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Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture

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Abstract

Soil apparent electrical conductivity (EC_a) has been used as a surrogate measure for such soil properties as salinity, moisture content, topsoil depth (TD), and clay content. Measurements of EC_a can be accomplished with commercially available sensors and can be used to efficiently and inexpensively develop the dense datasets desirable for describing within-field spatial variability in precision agriculture. The objective of this research was to investigate accuracy issues in the collection of soil EC_a data. A mobile data acquisition system for EC_a was developed using the Geonics EM38 [1] sensor. The sensor was mounted on a wooden cart pulled behind an all-terrain vehicle, which also carried a GPS receiver and data collection computer. Tests showed that drift of the EM38 could be a significant fraction of within-field EC_a variation. Use of a calibration transect to document and adjust for this drift was recommended. A procedure was described and tested to evaluate positional offset of the mobile EM38 data. Positional offset was due to both the distance from the sensor to the GPS antenna and the data acquisition system time lags. Sensitivity of EC_a to variations in sensor operating speed and height was relatively minor. Procedures were developed to estimate TD on claypan soils from EC_a measurements. Linear equations of an inverse or power function transformation of EC_a provided the best estimates of TD. Collection of individual calibration datasets within each surveyed field was necessary for best results. Multiple measurements of EC_a on a field were similar if they were obtained at the same time of the year. Whole-field maps of EC_a-determined TD from multiple surveys were similar but not identical. There was a significant effect of soil moisture and temperature differences across

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[1] Mention of tradenames or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

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measurement dates. Classification of measurement dates as hot vs. cold and wet vs. dry provided TD estimations nearly as accurate as when individual point soil moisture and temperature data were included in the calibration equation.

Keywords: Precision agriculture; Sensors; Soil electrical conductivity; Electromagnetic induction; Topsoil depth; EM38

1. Introduction

Precision agriculture is a crop management strategy which seeks to address within-field variability and to optimize inputs on a point-by-point basis within fields. By reducing over-application and under-application of inputs such as nutrients and pesticides, this strategy has the potential to improve profitability for the producer and also to reduce the threat of ground or surface water contamination from agricultural chemicals. Precision agriculture is being adopted by innovative producers in many parts of the world. Agricultural equipment manufacturers, farm input suppliers, and a host of other businesses are working along with public-sector research and education personnel to provide the necessary tools for farmers to implement this management strategy.

In the USA, much early work in precision agriculture focused on grid-sampling fields to determine variations in soil nutrients, along with variable-rate application of fertilizers (Wibawa et al., 1993). However, mapped yield data have been found to correspond more to landscape and soil physical properties related to water distribution and water availability than to soil nutrient status (Sudduth et al., 1996). Some of these water-related soil properties include soil water holding capacity, water infiltration rate, texture, structure, bulk density, organic matter, soil depth, and the presence of restrictive soil layers. Measurement of these properties is expensive and time consuming since it generally involves in-field characterization by a trained soil scientist and/or collection of a soil profile sample in the field, followed by laboratory analysis. Because of this, quantifying soil physical characteristics at the scale required for accurately mapping within-field variations has been impractical.

The ideal way to measure spatially-variable soil properties would be through the application of mobile sensor systems. A number of such sensors have been developed in government laboratories, universities, and industry, as reviewed by Sudduth et al. (1997). A sensor may provide either direct or indirect measurements of the soil property of interest. An example of direct measurement would be sensing the force on a tine to quantify soil strength, as accomplished by Stafford and Hendrick (1988). An example of an indirect measurement would be sensing the near-infrared reflectance of a soil to estimate soil moisture and organic matter (Sudduth and Hummel, 1993; Hummel et al., 1996). More indirect sensing techniques are available for soil properties than direct techniques, but issues of calibration and applicability are generally more difficult with these instruments.

Bulk soil electrical conductivity (EC_a) is one sensor-based measurement that can provide an indirect indicator of important soil properties. Factors that influence EC_a include soil salinity, clay content and cation exchange capacity (CEC), clay mineralogy, soil pore size and distribution, soil moisture content, and temperature (McNeill, 1992; Rhoades et al., 1999). Williams and Baker (1982) observed that, in areas of salt-affected soils, 65–70% of the variation in measurements could be explained by the concentration of soluble salts. However, in non-saline soils, conductivity variations are primarily a function of soil texture, moisture content, and CEC. The apparent conductivity of soils was found to increase with moisture and clay contents by Rhoades et al. (1976) and Kachanoski et al. (1988). Rhoades et al. (1989) presented a model that provided a theoretical basis for the relationship between EC_a and soil physical properties. In the model, EC_a was described 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.

Since EC_a is a function of a number of soil properties, EC_a measurements can be used to provide indirect measures of these properties if the contributions of the other affecting soil properties to the EC_a measurement are known or can be estimated. In some situations, the contribution of within-field changes in one factor will be large enough with respect to variation in the other factors that EC_a can be calibrated as a direct measurement of that dominant factor. Lesch et al. (1995a,b) used this direct calibration approach to quantify within-field variations in soil salinity under uniform management and where water content, bulk density, and other soil properties were "reasonably homogeneous." In our earlier work, we were able to establish direct, within-field calibrations between EC_a and the depth of topsoil above a subsoil claypan horizon (Doolittle et al., 1994; Sudduth et al., 1995; Kitchen et al., 1999).

Mapped EC_a measurements have been found to be related to a number of soil properties of interest in precision 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. Jaynes et al. (1995) used EC_a as an estimator of herbicide partition coefficients, theorizing that both were responding to changes in soil drainage class. Since soil EC_a integrates texture and moisture availability, two characteristics that both vary over the landscape and also affect productivity, EC_a sensing also shows promise in interpreting grain yield variations, at least in certain soils (e.g., Jaynes et al., 1993; Sudduth et al., 1995; Kitchen et al., 1999). Other uses of EC_a measurements for precision agriculture have included refining the boundaries of soil map units (Fenton and Lauterbach, 1999), interpreting within-field corn rootworm distributions (Ellsbury et al., 1999), and creating management zones for directed soil sampling (Lund et al., 1999).

Portable, within-field EC_a sensors were first used in agriculture to assess variations in soil salinity (Rhoades, 1993). Two basic designs have been utilized – an electrode-based sensor requiring soil contact, and a non-invasive electromagnetic induction (EM) sensor.

The electrode-based approach requires four electrodes inserted into the soil, coupled with an electric current source and resistance meter. The original sensor was used for hand-carried salinity surveys (Rhoades, 1993). A tractor-mounted version was later developed for mobile, georeferenced measurement of EC_a (Carter et al., 1993). The electrode-based approach was further refined into a commercial product by Veris Technologies of Salina, KS. This mobile system uses six rolling coulters for electrodes and simultaneously generates "shallow" (0–30 cm) and "deep" (0–90 cm) measurements of EC_a (Lund et al., 1999; Sudduth et al., 1999).

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).

The EM-EC_a sensor most often used in agriculture is the EM38, manufactured by Geonics Limited of Mississauga, Ontario, Canada. 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., Carter et al., 1993; Jaynes et al., 1993; Cannon et al., 1994; Kitchen et al., 1996). For accurate interpretation of the large amounts of EC_a data collected from these mobilized systems, it is necessary to understand and consider issues related to how the data were collected and its intended application. This is particularly true in non-saline soils, where the variation in EC_a across a field will generally be much smaller than in saline soils, and therefore more affected by operational differences.

The objective of this research was to investigate a number of issues believed to be important when using a mobile EM38 system for soil EC_a data collection, including instrument and data acquisition system accuracies, mobile system effects, calibration of EC_a readings to soil physical properties, and the effect of differences in ambient conditions. Where appropriate, methods and suggestions to minimize deleterious effects and to maximize the accuracy and reliability of the EC_a data collection process were developed.

2. Materials and methods

2.1. Soil conductivity sensor

The soil conductivity sensor used in this research was the EM38, manufactured by Geonics Ltd. The EM38 maintains 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 frequency of 14.6 kHz. Calibration controls and a digital readout of EC_a in milliSiemens per meter (mS/m) are included. An analog data output (2.5 mV per mS/m) 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, Fig. 1) provides an effective measurement depth of ≈ 1.5 m. The horizontal dipole mode (sideways orientation) provides an effective measurement depth of ≈ 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 (Fig. 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).

Fig. 1 illustrates the operation of the EM38 for discerning differences in topsoil depth (TD), given the constraint that the topsoil is of lower clay content (and lower electrical conductivity) than the subsoil. The EM38 induces horizontal electric 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 Fig. 1. The summation of the individual currents, weighted as a function of depth (Fig. 2), generates the instrument response. If more of the soil profile is of higher conductivity, a larger instrument response will result.

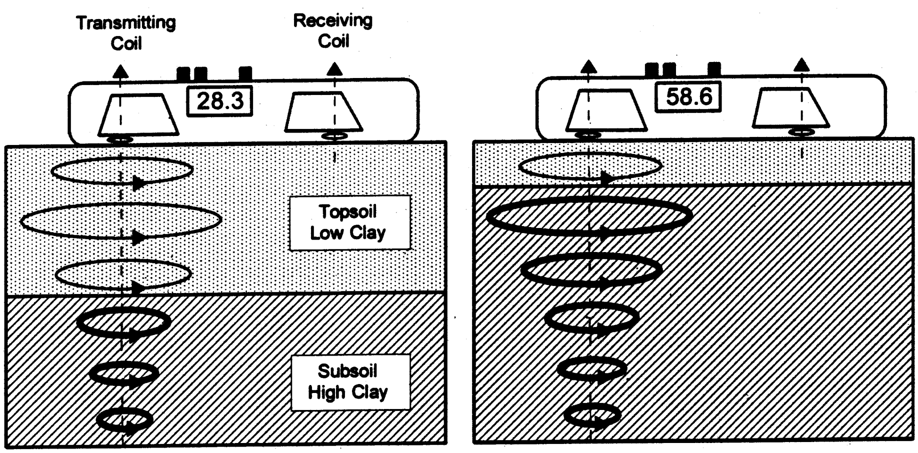

Fig. 1. Schematic showing operation of the Geonics EM38 soil conductivity sensor in vertical dipole mode over deep topsoil (left) and shallow topsoil (right).

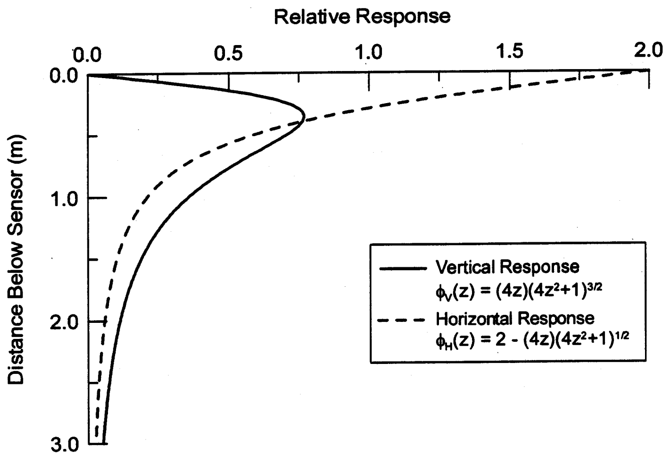

Fig. 2. Relative response of EM38 sensor as a function of distance (adapted from McNeill, 1992).

2.2. Mobile data collection system

In our mobile EC_a measurement system, the EM38 was mounted in vertical dipole mode to a 3-m long cart consisting of a wooden beam supported at the rear by two spoke-wheeled pneumatic tires (Fig. 3). Use of the wooden beam was necessary because the EM38 will respond strongly in the presence of metallic objects within ≈ 1 m. The tongue of this cart was attached to the rear of a second, similar cart, which was in turn attached to the rear hitch of a four-wheel all-terrain

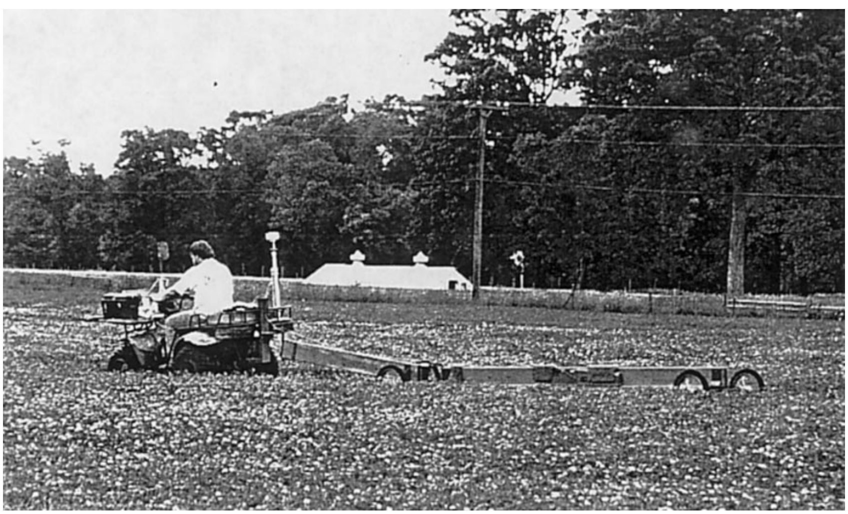

Fig. 3. Mobile EC_a measurement system incorporating Geonics EM38, GPS receiver, data logging computer, and ATV.

vehicle (ATV). The second cart was necessary to increase the distance between the EM38 and ATV, for eliminating the effects of ATV engine noise on instrument readings. In this configuration, the EM38 was suspended 20–22 cm above the ground surface during data collection. A later revision to the cart also allowed collection of data in the horizontal dipole mode, with the EM38 suspended 22–24 cm above the ground surface. The mobile system worked reliably in the field, collecting data over several hundred hectares. The turning radius of the system was ≈ 3 m.

Analog EC_a data from the EM38 were read into a computer mounted in front of the ATV operator through a commercial data acquisition module. Data were initially collected using an IOtech Daqbook/100 with a 12-bit A/D converter, which provided a resolution of ≈ 0.1 mS/m and manufacturer's stated accuracy of 0.6 mS/m as configured. For improved reliability, this device was later replaced by a DGH Model 1121 data acquisition interface with a 15-bit A/D converter. The DGH unit also provided a 0.1-mS/m resolution, along with a manufacturer's stated accuracy of 0.2 mS/m as configured. Differentially corrected GPS data were integrated with the EM38 data to provide the coordinates of each measurement point. Absolute position accuracies of the GPS data were better than 3 m and, in most cases, were between 1 and 1.5 m. Data were collected on transects spaced evenly over the study areas. Transect spacing ranged from 5 to 30 m depending on the size of the area and the expected variability in EC_a. Data were recorded on a 1-s interval, corresponding to a measurement every 3–6 m along the measurement transects.

2.3. Study area description

In this study, data were collected on four research fields located near Centralia, in central Missouri, USA. The soils found at these sites are characterized as claypan soils, primarily of the Mexico-Putnam association (fine, montmorillonitic, mesic Udollic Ochraqualfs). Mexico-Putnam soils formed in moderately-fine textured loess over a fine textured pedisediment. Surface textures range from a silt loam to a silty clay loam. The subsoil claypan horizon(s) are silty clay loam, silty clay or clay, and may commonly contain as much as 50–60% montmorillonitic clay.

Because of extensive weathering, the claypan soil is usually low in natural fertility and pH. Plant available water from the claypan is low because a large portion of the stored water is retained with the clay at the wilting point. With these characteristics, variations in the depth of topsoil above the claypan can lead to significant variations in crop productivity. As described previously, EC_a measurements can be related to a number of soil physical properties; however, our main interest was to use EC_a as an estimator of TD, and hence productivity, on these claypan soils. Differences in EC_a existed between the surface horizon and claypan horizon, due to the differences in clay content. The response of the EM38 to these contrasting layers was expected to be a function of both the thickness and conductivity of surface and subsurface claypan layers. For each study field, TD ranged from less than 10 cm to greater than 100 cm.

2.4. Stability of EM38 readings

It is well known that soil conditions, including temperature and moisture, influence EC_a (McNeill, 1992). Ambient conditions such as air temperature, humidity, and atmospheric electricity (spherics) can also affect measurement of EC_a with the EM38. Of these, air temperature generally has the largest effect (M. Catalano, Geonics Ltd, personal communication, 1999). Short-term (within a single day) instrument drift and the effect of ambient factors were investigated in two ways: (1) repeated data collection over time across a known transect during field data collection with the mobile EM38 system; and (2) measurement of instrument output changes over time with the EM38 positioned over a fixed point.

To document the effects of instrument drift during field data collection, a "calibration" transect at least 50 m in length was established at four fields where EM38 data were collected. Data were collected on the transect several times during the EC_a survey of the field to document any instability or drift in instrument output. Air temperature was obtained from a recording weather station located < 8 km from each field.

Data were collected with the EM38 positioned over a fixed point to quantify the instrument drift that might be expected within a working day and to relate those output changes to changes in ambient temperature. The instrument was placed in the vertical dipole orientation on a stand made of plastic pipe that held it 43 cm above the ground surface. Data collected at regular intervals over ≈ 8 h were ambient temperature, EC_a, and EM38 inphase (I/P) reading. The I/P reading measures the sensitivity of the EM38's receiver electronics to the primary signal induced by the transmitter (Geonics, 1998).

For optimum accuracy, the I/P reading should be maintained at zero using the controls on the EM38 (Geonics, 1998). However, with mobile EC_a surveys it is not practical to continuously monitor and readjust the I/P reading. Therefore, a series of tests was conducted to quantify the effect of non-zero I/P readings on EC_a readings. The EM38 was again placed on a plastic stand over a fixed point. The I/P zero control was adjusted over the range of -150 to 150 mS/m, and EC_a readings were recorded. This procedure was replicated six times at a relatively constant ambient air temperature (25–29°C).

2.5. Effect of mobile operation

Mobile operation of the EM38 system could potentially introduce error in EC_a surveys. With the system shown in Fig. 3, it was impractical to mount a GPS antenna immediately above the EM38. The distance between the GPS antenna (mounted on the ATV) and EM38 created a position error, or offset, in the direction of travel. Also, it seemed conceivable that the output of the EM38, an instrument designed for static operation, could have some dependance on operating speed.

To investigate the effects of mobile operation and variations in operating speed, a measurement transect ≈ 200 m long was established in a grassed area. Data were collected in a randomized complete block consisting of three replications of four nominal operating speeds (1.5, 2.5, 3.5, and 4.5 m/s). Each data collection run consisted of traversing the transect from east to west and then again from west to east. At one intermediate location an approximately 3-m length of thin steel pipe was staked to the ground surface perpendicular to the measurement transect. The purpose of this pipe was to provide a sharp "spike" in the EM38 response. The offset in the measured position of this spike between paired passes in opposite directions could be interpreted as twice the position offset of the mobile system at that particular operating speed. The mobile EM38 system was also used to collect static EC_a data along this transect for comparison to the mobile data. The EM 38 was positioned along the transect at 2 m intervals and its output recorded. The amount of time required for this static data collection made it impractical to include as a treatment in the randomization. As an alternative, one static dataset was obtained immediately before the mobile test sequence, and another dataset was obtained immediately after the conclusion of the mobile test sequence.

For these tests only, an Ashtech Z-Surveyor real-time kinematic (RTK) GPS system was used to provide position data. The RTK differential correction station was positioned adjacent to the test area to minimize the baseline between the receivers and maximize accuracy. The manufacturer's stated horizontal accuracy for this system was 3 cm as implemented (moving data collection and a short baseline). Position data from the GPS receiver and EC_a data were collected at 5 Hz. The faster data acquisition rate and the higher accuracy of the RTK-GPS receiver were required to provide the position accuracy needed in this evaluation.

Another consequence of mobile operation was that the EM38 was suspended above the ground surface during operation. This resulted in attenuation of the EC_a signal because air, with an assumed zero conductivity, occupied a portion of the sensing volume of the instrument. To quantify this reduction in measured EC_a, data were collected with the EM38 positioned at varying heights above a fixed point.

2.6. Topsoil depth estimation by EC_a

Our primary use of EC_a data has been as an estimator of TD on claypan soils (Doolittle et al., 1994; Sudduth et al., 1995; Kitchen et al., 1999). In this study, alternative calibration procedures for relating TD to EC_a were investigated. Calibration points were established to develop field-specific relationships between EC_a data and TD. Between 15 and 22 locations, spanning the range of landscape positions and TDs present in each of three fields, were selected for soil characterization. TD (depth to the Bt horizon) was measured in the field by an experienced soil scientist through a combination of visual and tactile observations. For Fields 1 and 2, both vertical and horizontal EC_a data were obtained with the mobile system at each calibration point. For Field 3, only vertical data were obtained. To investigate the long-term temporal variation in EC_a readings, EM38 vertical mode data were collected with the mobile system on Field 1 on three occasions – April 1994, November 1997, and April 1999. Comparisons between the three datasets were based both on EC_a variations and also on variations in estimated TD.

2.7. Effect of soil moisture and temperature

Since EC_a is known to be affected by both soil moisture and soil temperature, a study was carried out to establish the effect of moisture and temperature on TD estimation. Monitoring sites were established at Field 1 ($n = 7$) and Field 3 ($n = 5$) to span the range of TDs and landscape positions present within each field. Measured TD ranged from 10 to 100 cm at the sites. Data were collected approximately every 2 weeks during the growing season and monthly during the rest of the year, for a total of 19 sampling dates. Data included soil moisture measured by neutron probe, soil temperature, and EC_a. Neutron probe readings were obtained at 15, 30, 45, 60, 80, 100, and 120 cm depths. Soil temperatures were obtained by thermocouple at 5, 10, 15, 20, and 25 cm depths. Both horizontal and vertical EC_a data were collected 2 m from the neutron probe tube at each compass direction. At each site for each measurement date, means were calculated for soil moisture percentage, soil temperature, vertical EC_a, and horizontal EC_a. Models were developed to relate TD to $1/EC_a$, mean soil temperature, and mean soil moisture.

3. Results and discussion

3.1. Stability of EM38 readings

Repeated transect measurements of EC_a data over time showed an offset of several mS/m. Neglecting this offset, the overall shape of the EC_a response was very similar for repeated runs over the same transect (Fig. 4). The relationship of this drift in EC_a to elapsed time and changes in ambient (i.e., instrument) temperature were investigated. Mean EC_a readings were calculated for each run over each transect. For each of three vertical mode calibration transects, EC_a was significantly correlated to both elapsed time and ambient temperature change, which were highly collinear. The relationship of EC_a to elapsed time and ambient temperature differed between the three vertical mode transects. Drift in EC_a ranged from -0.8 to -3.2 mS/m per h, or from -0.4 to -6.3 mS/m per °C. For the one horizontal mode calibration transect, EC_a was not significantly correlated to either elapsed time or ambient temperature change.

In the fixed point drift experiment, ambient air temperature increased from 23°C to 35°C over the ≈ 8 h test. During the same time, EC_a increased from 32.2 to 42.3 mS/m and the I/P reading decreased from 0.2 to -101.2 mS/m (Fig. 5). This was in contrast to the field experiments, where increasing temperature was correlated to decreasing values of vertical mode EC_a. The effect of changing I/P on EC_a was nonlinear but repeatable (Fig. 6). From this data, the minimum sensitivity of EC_a to changes in I/P was found in the range of ≈ 0–50 mS/m. The shape of these curves was similar to the relationship between EC_a and I/P found in the fixed point drift experiment, where EC_a was relatively insensitive to I/P changes near zero, but exhibited a strong relationship over the rest of the measured range. There was an

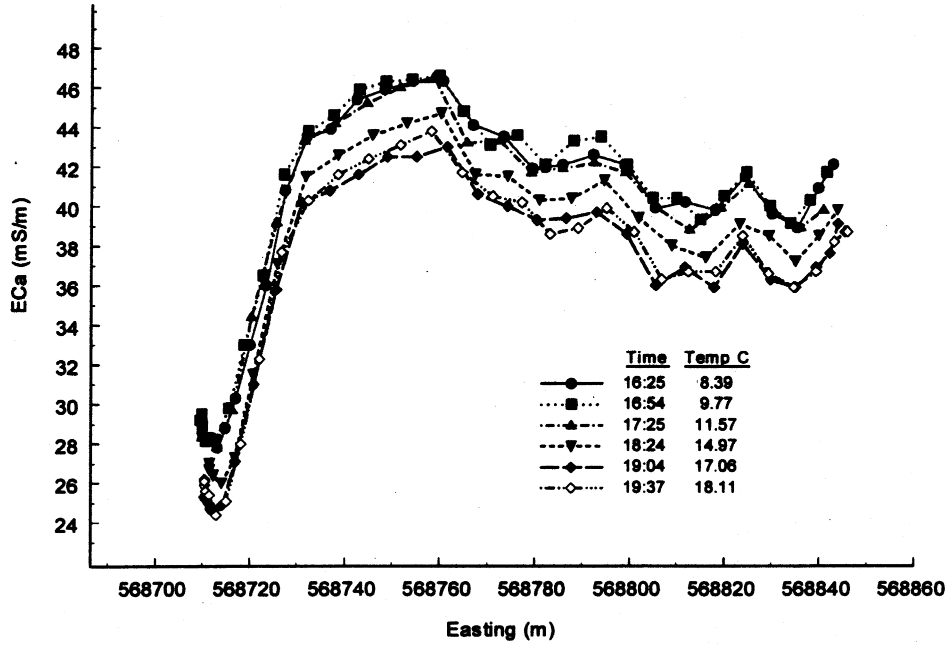

Fig. 4. Repeated EC_a measurements over a calibration transect, showing instrument drift over time.

offset in the value of EC_a measured at any given I/P reading, since the two tests were carried out in different locations with somewhat differing conductivities (Fig. 6).

Changes in vertical mode EC_a were negatively correlated with ambient air temperature in field calibration transect tests but were positively related to temperature in static tests. This suggests that EC_a drift may not be caused by temperature variations; rather drift may merely be a function of instrument instability integrated over time. In our tests, drift per time was relatively constant within a test but varied from day to day. There was a relationship between I/P drift and EC_a drift (Fig. 6), but this relationship was not completely consistent. The causative factors of this drift appear to be complex and not readily compensated with additional, readily obtained measurements, such as ambient air temperature.

We found that EM38 output could drift as much as 3 mS/m per h. This 3 mS/m could represent over 10% of the total EC_a variation in some fields, potentially a large error. Until the mechanisms causing this instrument drift are better understood, the best approach to dealing with the drift would be to either (1) re-zero the instrument I/P on a frequent basis; or (2) use the calibration transect approach to monitor drift over the course of a survey and adjust EC_a readings for that drift if necessary. To ensure quality data, re-zeroing or collecting data on a calibration transect should preferably be conducted approximately every half-hour or at a minimum once every hour. A convenient solution to this issue would be for the manufacturer to provide an instrument with the ability to automatically compensate for I/P drift.

3.2. Effect of mobile operation

Paired data collection runs clearly showed an offset in the position of the response caused by the metal pipe (Fig. 7). For each pair of runs, the distance between the center of the two responses was determined along with the mean operating speed. A graph of this distance offset vs. mean speed showed a strong linear relationship ($r^2 = 0.91$; Fig. 8). Greater scatter in the data at higher speeds (Fig. 8) was likely due to the 5 Hz sampling rate used. Interpolation between data points was used to improve the accuracy of the distance offset, but uncertainty in the measurement could have been as much as 0.2 m at the highest speeds.

The distance offset at zero speed (7.56 m) could be interpreted as twice the horizontal distance between the GPS antenna and the EM38. The actual measured center-to-center distance was 3.86 m, a difference of 0.08 m or 2.1%. Additional positional error was created due to time lags in the data acquisition system, and was therefore a function of operating speed. The magnitude of this error (0.28 s) was given by one-half the slope of the regression line in Fig. 8. Optimum

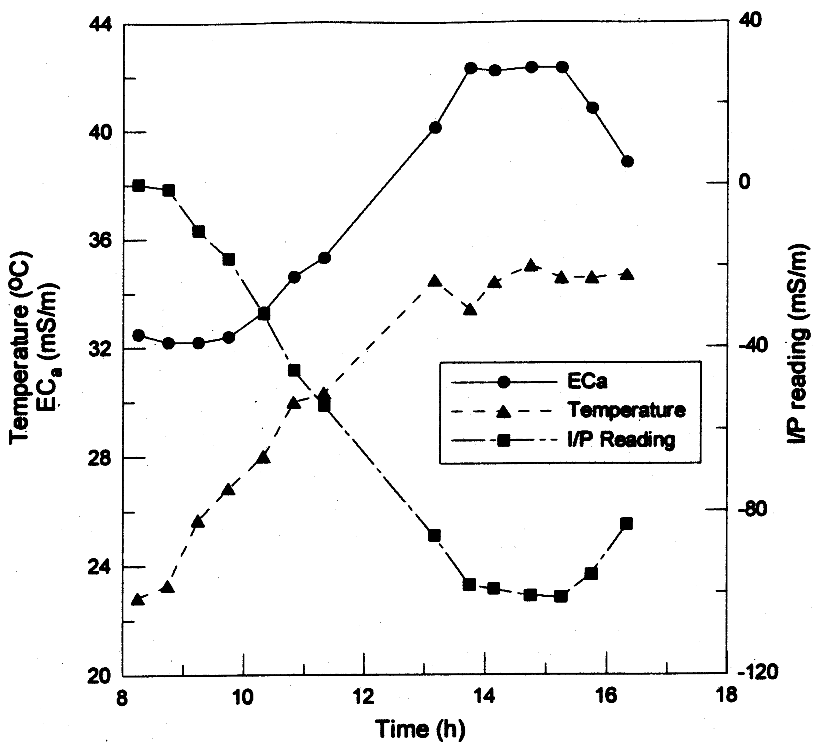

Fig. 5. Change in EC_a, I/P reading, and ambient temperature over time in fixed point drift experiment.

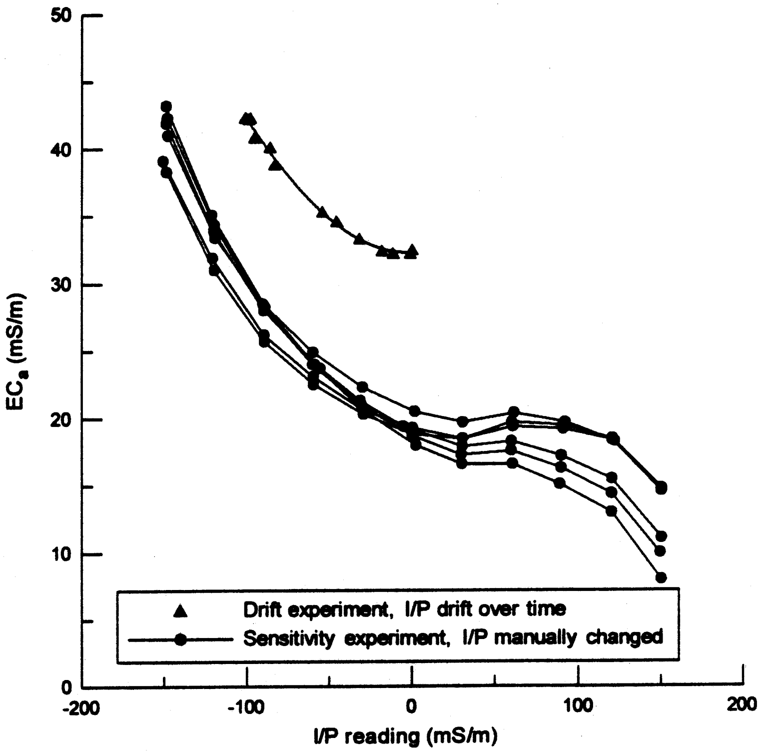

Fig. 6. Sensitivity of EC_a to changes in I/P reading.

compensation for positional offset could thus be accomplished by incorporating both a distance- and a time-based shift (Fig. 7). This might be replaced by a single distance-based shift if the system were operated at approximately constant speeds. At normal operating speeds of 3–6 m/s, the majority of the compensation would be distance-based for our system as tested. However, the time-based shift could be expected to vary depending on the specific operational characteristics of the data acquisition system used. This test procedure would provide a convenient and accurate way of assessing the appropriate shift to use for any EC_a measurement system.

These data were also used to determine the effect of operating speed on EM38 vertical mode EC_a readings. Based on the results described above, the appropriate position offset was applied to the data. A region 10 m long around the metal pipe was removed, and mean EC_a and mean operating speed were then calculated for the remainder of each data collection run. Analysis of variance showed that mean EC_a was significantly related to operating speed but not to travel direction or replication. This provided evidence that there was no significant time-based shift in EC_a (such as that shown in Fig. 5) over the course of this experiment. A graph of EC_a vs. operating speed showed a significant linear relationship ($r^2 = 0.74$; Fig. 9). The sensitivity of EC_a to operating speed was -0.39 mS/m per m/s. It was not possible to conclusively determine the reason for this relationship. However, a potential explanation might be a slight increase in mean EM38 height above ground at higher speeds due to increased bouncing of the cart.

Over the normal operating speed range of the system, speed effects could induce an error of slightly more than 1 mS/m. In general, operating speeds are a function of field conditions, with higher speeds generally used in larger or smoother fields and lower speeds in irregular fields or with rough surface conditions. Within any single field, the usual variation in speeds would likely be much less, with a potential error more on the order of 0.5 mS/m. Although compensation for operating speed effects would be easy to implement, the practical implication of these speed effects would be negligible in most circumstances.

Fig. 10 shows that raising the EM38 above the ground reduced the EC_a reading obtained. Due to the difference in weighting functions (Fig. 2), the horizontal dipole EC_a reading decreased more quickly with height above ground than did the vertical dipole EC_a reading. For our automated system, EC_a was decreased by 12% in the vertical mode and 35% in the horizontal mode, compared to readings obtained on the ground. During field operation, the height of the EM38 above ground may change when traversing ridges or depressional areas. Especially at high speeds, height may also vary due to bouncing of the EM38 trailer when traveling across crop rows or other rough areas. Our automated system positioned the EM38 $\approx$ 20–22 cm above the ground surface. At this height, the sensitivity of EC_a to height variation on a claypan soil was $\approx$ 1% per cm in both the vertical and horizontal operating modes (Fig. 10). The exact shape of the EC_a–height curve

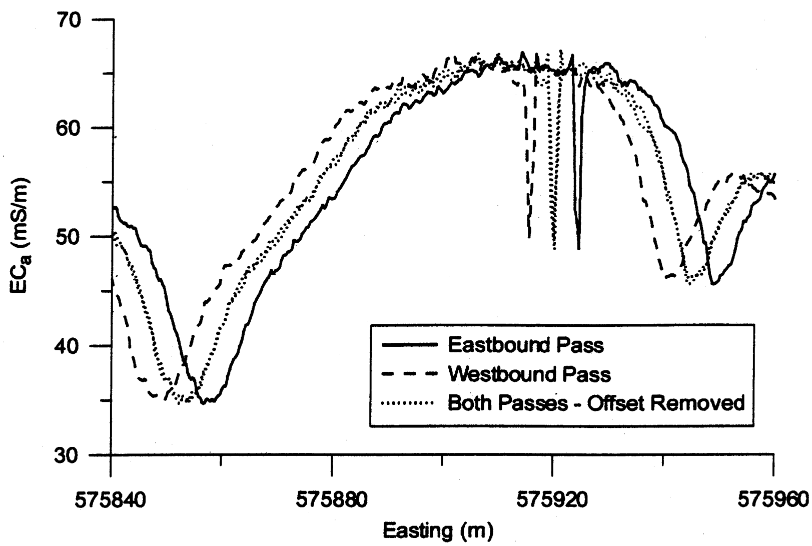

Fig. 7. Paired data collection runs at 1.9 m/s, showing position offset in the EC_a response caused by traversing a metal pipe, and correspondence of the two runs after removing the offset.

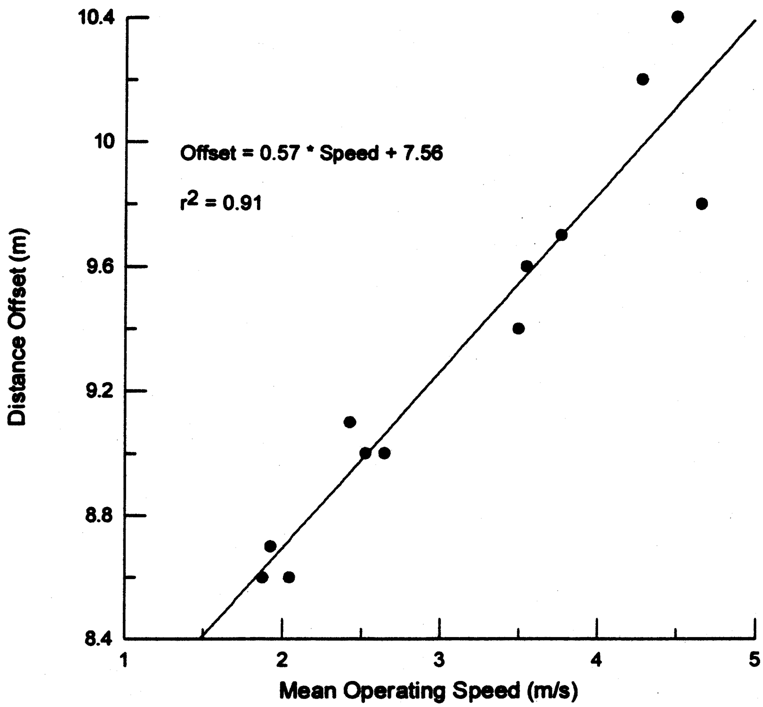

Fig. 8. Position offset between paired EC_a data collection runs as a function of operating speed.

(Fig. 10) for a particular measurement site would depend on the soil conductivity and the change in conductivity with depth at that site. In fact, this dependency has been used to infer the conductivity–depth relationship from EC_a readings obtained at multiple sensor heights (Rhoades and Corwin, 1981).

3.3. Topsoil depth estimation by EC_a

In our earlier work (Doolittle et al., 1994), we used an exponential regression on EC_a to estimate TD for claypan soils. In this study, a number of calibration equations were considered as candidates for modeling TD as a function of EC_a, including logarithmic, exponential, and power functions. Also considered were linear equations of inverse and power function transformations of EC_a. Each equation was applied to the calibration point dataset from each field, and fit statistics were calculated. The best fits were obtained with linear equations of the inverse and power function transformations of EC_a:

Inverse:

$$\mathrm{TD} = a^*(\mathrm{EC}_a^{-1}) + b, \tag{1}$$

Power Function:

$$\mathrm{TD} = a^*(\mathrm{EC}_a^b) + c, \tag{2}$$

where TD = topsoil depth (cm); EC_a, apparent electrical conductivity (mS/m); a, b, and c are regression coefficients.

The power function generally provided somewhat better fits to the calibration data than did the inverse function (Table 1). The greatest improvement in fit with the power function occurred for those datasets where the exponent in Eq. (2) was most different from -1. Standard errors in TD ranged from 6.0 to 14.7 cm. For some datasets TD estimation errors were lower with vertical dipole EM38 data, while errors for other datasets were lower with horizontal data. Averaged over all fields, vertical dipole EM38 data were slightly better at estimating TD than were horizontal dipole data.

Calibration equations incorporating inverse transformations of both horizontal and vertical EM38 data were developed where such data were collected simultaneously (Field 1, 1998). Calibrations including both horizontal and vertical data as independent variables have been reported to provide increased accuracy for salinity estimation (Lesch et al., 1992). However, we found that TD estimations incorporating both vertical and horizontal dipole data were only as good as the best single-dipole estimation (Table 1).

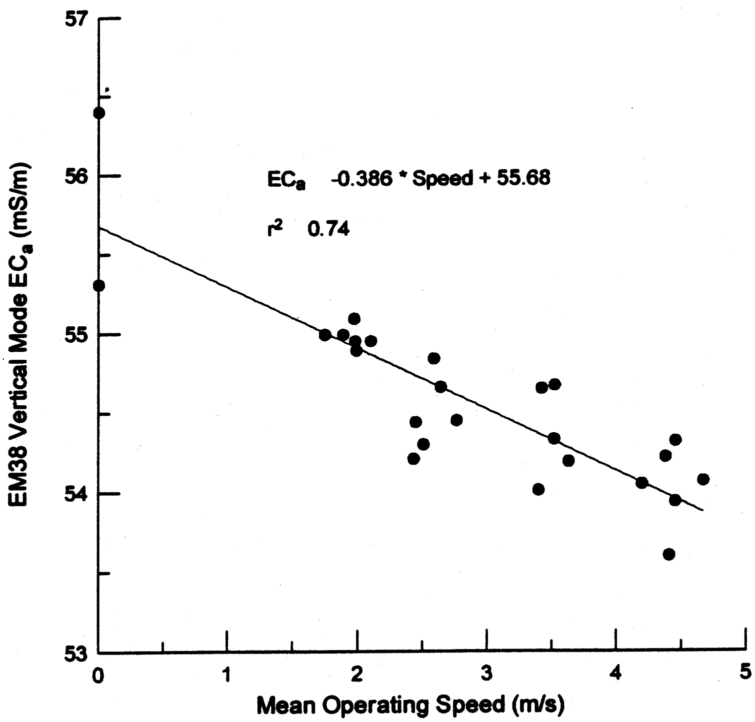

Fig. 9. Sensitivity of EC_a measurement to changes in operating speed.

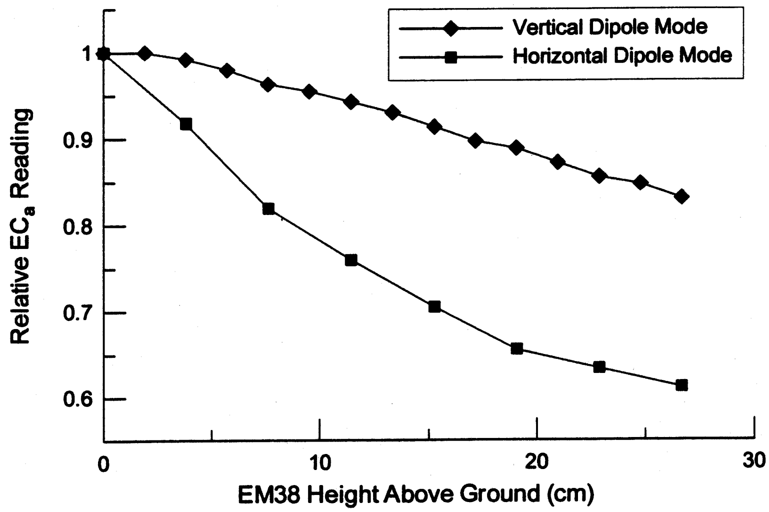

Fig. 10. Effects of changes in sensor height on EC_a.

For a given EM38 orientation, values of regression coefficients (Table 1) varied considerably between fields, even though the three subject fields were very similar and were located within 8 km of each other. This provided evidence that local calibration data collected within each study field is needed to provide the best results when estimating soil properties from EC_a. For Field 1, three sets of vertical mode calibration data were available for comparison. Even within the same field, regression coefficients were quite different when calibration data were collected on different dates at different calibration sites (April 1994 and November 1997; Table 1) or on different dates at the same sites (November 1997 and April 1998; Table 1).

To compare the multiple surveys conducted on Field 1, the data were processed to find those EC_a measurement points in each survey that were located within 2 m of an EC_a measurement point in one of the other surveys. Correlation coefficients were calculated for this subset of points from each combination of surveys (Table 2). The EC_a data from the two surveys conducted in the spring (1994 and 1999) showed a particularly high correlation (Fig. 11). The offset of the data from the 1:1 line may have been due to sensor calibration or differences in ambient effects, such as moisture and/or temperature, between the two surveys. Unfortunately, sufficient moisture and temperature data were not collected in these whole-field studies to separate the effects of temperature and moisture differences on EC_a measurements.

A measurement transect that was common to all three Field 1 surveys and that covered a wide range of EC_a readings was selected (Fig. 12). Near the ends of this transect, topsoil was shallow and EC_a was high, while near the center of the transect, topsoil was deep (>1 m) and EC_a was low. Over the transect, data from the two April surveys (1994 and 1999) were very similar in shape although displaced ≈ 10 mS/m in magnitude. A similar displacement was seen when comparing the two surveys on a whole-field basis (Fig. 11). Data from the November 1997 survey

Table 1
Calibration equations and associated data for estimation of TD as a function of EC_a

Data source	Calibration equation	r^2	Standard error, cm	Calibration points used
Field 1 *(April* 1994*)*				
EM38 vertical	$TD = 3540EC_a^{-1} - 60.4$	0.90	6.7	12
	$TD = 2.35 \times 10^5 EC_a^{-2.5} + 3.0$	0.92	6.0	
Field 1 *(Nov.* 1997*)*				
EM38 vertical	$TD = 9639EC_a^{-1} - 187$	0.85	14.6	20
	$TD = 7.46 \times 10^{10} EC_a^{-5.8} - 3.9$	0.95	8.3	
Field 1 *(April* 1998*)*				
EM38 vertical	$TD = 8286EC_a^{-1} - 169$	0.92	10.4	21
	$TD = 1.69 \times 10^6 EC_a^{-2.8} - 25.9$	0.94	9.0	
EM38 horizontal	$TD = 6524EC_a^{-1} - 186$	0.88	12.3	21
	$TD = 2.05 \times 10^6 EC_a^{-3.1} - 24.4$	0.92	10.3	
EM38 vertical & horizontal	$TD = 10983EC_{a-vert}^{-1} - 2184EC_{a-horiz}^{-1} - 162$	0.92	10.6	21
Field 2				
EM38 horizontal	$TD = 5350EC_a^{-1} - 121$	0.87	14.7	13
	$TD = 7613EC_a^{-1.1} - 101$	0.87	14.7	
EM38 vertical	$TD = 5055EC_a^{-1} - 72.1$	0.84	10.1	12
	$TD = 11790EC_a^{-1.3} - 47.0$	0.84	10.1	
Field 3				
EM38 vertical	$TD = 3970EC_a^{-1} - 84.2$	0.89	9.4	18
	$TD = 2.6 \times 10^6 EC_a^{-3.3} + 5.5$	0.93	7.3	

were also similar in shape, but the range in EC_a values across the transect was $\approx 20\%$ lower. This was likely due to spatial variation in the moisture status of the soil profile after the growing season. In shallow and moderate topsoil (higher EC_a) areas, subsoil water was depleted during the growing season, reducing EC_a in these parts of the field. In the deepest topsoil (low EC_a) areas, EC_a was higher at this survey date, due to concentration of surface runoff from antecedent precipitation events in these lower elevation sections of the field. Soil temperature differences across the three measurement dates were $\approx 10°C$ measured at the 10 cm depth at an on-site weather station. Temperature differences at greater depths were not measured but would be expected to exhibit less variation.

Table 2
Correlation coefficients and associated data comparing EC_a surveys of Field 1

Survey dates	Correlation coefficient (r)	Number of points used
April 1994 & Nov. 1997	0.89	1476
Nov. 1997 & April 1999	0.86	621
April 1994 & April 1999	0.97	623

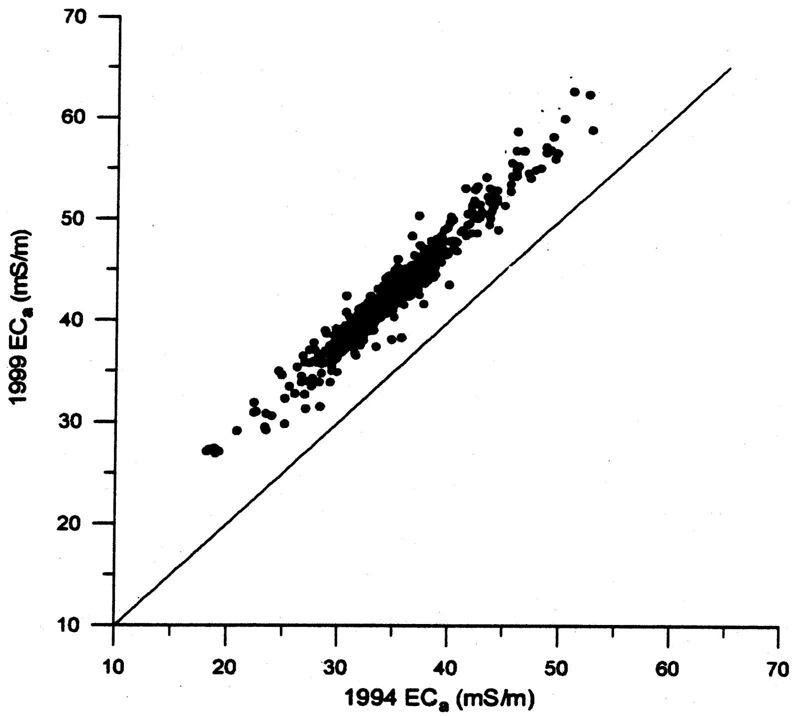

Fig. 11. Relationship of vertical mode EC_a data collected in April 1994 and April 1999 on Field 1.

The appropriate inverse ($1/EC_a$) equations of Table 1 were applied to the vertical mode Field 1 data of 1994 and 1997 so that differences between the two surveys could be compared on the basis of TD. Data were kriged to a 10-m cell size for mapping and visual comparison (Fig. 13). Although field-scale patterns of estimated TD were similar, some differences were apparent. TD estimates from 1997 data were generally lower for the shallow topsoil areas of the field and were higher for the deep topsoil areas of the field, when compared to the 1994 data. Since a better calibration was obtained with the 1994 data (Table 1), it may have been that whole-field TD maps from that dataset were more accurate. However, this was not certain, since different calibration points were used for the two datasets. The 1997 calibration data included points at both deeper and shallower topsoil than did the 1994 calibration data. The higher standard errors observed with the 1997 data may have been at least partially due to the wider calibration range and increased number of calibration points.

Direct calibration of EC_a to TD worked well on the claypan soils of central Missouri. It was possible to successfully estimate TD using a single EC_a reading. In general, vertical dipole mode EC_a readings were slightly better at estimating TD than were horizontal readings. Other researchers have developed procedures to infer the depth profile of soil conductivity changes (such as the topsoil–claypan subsoil transition) by means of multiple readings obtained with the EM38 held at

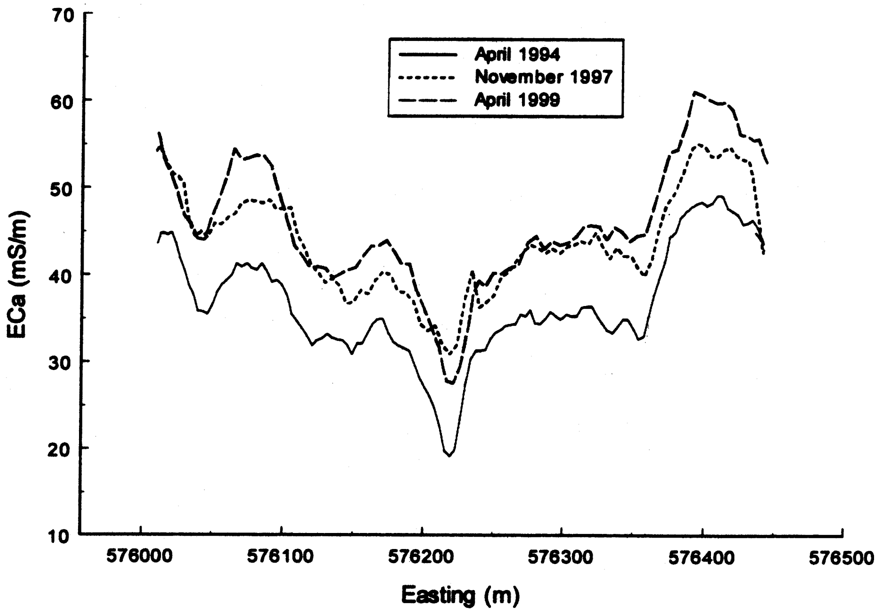

Fig. 12. Comparison of EC_a data colleted over a representative transect on Field 1 in April 1994, November 1997 and April 1999.

varying heights above the ground (e.g., Rhoades and Corwin, 1981). However, the ability to use single-height data significantly quickened the data collection process, since it was then possible to collect EM38 data using the mobile system. An inverse calibration on EC_a (Eq. (1)) was selected for TD estimation since it provided one

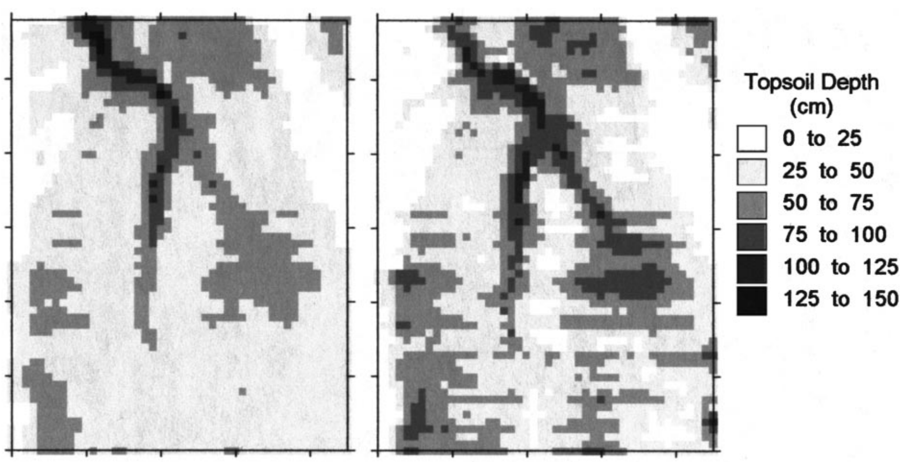

Fig. 13. TD maps from Field 1 EC_a surveys conducted in April 1994 (left) and November 1997 (right).

Table 3
Range in measured parameters for soil moisture and temperature sensitivity experiment, over all sites and measurement dates

Parameter	Minimum	Maximum	Correlation (r) with TD
TD (cm)	10	100	1.0
Vertical mode EC_a (mS/m)	28.4	77.0	0.80
Horizontal mode EC_a (mS/m)	18.5	71.9	0.61
Average soil temperature (°C)	4.7	27.8	n.s.*
Average soil moisture (%)	29.2	43.3	0.18

* n.s. – correlation not significantly different than zero.

of the best fits to measured data and was easy to implement. A modified power function calibration (Eq. (2)) generally provided somewhat more accurate predictions of topsoil depth and deserves additional consideration. Fitting of a spatial response TD surface in the calibration, as suggested by Lesch et al. (1995a,b), should also be considered to improve TD estimation. However, the methods used to collect calibration data in this study did not allow the response surface approach to be used. Field-scale data collected on three separate measurement dates showed similar, but not identical, patterns in EC_a and estimated TD. At the majority of locations, TD estimated by the surveys differed by less than 10 cm.

3.4. Effect of soil moisture and temperature

Across all measurement dates and sites, there was a wide range in TD, soil moisture, temperature, and EC_a (Table 3). There were significant correlations of TD with profile average moisture, vertical EC_a and horizontal EC_a but not with profile average soil temperature (Table 3). Separate inverse regressions were computed for each field and each measurement date, using Eq. (1) with the addition of two more independent variables – average moisture and average temperature. In general, the relationship of TD to EC_a was independent of soil moisture and temperature for a single date. When using vertical EC_a to estimate TD, average temperature was a significant parameter for only 4 of the 24 field–date combinations while average moisture was not significant for any. When using horizontal EC_a, average temperature was significant for 2 field–date combinations while average moisture was significant for one. Very good estimations of TD ($r^2 > 0.85$) were obtained for 21 of 24 vertical EC_a calibrations. TD estimations using horizontal EC_a were not as good ($r^2 > 0.8$ in 16 of 24 cases). On claypan soils, the effect of TD variability on an EC_a survey conducted on a single date is much greater than the effect of other soil properties. Thus, it was possible to develop good calibrations for TD estimation on claypan soils without measuring those other soil properties (such as moisture and temperature) that affect EC_a to a lesser degree. However, the relative effects of those soil properties on EC_a may be different elsewhere, and such interactions should be considered when interpreting EC_a surveys on other soils.

The effect of seasonal moisture and temperature changes on EC_a measurement were examined by developing calibration equations for TD over the entire dataset. The equation used was

$$TD = b_0 + b_1 * EC_a^{-1} + b_2 * T + b_3 * M, \tag{3}$$

where T = mean soil temperature (°C); M, mean soil moisture (%); b_0, b_1, b_2, and b_3 are regression coefficients.

In this case, both average moisture and average temperature were highly significant, for both the vertical mode and horizontal mode equations. TD estimations from vertical EC_a data were more accurate than those from horizontal EC_a. Also, the sensitivity of these estimates to changes in moisture and temperature were less for the vertical EC_a data (Table 4). For both vertical and horizontal mode, standard errors were reduced by more than 23% by including average moisture and average temperature in the regression, as compared to the EC_a-only regression (Eq. (1)). Considering the variation in soil moisture and soil temperature observed over all measurement dates along with the calibration sensitivity to these variations (Table 4), seasonal soil moisture differences had approximately twice the effect on EC_a as did seasonal soil temperature differences.

Obviously, collection of soil moisture and temperature data at each EC_a calibration point would be possible, but it would require significant additional effort. One possible alternative would be to classify moisture and temperature conditions at the time of each EC_a survey as "wet" or "dry" and "hot" or "cold." This classification variable could then be used in the regression calibrating EC_a to TD:

$$TD = b_0 + b_1 * EC_a^{-1} + b_2 * H + b_3 * W, \tag{4}$$

where$H = 1$ if $T > 16$°C; $H = 0$ otherwise; $W = 1$ if $M > 38\%$; $W = 0$ otherwise

Using the divisions of 38% soil moisture and 16°C, measurement dates were classified as hot–wet, hot–dry, or cold–wet based on mean moisture and tempera-

Table 4
Statistics for estimating TD from inverse EC_a, moisture, and temperature across all sites and measurement dates

Independent variables	Regression on vertical EC_a	Regression on horizontal EC_a
$1/EC_a$ only		
r^2	0.64	0.37
Standard error (cm)	14.7	19.4
$1/EC_a$, temperature, moisture		
r^2	0.79	0.63
Standard error (cm)	11.2	14.9
Soil temperature sensitivity (cm/°C)	0.60	0.66
Soil moisture sensitivity (cm/%)	3.1	4.5
$1/EC_a$, temperature/moisture class		
r^2	0.77	0.58
Standard error (cm)	11.7	16.0

ture over all measurement locations. No observations fell into the cold–dry category. Estimates of TD using this procedure were nearly as good as those obtained when numeric moisture and temperature data were used in the calibration model (Table 4).

Including moisture and temperature effects in this way would allow comparison of multiple datasets collected on different survey dates. For example, the EC_a–TD relationship could be expected to be similar for multiple dates in the spring of the year, falling into the cold–wet category. This category would also include sampling dates in the winter or late autumn after soil moisture had recharged following the growing season, and these dates would be expected to exhibit a similar relationship.

4. Conclusion

Sensor-based measurements of soil EC_a can provide information to quantify within-field spatial variability in precision agriculture. In this study, we adapted a Geonics EM38 sensor for mobile data collection and investigated a number of issues important for the implementation of mobile EC_a surveys.

The stability of EM38 readings over time was quite variable. In some cases instrument drift was as much as 3 mS/m per h, a very significant amount. It was not possible to relate drift to changes in ambient temperature in a reproducible manner. Drift per time was fairly constant within a test but varied from day to day. A practical approach to drift compensation is to establish a calibration transect on each field. Data should be acquired along that transect several times during the course of a field survey so that any drift can be documented and compensated. Another approach is to rezero the EM38 on a frequent basis during the course of the survey.

Mobile data collection introduced an offset between recorded GPS position and the actual point at which the EC_a measurement was obtained. This offset was due to both the distance between the EM38 and the GPS antenna and time lags associated with data acquisition. A procedure to quantify such offsets was developed and tested. Vertical mode EC_a decreased slightly with increasing operating speed (-0.4 mS/m per m/s). The sensitivity of measured EC_a to changes in the height of the sensor above the ground was about 1%/cm. During a normal field survey, the effect of changes in speed and height on EC_a measurement should be minimal.

Procedures were developed to estimate TD on claypan soils from EC_a. On these soils, TD is an important factor related to within-field productivity differences. The best estimates were obtained with linear equations of an inverse or power function transformation of EC_a. EM38 data collected in the vertical dipole mode were slightly more predictive of TD than were horizontal dipole mode data. Best results were obtained when calibration points from each field were used to develop field-specific regression equations. Multiple measurements of EC_a for the same location were similar if they were collected at the same time of year, with similar moisture and temperature conditions. For one field, maps of EC_a-estimated TD

Table 5
Approximate effect of various operational and ambient parameters on EC_a measurements obtained on claypan soils

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
TD*	0.4 mS/m per cm

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

obtained from separate surveys showed similar, but not identical, patterns. At the majority of locations, TD estimated from the two surveys agreed to within 10 cm.

In general, the effect of soil moisture and soil temperature variations on TD estimations was not significant for a single measurement date, indicating that variations in these parameters affected EC_a much less than did variations in TD. There was a significant effect of moisture and temperature across measurement dates spanning a 12-month period. It was possible to account for this effect by classifying each measurement date as hot vs. cold and wet vs. dry. This classification approach provided a practical way to integrate EC_a data collected at different measurement dates.

In this study, the relative effects of various operational and ambient parameters on EC_a readings obtained with the EM38 on claypan soils were estimated (Table 5). Although these effects may change somewhat for different soil types and EC_a levels, the results presented here can serve as a guide for successfully planning and interpreting EC_a surveys in precision agriculture.

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References

Cannon, M.E., McKenzie, R.C., Lachapelle, G., 1994. Soil salinity mapping with electromagnetic induction and satellite-based navigation methods. Can. J. Soil Sci. 74, 335–343.

Carter, L.M., Rhoades, J.D., Chesson, J.H. 1993. Mechanization of soil salinity assessment for mapping. ASAE Paper 931557, ASAE, St. Joseph, MI.

Doolittle, J.A., Sudduth, K.A., Kitchen, N.R., Indorante, S.J., 1994. Estimating depths to claypans using electromagnetic induction methods. J. Soil Water Cons. 49 (6), 572–575.

Ellsbury, M.M, Woodson, W.D., Malo, D.D., Clay, D.E., Carlson, C.G., Clay, S.A., 1999. Spatial variability in corn rootworm distribution in relation to spatially variable soil factors and crop condition. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc 4th Intl. Conf. on Precision Agriculture, St. Paul, MN, July 19–22 1998. ASA-CSSA-SSSA, Madison, WI, pp. 523–533.

Fenton, T.E., Lauterbach, M.A., 1999. Soil map unit composition and scale of mapping related to interpretations for precision soil and crop management in Iowa. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc 4th Intl. Conf. on Precision Agriculture, St. Paul, MN, July 19–22 1998. ASA-CSSA-SSSA, Madison, WI, pp. 239–251.

Geonics, 1998. EM38 ground conductivity meter operating manual. Geonics Ltd, Mississauga, Ont., Canada.

Hummel, J.W., Gaultney, L.D., Sudduth, K.A., 1996. Soil property sensing for site-specific crop management. Comput. Electron. Agric. 14, 121–136.

Jaynes, D.B., Colvin, T.S., Ambuel, J., 1993. Soil type and crop yield determinations from ground conductivity surveys. ASAE Paper 933552, ASAE, St. Joseph, MI.

Jaynes, D.B., Novak, J.M., Moorman, T.B., Cambardella, C.A., 1995. Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environ. Qual. 24, 36–41.

Kachanoski, R.G., Gregorich, E.G., Van Wesenbeeck, I.J., 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68, 715–722.

Kitchen, N.R., Sudduth, K.A., Drummond, S.T., 1996. Mapping of sand deposition from 1993 midwest floods with electromagnetic induction measurements. J. Soil Water Cons. 51, 336–340.

Kitchen, N.R., Sudduth, K.A., Drummond, S.T., 1999. Soil electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 12, 607–617.

Lesch, S.M., Rhoades, J.D., Lund, L.J., Corwin, D.L., 1992. Mapping soil salinity using calibrated electromagnetic measurements. Soil Sci. Soc. Am. J. 56, 540–548.

Lesch, S.M., Strauss, D.J., Rhoades, J.D., 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques: 1. Statistical prediction models: a comparison of multiple linear regression and cokriging. Water Resour. Res. 31, 373–386.

Lesch, S.M., Strauss, D.J., Rhoades, J.D., 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques: 2. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. Water Resour. Res. 31, 387–398.

Lund, E.D., Christy, C.D., Drummond, P.E., 1999. Applying soil electrical conductivity to precision agriculture. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc 4th Intl. Conf. on Precision Agriculture, St. Paul, MN, July 19–22 1998. ASA-CSSA-SSSA, Madison, WI, pp. 1089–1100.

McBride, R.A., Gordon, A.M., Shrive, S.C., 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J. 54, 290–293.

McNeill, J.D., 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Tech. Note TN-6, Geonics Ltd, Mississauga, Ont., Canada.

McNeill, J.D., 1992. Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters. In: Advances in Measurement of Soil Physical Properties: Bringing Theory Into Practice. Spec. Publ. 30, SSSA, Madison, WI, pp. 209–229.

Rhoades, J.D., 1993. Electrical conductivity methods for measuring and mapping soil salinity. Adv. Agronomy 49, 201–251.

Rhoades, J.D., Corwin, D.L., 1981. Determining soil electrical conductivity–depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J. 45, 255–260.

Rhoades, J.D., Raats, P.A., Prather, R.J., 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40, 651–655.

Rhoades, J.D., Manteghi, N.A., Shrouse, P.J., Alves, W.J., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Sci. Soc. Am. J. 53, 433–439.

Rhoades, J.D, Chanduvi, F., Lesch, S.M., 1999. Soil Salinity Assessment: Methods and Interpretation of Electrical Conductivity Measurements. FAO Irrigation and Drainage Paper 57. Food and Agricultural Organization of the United Nations, Rome, Italy.

Stafford, J.V., Hendrick, J.G., 1988. Dynamic sensing of soil pans. Trans. ASAE 31 (1), 9–13.

Sheets, K.R., Hendrickx, J.M.H., 1995. Noninvasive soil water content measurement using electromagnetic induction. Water Resour. Res. 31 (10), 2401–2409.

Sudduth, K.A., Hummel, J.W., 1993. Soil organic matter, CEC, and moisture sensing with a portable NIR spectrophotometer. Trans. ASAE 36 (6), 1571–1582.

Sudduth, K.A., Kitchen, N.R., Hughes, D.F., Drummond, S.T., 1995. Electromagnetic induction sensing as an indicator of productivity on claypan soils. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc. Site-Specific Management for Agricultural Systems, Second Intl. Conf., Minneapolis, MN, March 27–30 1994 . ASA-CSSA-SSSA, Madison, WI, pp. 671–681.

Sudduth, K.A., Drummond, S.T., Birrell, S.J., Kitchen, N.R., 1996. Analysis of spatial factors influencing crop yield. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc 3rd Intl. Conf. on Precision Agriculture, Minneapolis, MN, June 23–26 1996. ASA-CSSA-SSSA, Madison, WI, pp. 129–140.

Sudduth, K.A., Hummel, J.W., Birrell, S.J., 1997. Sensors for site-specific management. In: Pierce, F.J. Sadler, E.J. (Eds.) The State of Site-Specific Management for Agriculture. ASA-CSSA-SSSA, Madison, WI, pp. 183–210.

Sudduth, K.A., Kitchen, N.R., Drummond, S.T., 1999. Soil conductivity sensing on claypan soils: comparison of electromagnetic induction and direct methods. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proc 4th Intl. Conf. on Precision Agriculture, St. Paul, MN, July 19–22 1998. ASA-CSSA-SSSA, Madison, WI, pp. 979–990.

Wibawa, W.D., Dludlu, D.L., Swenson, L.J., Hopkins, D.G., Dahnke, W.C., 1993. Variable fertilizer application based on yield goal, soil fertility, and soil map unit. J. Prod. Agric. 6 (2), 255–261.

Williams, B.G., Baker, G.C., 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Aust. J. Soil Res. 20, 107–118.

Williams, B.G., Hoey, D., 1987. The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. Aust. J. Soil Res. 25, 21–27.