6 to 60 m (McNeill, 1980). These devices gave integrated profile EC_a measurements that were useful for detecting changes in underlying geology as they were carried by hand from point to point. Researchers at the US Department of Agriculture's Salinity Laboratory recognized the potential of EM-measured EC_a for assessing soil salinity, since they had previously related EC_a measured with standard geophysical techniques to salinity (Rhoades and Ingvalson, 1971). Because the measurement depth (6 to 60 m) of geophysical EM sensors did not provide a good measure of root zone (~1 to 2 m) salinity, these scientists requested that a new EM sensor be developed specifically for agriculture (Rhoades and Corwin, 1981; Rhoades, 1993).

Geonics EM38

This agricultural EM sensor was the EM38 (Fig. 1), manufactured by Geonics Limited (Mississauga, Ontario, Canada). The EM38 is constructed with a spacing of 1 m between the transmitting coil located at one end of the instrument and the receiver coil at the other end, and operates at a transmitting frequency of 14.6 kHz. Calibration controls and a digital read-

2. Mention of trade names or commercial products is solely for the purpuse of providing specific information and does not imply recommedation or endorsement by the US Department of Agriculture

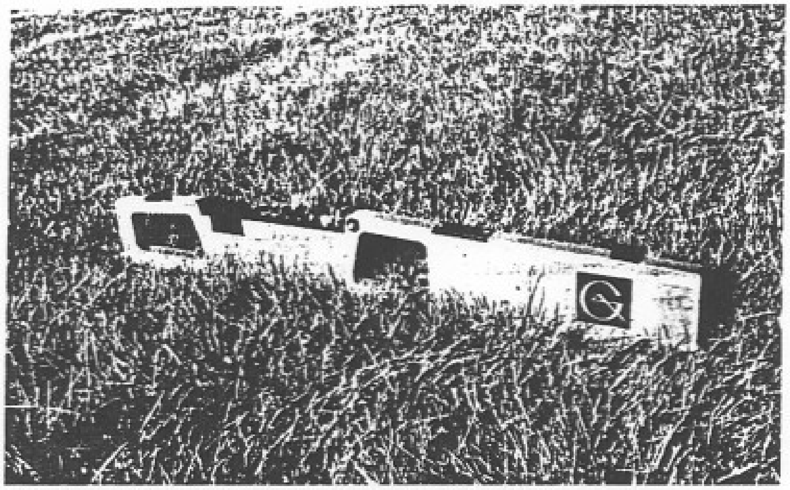

Figure 1: Geonics EM38 soil conductivity sensor in vertical dipole mode

out of EC_a in milliSiemens per meter (mS m^{-1}) are included. Analog or digital (on newer models) data output is provided to allow data to be recorded on a data logger or computer.

The EM38 may be operated in one of two measurement modes. The vertical dipole mode (upright orientation, Figure 1) provides an effective measurement depth of approximately 1.5 m. The horizontal dipole mode (sideways orientation) provides an effective measurement depth of approximately 0.75 m. The EC_a measurement from the EM38 is averaged over a lateral area approximately equal to the measurement depth. The instrument response to soil conductivity varies as a nonlinear function of depth (Figure 2). Sensitivity in the vertical mode is highest at about 0.4 m below the instrument, while sensitivity in the horizontal mode peaks at the instrument. The EC_a measurement from the instrument is determined by the soil conductivity with depth, as weighted by these instrument response functions (McNeill, 1992).

Figure 3 further illustrates the operating principle of the EM38. For the purposes of this illustration, we assume that the soil profile is composed of topsoil and subsoil layers with the

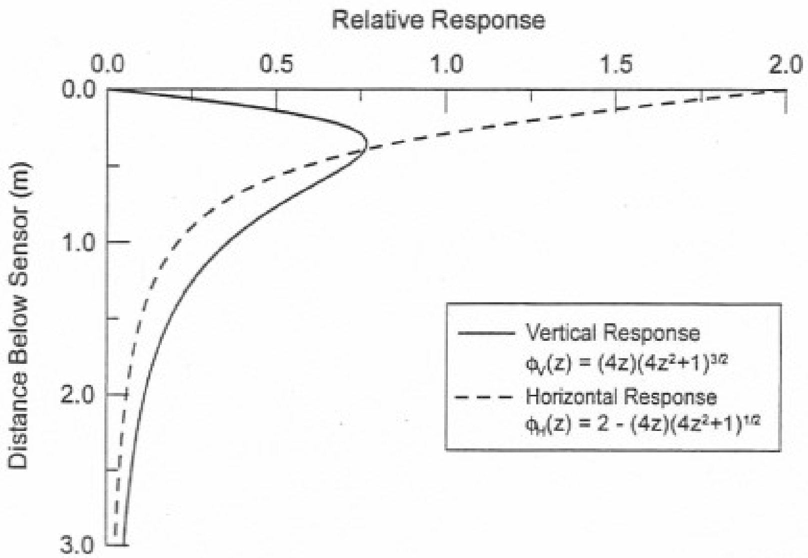

Figure 2: Relative response of EM38 sensor as a function of distance (adapted from McNeill, 1992)

topsoil of lower clay content (and therefore lower electrical conductivity) than the subsoil. The EM38 induces horizontal current loops in the soil. The current in each loop is proportional to the conductivity of the soil in that layer, as shown schematically by the thickness of the ellipses in Figure 3. The summation of the individual currents, weighted as a function of depth (Figure 2), generates the instrument response. If more of the soil profile is of higher conductivity, a larger instrument response will result. Note that, since the depth weighting is nonlinear (Figure 2), the effect of a soil volume with a given conductivity will be different if it is located at a different depth in the profile. This is why the EM38 reading is generally denoted as "apparent" profile bulk soil electrical conductivity.

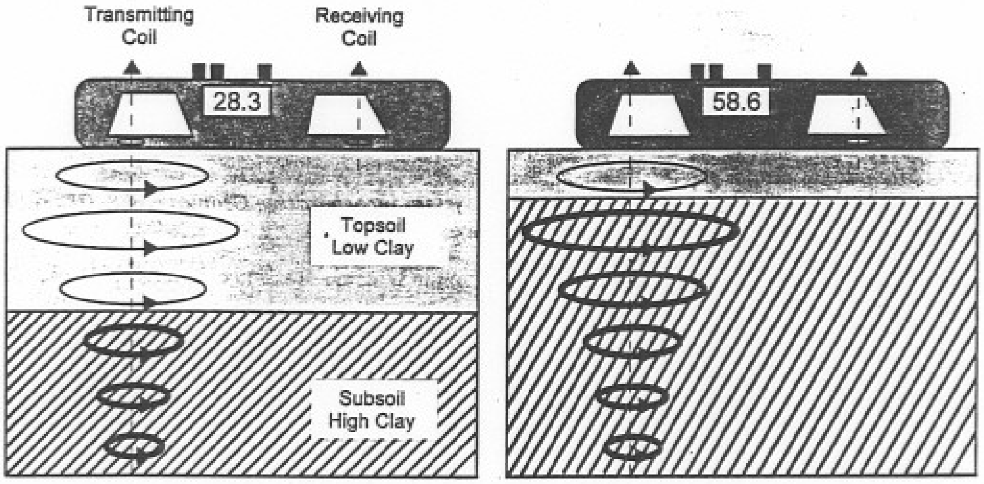

Figure 3: Schematic showing operation of the Geonics EM38 soil conductivity sensor over deep topsoil (left) and shallow topsoil (right)

Mobile EM Data Collection Systems

The EM38 is a lightweight bar and was initially designed to be carried by hand from place to place, to obtain stationary EC_a readings. With the advent of GPS technology, researchers have developed systems to mobilize the EM38 and synchronize its output with GPS positioning data (e.g., Jaynes et al., 1993; Cannon et al., 1994; Kitchen et al., 1996). These systems have generally used some sort of cart or sled pulled behind a vehicle to transport the EM38 across fields, along with a data collector or computer, appropriate interface circuitry, and a differential GPS receiver. Using a wheeled cart pulled by an all-terrain vehicle (ATV) (Figure 4), an EM38 system is adaptable to a wide variety of data collection conditions. Data can be collected under wet or soft soil conditions. Also, data can be obtained after a row crop has been planted, up until the time that the crop is too tall to pass under the vehicle and cart system.

Several issues are important in implementing mobile EM38 data collection systems. First, it is necessary to use a nonconductive material such as wood or plastic to construct the transport device because the EM38 will respond strongly in the presence of metallic objects within approximately 1 m. In our implementation, we built the body of the cart from wood, and placed the metal wheels > 1m from the EM38. Second, electrical noise from the towing vehicle must be considered. We needed to use two carts in tandem (Figure 4) so that the EM38 would be further away from the electrical noise generated by the ATV. Third, the EM38 transport device should maintain the sensor at a relatively constant height above the soil surface. Changes in this height affect EC_a readings by approximately 1% per cm (Sudduth et al., 2001).

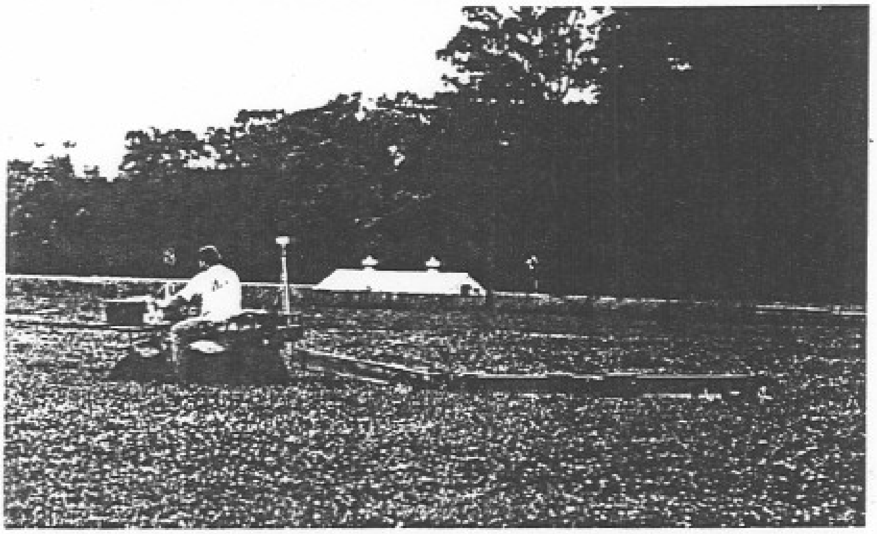

Figure 4: Mobile soil conductivity measurement system incorporating Geonics EM38, GPS receiver, data logging computer, and ATV

Data Collection Considerations

For accurate EC_a data collection, EM38 users should be aware of several operational considerations. The EM38 requires the user to complete a daily calibration procedure before use. Changes in ambient conditions such as air temperature, humidity, and atmospheric electricity (spherics) can affect the stability of EM38 measurements. Sudduth et al. (2001) reported that EM38 output could drift by as much as 3 mS m^{-1} h^{-1}, and that this drift was not consistently related to ambient conditions. They suggested that drift compensation be accomplished by use of a calibration transect, or through frequent recalibration of the EM38.

Soil EC_a data are most often collected on transects spaced from 5 to 30 m apart. Transect spacing should be determined by the expected variability of the study area and the intended use of the data. A 10 to 20 m transect spacing is a reasonable compromise between efficiency and accuracy in most situations. A GPS light bar may be useful for navigation and for keeping transect alignment parallel. A 1 s data collection interval is commonly used, resulting in a measurement every 3 to 6 m along the transects and a data density of approximately 100 to 300 points per ha.

Since EC_a is dependent on temporally variable parameters such as temperature and soil moisture, as well as more stable parameters such as clay content and CEC, different readings will be obtained for the same location at different measurement times. Often the major change between measurement dates will be in terms of scaling; the relative patterns of EC_a variation will remain similar. For example, we collected EM38 data on three measurement dates - April 1994, November 1997, and April 1999 for a 36 ha field. Correlations between the sampling dates ranged from $r = 0.86$ to $r = 0.97$ (Figure 5). Variations between the measurement dates may have been due to differences in sensor calibration and/or ambient conditions (Sudduth et al., 2001).

In a study conducted on claypan soils (Sudduth et al., 2001), we estimated the relative effects of various operational and ambient parameters on EC_a readings obtained with the EM38 (Table 1). Although some change may be expected for different soil types and EC_a lev-

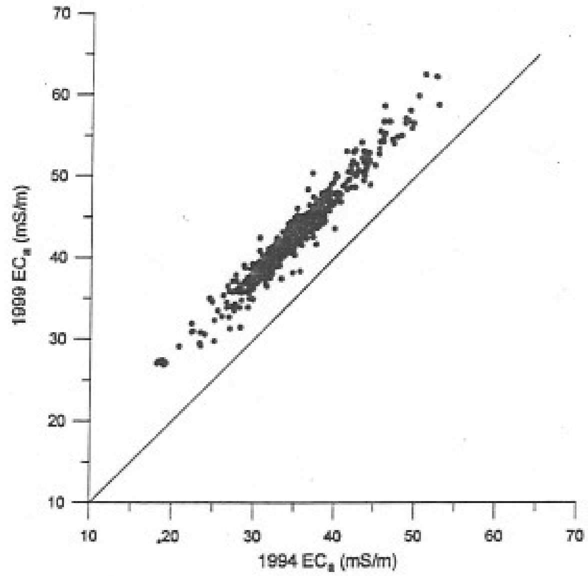

Figure 5: Relationship of EM38 vertical mode ECa data collected in April 1994 and April 1999 on a 36 ha field (r=0.97)

els, these results can provide general guidance for successfully planning and interpreting EC_a surveys.

Table 1: Approximate effect of various operational and ambient parameters on ECa measurements obtained on claypan soils (from Sudduth et al, 2001).

Parameter	Effect on EC_a
Instrument drift	up to 3 mS/m per h
Operating speed	-0.4 mS/m per m/s
Operating height	0.3 mS/m per cm
Soil moisture ‡	1.1 mS/m per %
Soil temperature ‡	0.2 mS/m per °C
Topsoil depth ‡	0.4 mS/m per cm

‡ Effect calculated at a claypan-field average EC_a of 35 mS/m for this nonlinear relationship.

Applications of Soil Electrical Conductivity Sensing

Correlation with Soil Properties

Mapped EC_a measurements have been found to be related to a number of soil properties of interest in agriculture. For example, Sheets and Hendrickx (1995) measured EC_a along a 1950 m transect in New Mexico over a 16 month period and found a linear relationship between conductivity and profile soil water content. Independent measurements of soil water at several calibration points along the transect were required for each measurement date. Williams and Hoey (1987) used EC_a to estimate within-field variations in soil clay content. McBride et al. (1990) related EC_a measurements to CEC and exchangeable Ca and Mg.

We have estimated the depth of topsoil above a subsoil claypan horizon using EC_a (Doolittle et al., 1994; Kitchen et al., 1999; Sudduth et al., 2001). Good calibrations (r^2 = 0.84

to 0.95) were possible using various transformations of EM38 vertical and horizontal data (Sudduth et al., 2001). Overall, we have obtained the best results when using EM38 vertical data and individual calibrations for each field.

We investigated the relationship of EC_a to soil properties in the Midwestern USA (Sudduth et al., 2002; 2003). Soil EC_a data were obtained in two production fields in each of six states, using both the EM38 and a contact-based sensor, the Veris 3100. Prevailing surface soil texture varied across research sites as follows: loam (Michigan), silt loam (Wisconsin), loam to clay loam (Iowa), silt loam to silty clay loam (Illinois, Missouri, South Dakota). Subsoil texture was even more variable, ranging from loamy sand at the Michigan fields to clay at the Missouri fields (Sudduth et al., 2002).

Within each field, between 12 and 20 sampling sites were selected to cover the range of EC_a values present. These sites were chosen by a soil scientist familiar with the local soils, who attempted to include samples from all the landscape positions and soil map units present in the field. One 4.0 cm diameter core 120 cm in length was obtained at each site using a hydraulic soil coring machine. Cores were examined within the field, pedogenic horizons were identified, and the cores were segmented by horizon for laboratory analysis. Soil moisture was determined gravimetrically. Additionally, samples from each horizon were analyzed for the following properties: sand, silt, and clay fractions (pipette method); CEC (ammonium acetate method); organic C; and saturated paste EC. To facilitate comparison across calibration points, a depth-weighted mean was calculated for each soil property at each calibration point. To account for the fact that the response of the EC_a sensor is not constant with depth, an additional dataset was created by weighting each soil property profile by the sensor response curve (Figure 2).

Significant correlation coefficients (P # 0.05) between EC_a and profile-weighted soil properties were determined by state and for the dataset as a whole (data for Missouri and Illinois fields shown in Table 2). Correlations of EC_a with sensor-weighted clay content and sensor-weighted CEC were generally highest and most persistent across all states and EC_a data types. This higher correlation with sensor-weighted data supported our hypothesis that transformation of soil property data by weighting with the sensor response function is an appropriate way to help account for curvilinearity in the functional relationship.

Other soil properties that exhibited a significant correlation for most states were clay and CEC of the upper soil horizon, and the same two properties averaged over the entire measurement depth. Some properties were strongly related to EC_a for some fields but not for others. Examples included soil moisture (South Dakota, Iowa), silt (Missouri, Illinois, Iowa), sand (Iowa), organic C (Iowa), and saturated paste EC (South Dakota). Soil property estimates based on combining EC_a data from both EM38 and Veris sensors were also developed, and were often somewhat better than estimates obtained using only EM38 data (Sudduth et al., 2002).

Figure 6 shows the relationship of the EC_a datasets to profile-average clay and CEC. The data from the various fields and states appeared to merge into a unified data distribution. The clay-EC_a relationship was somewhat different for the Iowa data than for the other states (Figure 6a); however this difference was not apparent when considering the CEC-EC_a relationship (Figure 6b). The relationships of EC_a data to CEC and clay across all sites were surprisingly good, considering that data were collected on the different fields at different times of the year and under different soil moisture conditions. These results indicate that it may be possible to develop calibrations relating EC_a to soil CEC and clay content that are applicable across a wide range of soil and climatic conditions.

Table 2: Significant (P < 0.05) correlations between soil properties and EM38-measured ECa data for Missouri and Illinois fields.

Soil Property	Weighting	Missouri Fields		Illinois Fields	
		Field F1	Field GV	Field WN	Field WS
Soil moisture	sensor[‡]			--[§]	--
	profile avg.			--	--
	top layer			--	--
Clay	sensor	0.60	0.88	0.59	0.78
	profile avg.		0.81		0.80
	top layer		0.75	0.60	0.54
Silt	sensor	-0.65	-0.84		
	profile avg.	-0.50	-0.74		
	top layer	-0.52	-0.68	-0.63	-0.60
Sand	sensor				
	profile avg.			-0.60	
	top layer	0.46			
CEC	sensor	0.76	0.88	0.63	0.60
	profile avg.	0.68	0.82		
	top layer		0.74	0.79	0.78
Organic C	sensor		-0.75		
	profile avg.	-0.54	-0.72		
	top layer				

‡ Weighting applied to soil property data before calculating correlations: sensor = weighting function from Figure 3 for the EM38 sensor; profile avg. = depth-weighted average for 120-cm deep profile sample; top layer = value from top layer of profile sample

§ Soil moisture data not available for Illinois fields.

Estimating Crop Productivity Potential

Since soil EC_a integrates texture and moisture availability, two characteristics that both vary over the landscape and also affect productivity, EC_a sensing can help to interpret grain yield variations, at least in certain soils. Jaynes et al. (1993) reported strong negative correlations between EC_a and corn and soybean grain yield in a wet year, due to negative impacts of poor soil internal drainage in the higher-clay (and therefore higher EC_a) areas of Iowa fields. However, in a year of more normal rainfall, no significant correlation was found.

Sudduth et al. (1995) investigated the relationship of EC_a to grain yield on the claypan soils of central Missouri. They estimated the topsoil depth above the claypan horizon as an inverse function of EC_a and then related yields to topsoil depth. In this study, grain yield was correlated positively to topsoil depth and negatively to EC_a in a dry year, with little effect found in a year with more optimum precipitation patterns. This was explained by the fact that the lower-EC_a (and therefore greater topsoil depth) areas were able to store more plant-available water and support greater yields during a year when crops were moisture-stressed.

Differences between the two studies cited above illustrate the point that the relationship between EC_a and crop yields may vary both spatially due to soil differences and temporally

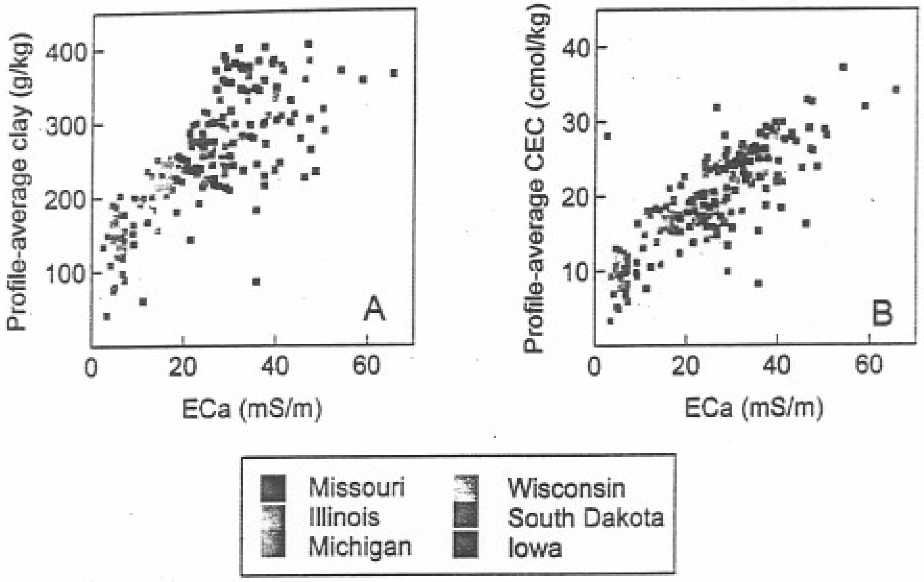

Figure 6: Relationships between EM38 EC_a data and CEC and clay content measured at calibration points for 12 fields in the north-central US

due to climatic differences. Kitchen et al. (1999) addressed this issue by relating EC_a and grain yields for 13 site-years on claypan soils. Using a boundary line approach, they found that within a single field in a given year the relationship between productivity and EC_a fell into one of four categories: (1) positive, (2) negative, (3) positive in some portions of the field and negative in others, or (4) no relationship. The strongest relationships were negative (Figure 7), reflecting the tendency of claypan soils to be water-limited for crop production in the majority of growing seasons.

Soil EC_a can be used to help define within-field productivity zones, areas where crop production can be expected to be reasonably homogeneous. In some cases, these productivity zones may be used as management zones for differential or variable-rate application of crop

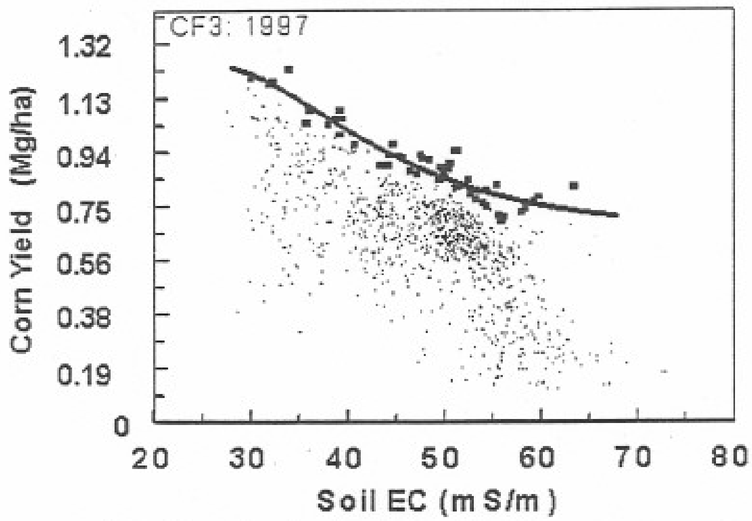

Figure 7: Scatter plot and boundary line fit of EC_a and yield representing condition (2), where yield increased with decreasing EC_a

inputs. We used a combination of EC_a and topographic features to develop zones and evaluated their ability to describe yield variability (Fraisse et al., 2001). By dividing a field into four or five zones based on EC_a, slope, and elevation, we were able to describe between 10% and 37% of the corn and soybean yield variation. Zones were particularly helpful for describing yield variability in years when crop growth was moisture-limited. Zones based on EC_a and topography were generally better at describing yield variability than were detailed soil type maps of the study fields.

Other Precision Agriculture Uses of EC_a

Another application of EC_a data is the creation or refinement of soil type maps. The Natural Resources Conservation Service of the USDA, the US government agency charged with mapping soils, is now actively using both EM38 and Veris instruments in the field as they develop soil type maps. Of particular interest is the use of EC_a data as an aid in the development of the high-resolution maps needed for site-specific crop management. For example, Doolittle et al. (2002) used EC_a measurements to locate small inclusions of sandy soils within predominately fine-textured alluvial landscapes. They were interested in finding and avoiding these inclusions when locating fields suitable for flood-irrigated rice production. Anderson-Cook et al. (2002) reported classification accuracies of 60 to 80% when relating detailed soil type maps to EC_a data.

Soil EC_a has been used to delimit zones of "soil condition" as a precursor to directed soil sampling (Johnson et al., 2001; Lund et al., 1999). To the extent that the soil properties of interest are a function of soil formation and landscape effects, and not management-induced factors (e.g., differential fertilizer application), this approach can potentially result in a considerable cost and effort savings compared to soil sampling on a grid. Others (e.g., Chen et al., 2000) have similarly used remotely-sensed soil color as an indicator of spatial variability in soil organic matter and hence soil condition. A distinct advantage of the EC_a approach is that it can be applied to fields under no-till management, while the soil color approach relies on the availability of a tilled soil condition.

Environmental Assessment

Soil EC_a as measured by EM38 has been used in a number of ways to assess environmental susceptibility and/or effects. For example, Jaynes et al. (1995) used EC_a as an estimator of the partitioning of a triazine herbicide between the soil and soil solution. Knowledge of the spatial variability of this partitioning coefficient (K_d) could allow mapping fields for their susceptibility to leaching of the herbicide. Maps of EM38-estimated K_d were found to be similar to measured K_d maps, but with less well-defined spatial patterns.

Other researchers have applied EM data for measuring and mapping animal waste effects. Brune and Doolittle (1990) surveyed the area around a number of animal waste lagoons using the Geonics EM34, an instrument similar to the EM38, but with a greater measurement depth. They found EC_a measurements to be useful for detecting lagoon seepage. Additional work applying this technique to more locations was reported by Brune et al. (1999). In another study, Huffman and Westerman (1993) stated that a series of periodic EM surveys would provide good information for locating contaminant plumes from lagoons, through monitoring of temporal changes in EC_a patterns. They further noted that locating contaminant plumes with a single EC_a survey would be difficult due to variations in EC_a caused by inherent soil variability.

Soil EC_a measurements by EM38 (horizontal mode) were able to discriminate areas of manure and compost application from areas that instead received a commercial fertilizer (Eigenberg and Nienaber, 1999). Treatment comparisons were facilitated by subtracting a map of the underlying EC_a variation obtained before fertilizer was applied from a map of EC_a after fertilizer application. Soil nitrogen measurements appeared to explain some, but not all, of the variation between treatments. The authors suggested that conductivity changes could be due to soil temperature dynamics and the decomposition of the organic amendments. Further research by the same group (Eigenberg et al., 2002) found that a time sequence of EC_a maps could be related to temporal changes in available soil nitrogen. They hypothesized that it might be possible to use EC_a measurements as an indicator of soluble nitrogen gains and losses in the soil over time.

Opportunities and Needs

Focus group interviews conducted in the US Midwest showed that crop producers realize sensors are the preferred way of collecting site-specific data in an efficient manner and at the spatial resolution needed to define within-field variability (Wiebold et al., 1998). Soil EC_a sensors are one of the few commercially available sensor options that producers can use today to evaluate soil differences in their fields. In some areas, EC_a surveys are beginning to see considerable use. Producers find the EC_a maps useful for visualizing and understanding soil differences in their fields; however knowing what intrinsic soil property or properties causes these EC_a differences is for the most part an unmet goal. Much like the situation with grain yield maps, the technology to create EC_a maps has become available before the knowledge of what the data represents and how it can be used for crop management has been developed.

Thus, the main needs and opportunities in EC_a mapping are in developing new ways to interpret the data and to use it for management decisions. As reviewed earlier in this paper, researchers have developed an understanding of the relationship between EC_a and soil properties for certain specific soils and conditions. However, a general, more widely applicable understanding would make EC_a data more useful to producers and crop advisors. Coordinated, multi-location research is needed to provide the large datasets needed. Additionally, refinement and application of theoretical models relating EC_a to soil physical and chemical parameters would aid in developing this general relationship.

Even if EC_a can be used in a general way to estimate soil properties, most management decisions will likely require multiple datasets to be considered. For example, combining EC_a and topography data may improve estimates of crop productivity compared to a single explanatory variable (Fraisse et al., 2001; Kitchen et al., 2003). Development of algorithms, procedures, and systems that integrate multiple datasets for guiding management decisions would enhance the usefulness of EC_a and other dense spatial datasets. Finally, field evaluation of the agronomic, economic, and environmental effects of EC_a-based management systems will be important to provide producers with confidence in their performance under a range of growing conditions.

Conclusions

Among remote sensing methods, soil EC_a measurement is distinguished by the fact that it provides an integrated reading over a significant depth of the soil profile, as opposed to merely the surface. Because of this, EC_a provides a more direct indication of soil conditions than most other sensing methods. Soil EC_a measurements are affected by many of the same soil properties that affect plant growth and yield, so EC_a has been used as an indicator of productivity potential. Until now, most applications of EC_a data have relied on an empirical understanding of its relationship to soil or environmental properties of interest, usually developed for a single soil or a narrow range of conditions. Future use of EC_a data will be enhanced if a more general framework relating EC_a to soil properties can be developed and validated over a wide range of soil and environmental conditions.

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