Soil conductivity sensing using non-invasive electromagnetic induction-based and electrode-based methods

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Abstract

Recently, methods have been developed to remotely and rapid sensing soil electrical conductivity (EC) without disturbing using commercially available apparent soil electrical conductivity (ECa) sensors that are used extensively in precision agriculture. This study was carried out to to compare soil EC measurements from a contact and electrode-based sensor (VERIS 3100, both shallow (VERIS_sh) and deep (VERIS_dp) modes) and a non-contact, electromagnetic induction (EMI)-based sensor (Geonics EM38, both horizontal (EM38_h) and vertical (EM38_V) orientations). ECa data were collected on a 1 second interval in a data density of 830 to 1250 points per hectare. This study showed that while qualitatively similar, quantitatively differences were attributed to differences between the depth-weighted response functions for the four data types and the differences in sensing depth between the different sensors and data collection modes. In this research, the advantages of using EMI methods were found to be the ease of making measurements. In general, there was a big difference between EM38 and VERIS readings, however the VERIS_sh and VERIS_dp readings were somewhat equal. Highest correlations were generally found between EM38_h and EM38_v ($r = 0,712$) however variation in VERIS 3100 readings was higher than EM38 readings. Very low correlations were found between VERIS_sh to EM38_h, VERIS_sh to EM38_v and VERIS_dp to EM38_v.

Keywords: soil electrical conductivity, EM38, VERIS3100

Introduction

Apparent profile soil electrical conductivity (ECa) can be used as an indirect indicator of a number of soil physical and chemical properties. Commercially available ECa sensors can efficiently and inexpensively develop the spatially dense datasets desirable for describing within-field spatial soil variability in precision agriculture. Recent developments in EC sensors and their ability to produce EC variation maps has attracted much attention among producers about potential applications of this sensor for improving field management. Apparent profile soil electrical conductivity (ECa) is one sensor-based measurement that can provide an indirect indicator of important soil physical and chemical properties. Factors that influence ECa include soil salinity, clay content and clay mineralogy, soil pore size and distribution, soil moisture content, and temperature (James et al., 2000; Hendrickx et al., 1992; McNeill, 1992). In saline soils, most of the variation in EC_a can be related to salt concentration (Williams and Baker, 1982), but in non-saline soils, conductivity variations are primarily a function of soil texture, moisture content, and CEC (Kachanoski et al., 1988). In some cases, the within-field variations in EC_a are predominated due to one soil property and EC_a can be calibrated directly to that dominant factor. 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 ECa can be calibrated as a direct measurement of that dominant factor. In general, ECa can be affected by a number of different soil properties, including clay content (Williams and Hoey, 1987), soil water content (Kachanoski et al., 1990; Sheets and Hendrickx, 1995, Morgan et al., 2001), topsoil depth above a subsoil claypan horizon in Missouri (Doolittle et al., 1994, Kitchen et al., 1999 and Sudduth et al., 2001), grain yield (Kitchen et al., 1999), total available water content using a methodology by ECa measured in field capacity (Waine et al. 2000, AL-Karadsheh et al. 2002, Hezarjaribi and Sourell, 2006) varying depths of conductive soil layers, temperature, salinity, organic compounds, and metals (Geonics Limited, 1992, 1997). Because many of these factors impact plant growth, ECa measurements can be used on some soils as a surrogate measure of more costly soil chemical and physical measurements (Jaynes, 1996; Clark et al., 2001; Hartsock et al., 2001). For example, ECa has been found to be highly correlated with claypan topsoil thickness i.e., depth to the Bt horizon (Doolittle et al., 1994; Sudduth et al., 2001). Rapid methods for scanning large volumes of information, i.e., scanning soils EC using EC sensor (Sudduth et al., 2004, Fleming et al., 2004a,b; Sudduth et al., 2002; Domsch, 2001a,b; Sudduth et al., 2001; Ehlert et al., 2001; Fridgen et al., 2000b; Kitchen et al., 1999) are to be used extensively in precision agriculture decision making. One type of these sensors is electromagnetic induction (EMI)-based sensor. EM38 (manufactured by Geonics Limited of Mississauga, Ontario, Canada-www.geonics.com) and GEM-300 (Geophex, http://www.geophex.com) are two popular models of non-contact sensors that are available on the market. GEM-300 is a digital and multi-frequency sensor that can operate in a frequency range of 300 Hz for about 6 to 10 m investigation depth and to 24 KHz for about 1 m investigation depth. EM38 works only with a fixed frequency and has an effective measurement depth of 0,75 m in horizontal dipole mode (EM38_h) or 0.75 m in vertical dipole mode (EM38_v). Another EC sensor is electrod-based or contact method such as VERIS EC mapping system (VERIS Technologies, Salina, Kansas – www.veristech.com) and the Multi-depth Continues Electrical Profiling (MuCEP or ARP) system (Dabas et al., 2000). This type of sensor uses electrodes, usually in the shape of coulters that make contact with the soil to measure the electrical conductivity. In this approach, two to three pairs of coulters are mounted on a toolbar; one pair applies electrical current into the soil while the other two pairs of coulters measure the voltage drop between them resulting in simultaneous EC measurements for the top 1 foot of soil and the top 3 feet of soil.

Each of the commercial ECa sensors has operational advantages and disadvantages (Sudduth et al., 2001). In some research similarities and differences were found between data obtained with both types of ECa sensors. Similar data and relationships to soil physical and chemical properties were exhibited by Doolittle et al. (2001 a, b and 2002); Sudduth et al. (1999,2003), and Bramley (2002). Doolittle et al.(2001 and 2002) compared EM38-h, EM38-v, GEM300-h and GEM300-v measurements. In this research, correlation coefficients between the ECa data sets obtained were 0,80 and 0,86 in the horizontal and vertical dipole orientations for EM38 and GEM300, respectively. All three tools produced similar gross spatial patterns of apparent conductivity that corresponded to mapped soil delineations and changes in clay content. Also Bramley (2002) showed that the best correlation between EM38 and VERIS 3100 were between EM38-v and VERIS-dp. Sudduth et al. (1999) compared soil EC measurements from EM38-v, EM38-h, VERIS-sh and VERIS-dp on claypan soil (fine, smectitic, mesic aeric Vertic Epiaqualfs and Albaqualfs). The EM38 and VERIS 3100 sensors were both able to measure ECa on claypan soils, and maps generated from the two sensors exhibited similar patterns at the field scale. Differences between maps were attributed to the differences in sensing depth between the different sensors and data collection modes (vertical vs. horizontal or deep vs. shallow, respectively). Sudduth et al. (2003) also compared ECa measurements from EM38 and VERIS 3100 to relate ECa data to soil physical properties on two fields. Within a single field and measurement date, EM38 data and VERIS-dp data were most highly correlated (r = 0.74-0.88). Differences between ECa sensors were more pronounced on the more layered soils due to differences in depth-weighted response curves. Correlations of ECa with response curve-weighted clay content were generally highest and most persistent across all fields and ECa data types. Although the ECa data from the two sensing approaches was generally similar. Also Dabas et al. (2003) recognized error in positioning, instrumental errors and errors when data processing during a field experiment. The errors in positioning could originate from the accuracy of GPS and GPS offset, from a bad calibration of EM38, high contact resistance of VERIS 3100, disturbances coming from temperature effect, vibrations, presence of scattered metal objects. Finally during data processing, they found problems related to sampling rate and/or resolution, processing delay – or latency- in some instruments, which means that their output is buffered. In this research, the advantages of using EMI methods were found to be the ease of making measurements. It was also clear that the best measurements were made by hand with a very careful check of the instrument. The objective of this study was to compare soil EC measurements from a contact and electrode-based sensor (VERIS 3100, both shallow and deep readings) to those obtained from a non-contact, EMI-based sensor (Geonics EM38, both horizontal and vertical orientations). Triantafilis and Lesch (2005) have found a high correlation (R^=0.94) between EM38-v EM38-h. Sudduth et al. (2002) found that within single paddocks, the EM38 data were generally less variable than VERIS 3100 and that there was more variation amongst strongly layered soils compared to those with little texture variation with depth. Also Lück (2002) presented very similar findings and noted that an additional benefit of EM38 over VERIS 3100 was its portability. This result is consistent with results of Bramley (2002) that, in general, EM38 sensing is much more appropriately used as a crude identifier of soil variation, albeit at high spatial resolution, than as a surrogate measure for specific soil properties.

Materials and methods

The two ECa sensors used in this study were the EM38 (applied about 30 cm as suspended above the ground surface) and the VERIS Model 3100 sensor. Data were collected on an 16.6 ha field in the Federal Agricultural Research Centre (FAL)/Institute of Production Engineering and Building Research / Braunschweig / Germany. Soil texture, determined by feel was dominated by loamy sand in the upper 40 cm and more sandy in the greater depths. EM38 and VERIS3100 measured soil conductivity while being pulled through the field. Relative response of EM38 and VERIS 3100 as a function of depth are shown in figure 1. The ECa readings from these two sensors are depth-weighted. The response curves of Figure 1 are based on equations that assume a homogeneous soil volume. The EM38 has an intercoil spacing of 1.0 m with a nominal depth of investigation, defined as the depth to which approximately 70% of the measured response is generated, of 1.50 m when operated in the vertical dipole mode (EM38_h), and 0.75 m when operated in the horizontal dipole mode (EM38_v) (Mc-Neill 1980). The vertical

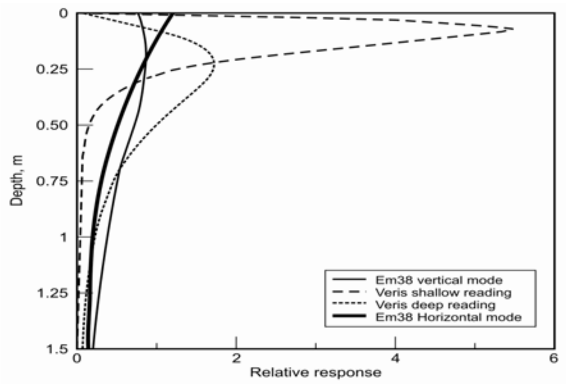

Figure 1. Relative response of ECa sensors as a function of depth responses are normalized to yield a unit area under each curve related curves to EM38 is shifted 30 cm above the ground). (McNeill,1992,1980).

dipole mode response is less sensitive than the horizontal dipole response to near surface material (< ~0.40-m depth) and more sensitive to deeper material. In VERIS 3100 measurement, electrodes are configured to provide both shallow (VERIS_sh) and deep (VERIS_dp) readings of ECa. With the VERIS_sh and VERIS_dp readings, 90% of the response is obtained from the soil above the 0.3 m and 0.9 m depth respectively. ECa data were collected on a 1 second interval in a data density of 830 to 1250 points per hectare in tandem operating. Soil ECa readings and location information were recorded in a laptop. Moreover a Differential Global Positioning System (DGPS) provided the location information to the data logger. Data obtained by DGPS were associated with each sensor reading to provide positional information with an accuracy of 2 m. Because of different soil temperature records measured using thermistors at different depths during ECa measurements, apparent electrical conductivity measurements were standardized to 25°C using correction factor derived from the equation here under:

$$EC_{25} = ECa(0.4779+1.3801*EXP(-T/25.654)) \quad \text{(Anonymous,1954)} \qquad (1)$$

where EC_{25} = ECa standardized to 25°C; and T(°C) = average temperature over a given depth interval. The reading were logged to a data logger and interpolated using a spherical kriging model in ArcView (ESRI) software program to create an ECa map, as shown in Figure 2.

Results and Discussion

EC25 data collected in each of the two operating modes with each of the two sensors were mapped (Figure 2). Within each map, an equal number of readings were represented within each classification interval. Conductivity readings obtained with each sensor (in mS/m) were considerably different in magnitude. However, we found similar trends at field scale within a single EM38 measurement.

A statistical summary of the different EC_{25} readings obtained with VERIS 3100 and EM38 data for each measurement data after deleting the unreasonable data, is shown in Table 1. Maximum and minimum ECa readings were found in the EM38_h and VERIS_dp readings, respectively compared with other sensor-based ECa reading, however, the VERIS_sh and VERIS_dp readings were somewhat equal. In general, there was a large difference between EM38 and VERIS readings. The ECa readings by the

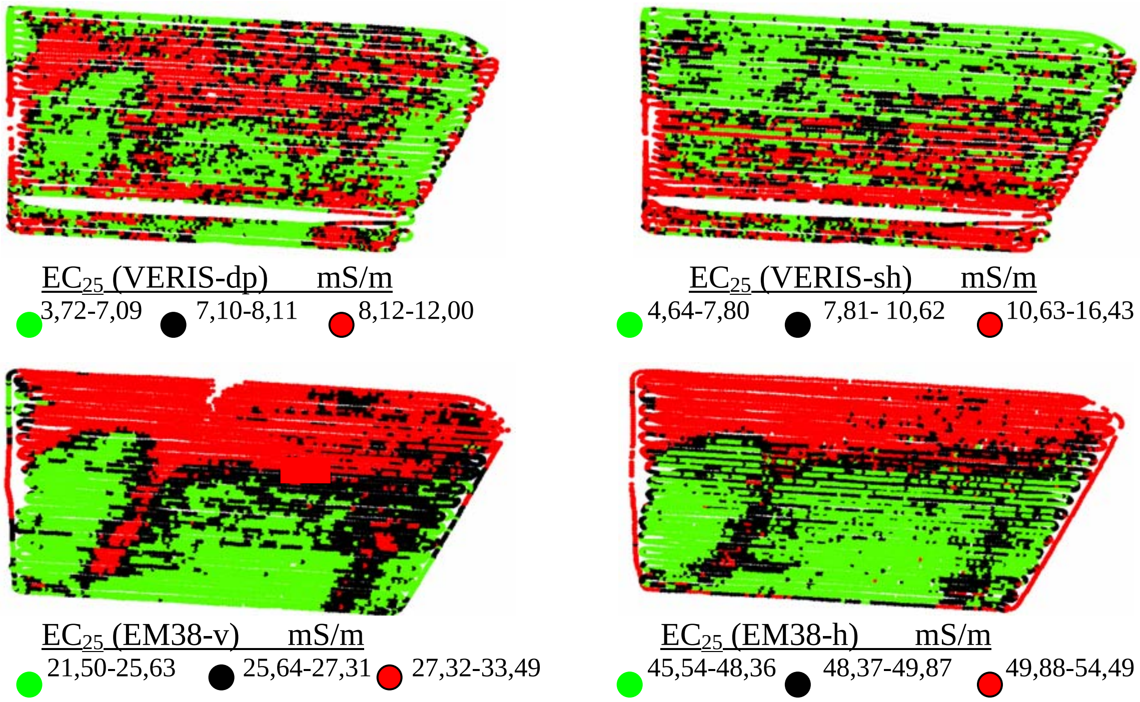

Figure 2. Comparison of the different EC_{25} readings obtained with VERIS-sh, VERIS_dp, EM38-h and EM38_v.

the EM38 were higher than ECa readings by VERIS 3100, though variations among VERIS 3100 readings were significantly higher than EM38 readings as shown by the measured CV in Table 1 (CV(VERIS_sh)=22,3% and CV(VERIS_dp)= 17,3%), and can be found from visual comparison in Figure 2 and specially in Figure 1 where about 94%, 56%, 40% and 24% of cumulative responses of the VERIS_sh, VERIS_dp, EM38_h and EM38_v, respectively, are laid in the upper 40 cm. These results are in agreement with soil-depth variation in our field that is more variable in the upper 40 cm (mix of loam and sand) and more uniform in the greater depths (mostly sandy). That means the major variability in the soil properties that affect ECa may be in the upper layers that are more heavily weighted in the VERIS 3100 ECa measurements and more uniformity in the soil properties that affect ECa may be in the greater depths that are less heavily weighted and more uniform in the EM38 ECa measurements as shown in Figure 1.These results are in agreement with those found by Sudduth et al. (2002). A combined data set (about 300 points) with equal measurement of transect locations between EM38_v, EM38_h, VERIS 3100_sh and VERIS 3100_dp readings were created at different EC_{25} to allow comparison between EC_{25} readings. Based on DGPS coordinates the nearest EM38_v, EM38_h, VERIS 3100_sh and VERIS 3100_dp readings were combined. If a match was not found within a 2,5 m radius, that point was removed from the data set. Comparison of pearson correlation coefficients (r) between ECa measurements have shown that highest correlations were generally found between EM38_h and EM38_v (r=0,712) as shown in Table 2. This result can be discerned from visual comparison between maps in Figure 2 and from the EM38_h and EM38_v curves as shown Figure 1 where these two curves lie closer than other curves. However there was somewhat lower correlations between VERIS_dp and EM38_h (r=0,54) and VERIS_dp and VERIS_sh (r=0,51) and very low correlations between VERIS_sh to EM38_h ,VERIS_sh to EM38_v and VERIS_dp to

EM38_v (Table 2). These results also can be discerned from the Figure 1 where related curves lie further away from the other curves.

Table1. Statistical values of the different EC_{25} readings with VERIS 3100 and EM38

EC25 (mS/m)	Maximum (mS/m)	Minimum (mS/m)	Mean (mS/m)	Standard deviation	CV %
EC25 (VERIS-sh)	14,94	4,65	8,16	1,82	22,3
EC25 (VERIS-dp)	12,00	3,72	7,64	1,29	17,3
EC25 (EM38-h)	54,49	45,54	49,14	1,66	3,4
EC25 (EM38-v)	33,49	21,51	26,71	2,11	7,9

Table 2. Linear correlations between EC_{25} obtained with different sensors and methods

	EC_{25} (VERIS-dp)	EC_{25} (EM38-h)	EC_{25} (EM38-v)
EC_{25} (VERIS-sh)	1		
EC_{25} (VERIS-dp)	0,510	1	
EC_{25} (EM38-h)	0,337	0,536	1
EC_{25} (EM38-v)	0,218	0,401	0,712

Conclusions

This study showed that, while qualitatively similar, apparent soil electrical conductivity readings obtained with two different commercial sensors were quantitatively different. Highest correlations were generally found between EM38_h and EM38_v ($r=0.712$). In general, there were big differences between EM38 and VERIS readings, however the VERIS_sh and VERIS_dp readings were somewhat equal but there was a significant difference between EM38_h and EM38_v readings. We think that the low correlation values between the four methods resulted from different soil textures at different layers of our field (loamy sand in the upper 40 cm and sandy in the greater depths).

Variation in VERIS 3100 readings was more than EM38 readings. It means that the major variability in the soil properties of our field that affect ECa may be in the upper layers that are more heavily weighted in the VERIS 3100 ECa measurement. More uniformity in the soil properties of our field that affect ECa may be in the greater depths that are more uniform and less heavily weighted in the EM38 ECa measurement, as ECa readings by the EM38 were higher than ECa readings by VERIS 3100. Thus, some soil samples are needed to distinguish and calibrate the predominated soil property that has the most and large effect on site-specific ECa changes.

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