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Institute of Plant Nutrition and Soil Science

Holger Lilienthal
Jutta Rogasik
Christiane Itter
Ewald Schnug

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Comparison of different geo-electric measurement techniques to detect in-field variability of soil parameters

Holger Lilienthal, Christiane Itter, Jutta Rogasik and Ewald Schnug[1]

Abstract

The knowledge of the natural soil variability of agricultural land is an important base information for the application of site-specific management strategies. Geo-electric measurement techniques gain increasing popularity for mapping soil variability. So far only little systematically investigations on the correlation between measured signal and soil parameters have been performed. On the test sites of the FAL small scale plots with well-known soil parameters were sensed with two different geo-electric principles (electromagnetism, electric resistivity). The point measurements were interpolated to a grid by geostatistics and then correlated with the soil parameters. Due to their different measurement equipment the two geo-electrical principles supplied varying spatial information.

The conductivity measurements based on electromagnetism showed a strong correlation with soil texture, but buried metal objects in the soil heavily affected the signal. Also the dynamic range of the measurements and the variability in soil texture was very low. The measurements based on electric resistivity revealed a weak positive correlation with the pH value.

Since electromagnetic techniques react very sensitive to metal objects in the soil (power lines, drainage and water pipes) the measured electric conductivity data needed to be screened for outliers. But even the screened data showed structures of old facility lines, so the use of data, affected by buried metal objects in the ground is very questionable.

The measurements based on electric resistivity showed spatial patterns from fertilising experiments, additional research is needed to evaluate the correlation with soil nutrients.

Keywords: Conductivity, EC, site-specific management, soil, variability

Zusammenfassung

Untersuchung verschiedener geo-elektrischer Messverfahren zur Abbildung der räumlichen Variabilität bodenkundlicher Merkmale

Die Kenntnis der natürlichen, bodenbedingten Variabilität landwirtschaftlich genutzter Flächen ist eine wichtige Basisinformation für den Einsatz von teilflächenspezifischen Bewirtschaftungsmaßnahmen. Geo-elektrische Messverfahren erfreuen sich zunehmender Beliebtheit bei der Kartierung der Bodenvariabilität. Die Zusammenhänge zwischen Bodenparametern und Messsignal sind bisher jedoch wenig systematisch untersucht worden.

Kleinparzellen mit bekannten Bodenparametern sind mit zwei Messprinzipien (Elektromagnetismus und elektrische Widerstandsmessung) auf den Versuchsfeldern der FAL erfasst worden. Die Punktmesswerte wurden mit Hilfe geostatistischer Verfahren auf die Fläche interpoliert und mit den Bodenparametern korreliert. Die beiden Messverfahren lieferten aufgrund ihres verschiedenartigen Messprinzips unterschiedliche räumliche Strukturen.

Die Leitfähigkeitswerte, die mit Elektromagnetik gemessen wurden, wiesen einen starken statistischen Zusammenhang mit der Bodentextur auf. Allerdings wurde das Signal durch im Boden vergrabene Versorgungsleitungen stark beeinflusst. Zudem war der Dynamikbereich der Leitfähigkeitsmesswerte sowie die Variabilität der Bodentextur sehr niedrig.

Die Daten der elektrischen Widerstandsmessungen zeigten eine schwache positive Korrelation mit dem Boden pH-Wert.

Da Elektromagnetismus sehr empfindlich auf Metallobjekte im Boden reagiert (Stromleitungen, Drainage- und Wasserrohre) konnte die gemessene elektrische Leitfähigkeit nicht zur Kartierung der Texturvariabilität verwendet werden, da die Strukturen selbst nach Bereinigung der gestörten Messungen erhalten blieben.

Die Messungen des elektrischen Widerstandes zeigten allerdings räumliche Muster, die mit der Lage von Düngungsversuchen korrespondierten. Weitere Arbeiten sind erforderlich, um die Beziehungen zwischen elektrischer Leitfähigkeit und Nährstoffgehalten in Böden zu untersuchen.

Schlüsselwörter: Geo-Elektrik, elektrische Leitfähigkeit, teilflächenspezifische Bewirtschaftung

[1] Institute of Plant Nutrition and Soil Science, Federal Agricultural Research Centre (FAL), Bundesallee 50, 38116 Braunschweig/Germany

1 Introduction

In-field variability is the major factor influencing different yield levels. In the framework of precision agriculture the knowledge of the accurate location of these in-field variability is the key to address variable rate application as well as other site-specific management techniques. As precision agriculture is a very technology driven approach, several sensing and measuring techniques are available to locate and identify spatial variability, but there is only little knowledge about the relationships between sensed signal and agronomic relevant factors.

An increasing popular technique is the measurement of electric conductivity (EC), in order to evaluate site-specific variability as starting information for precision agriculture. Mc Neal et al. (1970) established a relationship between electrical conductivity and molar concentration of ions in the soil solution. The first application of electric conductivity measurements in agriculture was then used to map soil salinity (Rhoades et al., 1970). Later Williams et al. (1987) and Sudduth and Kitchen (1993) used EC to map the clay content in soils. Recently Cockx et al. (2004) used EC measurements to delineate nitrogen management zones.

Not knowing the relation between mapped classes and underlying factors, could lead to false interpretation in the simplest case, or to severe economical and ecological risks (e.g. wrong application of fertilizers) in the worst case.

In order to understand the influencing factors that produce an EC signal a short introduction into the background of geo-electric measurements is given.

1.1 Background of geo-electric measurements

The basic physical principles of geo-electric measurements are differences in the magnetic field or in the electrical potential. Since these sensing techniques are complex this introduction will only cover the very basic principles; as further reading Corwin and Plant (2005) is recommended.

The pathways of the current flow contribute to the EC of a soil are (Corwin and Lesch, 2005):

a) Liquid phase: Dissolved solids contained in the water which is hold in large pores
b) Solid/liquid phase: Exchangeable cations associated with clay minerals
c) Solid phase: Soil particles

The gaseous phase has no impact on EC since air reacts as a good isolator.

The measured EC is a product of static and dynamic factors. The main static factor is clay, whereas organic matter content as well as soil salinity are changing properties, but at a long term scale. The dynamic factors are soil water content (water saturation) and temperature since the electrolytic conductivity increases with temperature (Corwin and Lesch, 2005). The variation in EC response is related to changes in the ionic concentration of the liquid soil phase. Soil parameters such as moisture content, amount and type of ions in the soil, water amount and type of clay in the soil matrix are correlated to the response of the system (Doolittle et al., 1994).

Corwin and Lesch divide between

a) texture driven systems, were the spatial patterns remain consistent over time. In these systems the EC signal is only affected in the magnitude of the measurement (Johnson et al., 2003) and
b) salt driven systems, were the amount of dissolved salt lead to in increase of the EC signal. These systems exist mainly in arid and semi-arid regions.

According to Johnson (2003) texture driven systems can change to salt driven systems by fertilisation. In the temperate climate zones the EC is mainly affected by texture.

In practical agriculture mainly two EC sensing systems are used: The EM38 by Geonics[1] and the Veris 3100 by Veris Technologies[2].

1.2. Electromagnetism

The principle of electromagnetism is used to measure the electric conductivity with the EM38 equipment (Lück et al., 2002). The device is composed of a transmission and a receiver coil installed in a non-conductive (wooden or plastic) bar. These coils induce circular eddy-current loops into the soil. The magnitude of these loops is direct-

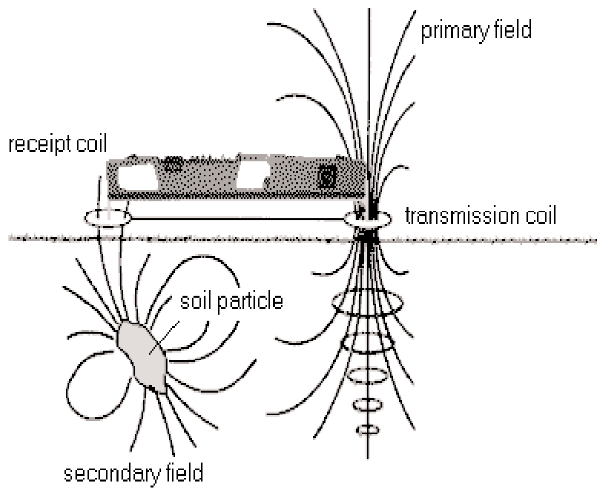


Fig. 1:
Measurement principle of electromagnetism (EM38 equipment)

[1] Geonics Limited (Canada) (www.geonics.com). Product identification is provided solely for the benefit of the reader and does not imply the endoresemt of the FAL.

[2] Veris Technologies (USA) (www.veristech.com). Product identification is provided solely for the benefit of the reader and does not imply the endoresemt of the FAL.

ly proportional to the electric conductivity (Corwin and Lesch, 2005). The transmission coil induces a primary electromagnetic field into the soil. The soil matrix produces a weak secondary field; the receipt coil registers this signal.

The transmission coil is working with an alternating current and generates a time-varying magnetic field in the soil. This magnetic field causes current to flow in the soil and generates a secondary magnetic field. The ratio of the secondary to the primary magnetic field is proportional to the ground conductivity of the soil (McNeill, 1980; Sudduth et al., 1993).

There is no contact between the device and soil during the measurement, so this technique is non-destructive and can be used also when a low vegetation canopy is present.

The penetration depth of the signal depends on the distance above ground, the used frequency, the conductivity of the soil and the spatial set-up of the coils (Lück et al., 2000). Vertically arranged coils can penetrate up to 1.5 m into the ground, horizontally arranged coils 0.75 m. In the presented experiments horizontally arranged coils were used.

1.3 Electrical resistivity

Electrical resistivity as a measurement principle is used by the Veris 3100 equipment (Corwin and Lesch, 2005). An electrical current is introduced into the soil by electrodes and the difference in the current flow potential is measured at two potential electrodes. The depth of penetration and the measured volume increases with the electrode spacing. Using several electrodes allows to sense different depth levels of the soil. This invasive technique needs good contact between soil and electrodes. In dry and stony soils the measurements are less reliable since the contact to the soil can be interrupted, resulting in measurement gaps (Corwin and Lesch, 2005).

Compared to the techniques using electromagnetism contact with the soil is needed. The electrical resistivity measurements are invasive, so the equipment can damage the plant canopy.

The EC equipment needs to be set up with DGPS-devices in order to record the correct geographic position of each measurement.

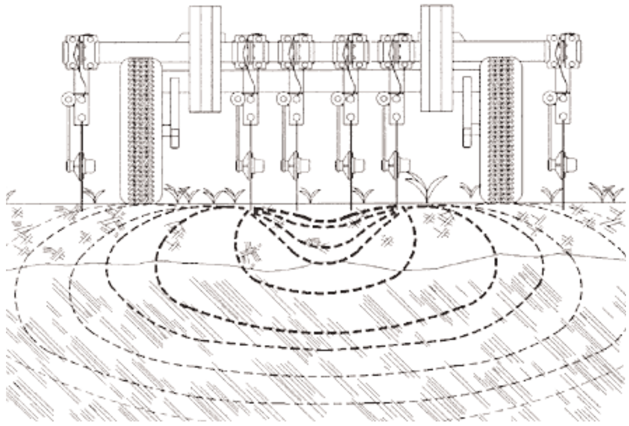


Fig. 2:
Measurement principle of electrical resistivity (Veris 3100 equipment) (Lund et al., 1999)

2 Material and Methods

In this case study two different EC sensors have been used to map the test sites of the Federal Agricultural Research Centre in Braunschweig, Germany (Location: 10°25’50 N ; 52°17’2 E). For several of the test plots a large set of information on soil texture and other agronomical parameter is available.

The EC measurements were conducted on the 3rd (EM38) and on the 21st (Veris 3100) of March 2005 respectively. Parts of the test site have been measured again with a handheld EM38 device on the 8th of April 2005. The soil moisture conditions had been at field capacity at all dates.

Table 1 gives an overview of the measurement set-up and weather conditions.

The raw data has been manually screened and corrected for obvious data errors (e.g. no GPS position or no sensor reading) and interpolated to a 1 by 1 meter grid by simple Kriging interpolation algorithm.

The soil data of two plot test sites (FV 4, FV 36) has been implemented into a geographic information system (GIS) and the corresponding EC values of the EM38 and Veris 3100 measurements have been extracted for each plot.

Table 1:
Basic description of the electric conductivity measurements on the test sites of the FAL

	EM38 (vehicle mounted)	Veris 3100	EM38 (handheld)
Date	03.03.2005	21.03.2005	08.04.2005
Mean temperature	-2.2 °C	3.7 °C	7.6 °C
Soil depth	0 – 75 cm	0 – 30 cm	0 – 75 cm
Test site	FV 4, FV 36	FV 36	FV 4, FV 36
Coordinates	10°25’50 N ; 52°17’23 E		

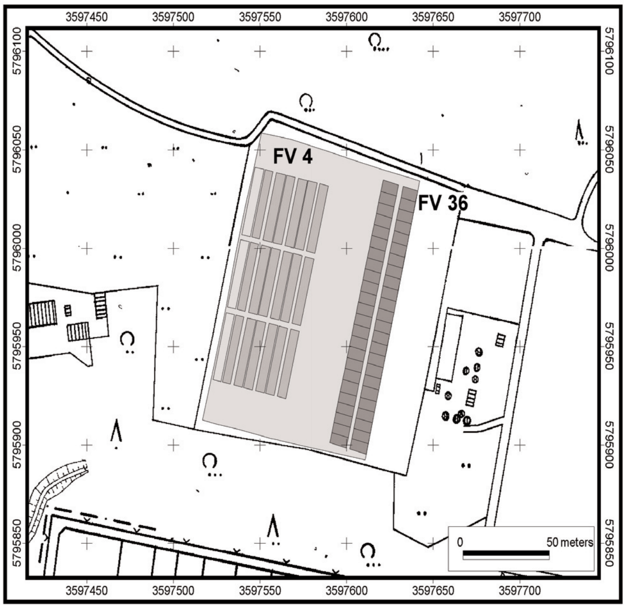


Fig. 3:
Plot test sites at the Federal Agricultural Research Centre (FAL).

Test site FV 4 is separated into 18 plots with the dimension of 5.0 by 38.0 m; the test site FV 36 consists of 48 plots with the dimension of 9.0 by 5.7 m (Fig. 3). The total observed area is 1.4 ha. Figure 3 gives an overview of the test sites.

The soil of the test sites is mainly composed of large portions of silt and sand with relatively low clay content. The soil pH is acidic to slightly acidic (Table 2).

Table 2:
Descriptive statistics for soil parameters of the plot test sites of the FAL.

Texture [0 – 60 cm]	FV 4 [n = 18]	FV 36 [n = 48]
Sand [%]		
Min	36.3	36.1
Max	50.3	57.7
Mean	43.6	45.2
Median	42.9	44.3
Silt [%]		
Min	44.4	36.5
Max	57.3	56.6
Mean	50.5	48.1
Median	51.0	49.0
Clay [%]		
Min	4.8	5.6
Max	6.9	7.6
Mean	6.1	6.7
Median	6.2	6.7
pH		
Min	4.9	5.3
Max	5.6	6.3
Mean	5.2	5.9
Median	5.3	5.9

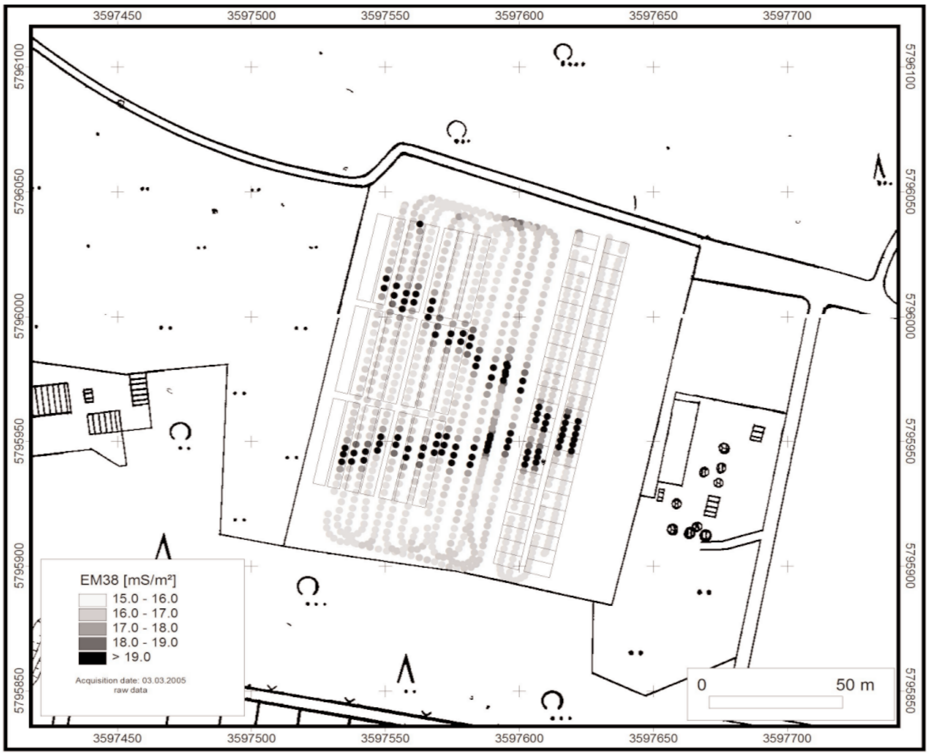


Fig. 4:
Raw data of the EM38 electrical conductivity measurement of the 3rd of March 2005 on the test sites of the FAL.

The EC-values have been extracted for the entire test plots from the interpolated data. The soil data and the EC values have been correlated using the statistical software package SPSS®.

3 Results

The raw data of all EM38 measurements showed a strong distortion (Fig. 4). Lück et al. (2000) report of similar spatial structures caused by metal objects buried in the ground. The metal objects have a much stronger impact on the measured EC-values, than the tested soil. Lück et al. (2000) recommend to exclude the data from further analysis.

It can be assumed that old facility lines for water or energy supply of a former biogas experiment might cause these structures, but additional diggings are required.

The data has been manually screened and the distorted measurements have been excluded for further processing.

Table 3 shows the differences in the descriptive statistics between raw and screened EM38 data. The range of the EC values is much smaller after excluding the distorted data (2.1 mS/m^2 for the screened data compared to 11.6 mS/m² for the raw data).

The data was tested for normal distribution by computing a Q-Q-Plot. After screening, the EC data can be accepted as normal distributed (Fig. 5, right) and interpolated by using a simple Kriging algorithm.

Table 3:
Descriptive statistics for the raw and screened EM38 electric conductivity measurements on the test sites of the FAL

03.03.2005	EM38 (raw) [mS/m^2]	EM38 (screened) [mS/m^2]
Min	15.1	15.1
Max	26.7	17.2
Mean	16.7	16.0
Median	16.0	15.9

Fig. 5:
Q-Q-Plot for the raw (left) and the screened (right) data of the EM38 electrical conductivity measurement of 3rd of March 2005 on the test sites of the FAL

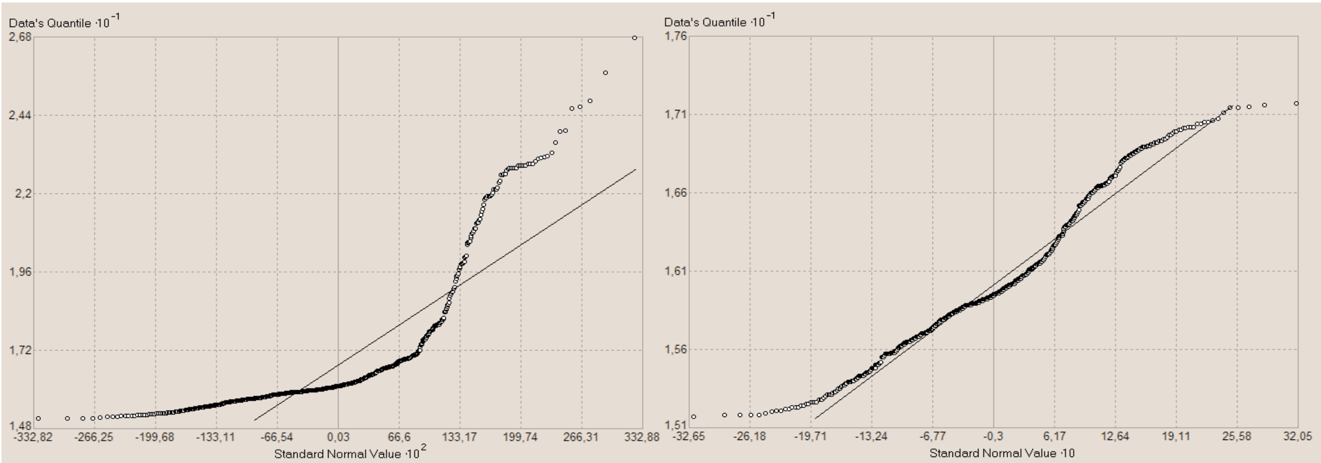


Table 4:
Kriging model parameters for the electrical conductivity measurements on the test sites of the FAL

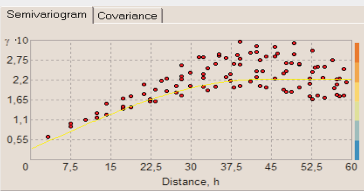
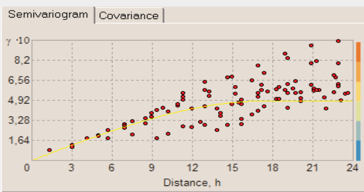
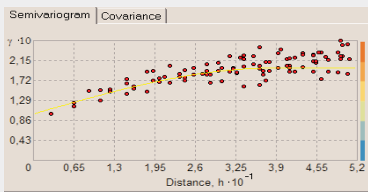
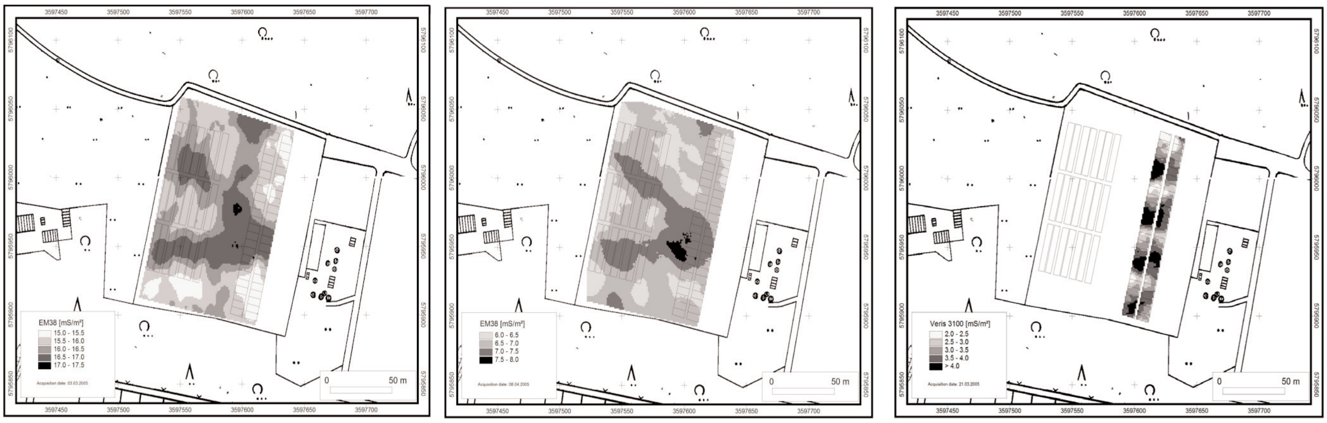
	EM38 (vehicle mounted)	Veris 3100	EM38 (handheld)
Date	03.03.2005	21.03.2005	08.04.2005
Kriging model	Spherical	Spherical	Spherical
Nugget	0.027779	0	0.099701
Partial sill	0.193860	0.48679	0.098949
Range distance	43 m	24 m	51 m
Semi-Variogramm			

Fig. 6:
Interpolated EC-Maps for EM38 (left: measurement from 03.03.2005, middle: measurement from 08.04.2005) and Veris 3100 (right: measurement from 21.03.2005), measured on the test sites of the FAL



The parameters of the Kriging interpolation can be found in table 4.

The variogram analysis (Table 4) showed that the range distances of both electromagnetic measurements (EM38) are similar (43 m, 51 m respectively). The range for the electrical resistivity measurement (Veris 3100) is much smaller (24 m). As regards content this means that points up to a distance of 43 m / 51m for EM38 and 24 m for Veris 3100 are auto-correlated.

The interpolated EC-Maps for the two EM38 and the Veris 3100 measurements are presented in Figure 6.

The electromagnetic measurements (EM38) taken on different dates yield in similar spatial structures after interpolation (Fig. 6, left and middle). The structure of the interpolated electrical resistivity measurement (Veris 3100) provide a different spatial structure compared to the electromagnetic measurements (Fig. 6, right).

Based on the interpolated EC-maps, the conductivity values for every plot were extracted and averaged in order to correlate them with the soil data that was available for each plot. Table 5 represents the results of the correlation analysis.

The electric conductivity measured by electromagnetism (EM38) revealed strong correlations on an equal level to sand, silt and clay (Table 5). The electrical resistivity measurement (Veris 3100) only showed a weak correlation to soil pH value.

Table 5:
Results of the correlation analysis of EC and soil texture data

	EM38 (vehicle mounted)	Veris 3100	EM38 (handheld)
Date	03.03.2005	21.03.2005	08.04.2005
Soil depth	0 – 75 cm	0 – 30 cm	0 – 75 cm
Sand	0.931**	0.429	0.929**
Silt	0.941**	0.310	0.932**
Clay	0.943**	0.509	0.964**
pH	0.208	0.554**	0.176

** Correlation is significant at the 0.01 level (2-tailed)

4 Discussion

The electromagnetic measurements (EM38) showed a strong correlation with sand, silt and clay, but for all soil types at a similar level (Table 5).

No correlation with texture could be found for the electrical resistivity measurement (Veris 3100), just a weak positive correlation to soil pH could be identified. The results have to be evaluated carefully since the texture variation within the plot test sites are not very strong (Table 2), which is of course wanted for plot test sites. Also the range of the EC-values is not very large (2 mS/m^2, Table 3).

The spatial pattern of both EM38 measurements were very similar for the different acquisition dates (Fig. 6), this corresponded well to other EC-studies (Lück et al., 2000) and showed the robustness of the sensor. The absolute values of both EM38 measurements were not the same. This variation in the magnitude of the measurements can be explained by different heights above ground at both measures. The first EM38 measurement (3.3.2005) has been a vehicle-mounted device, whereas the second EM38 measurement (08.04.2005) has been a handheld device carried 30 cm above ground. In the latter case the influence of the air needed to be taken into account (Lück et al., 2000). Also a temperature correction is needed to compare absolute EC values, this has been neglected since only the structural patterns were of interest.

The major drawback of EM38 measurements is the sensitivity of the sensor to metal. Metallic facility lines had a very strong impact on the EC-measurement, and even after screening the data, which results in a reduction of the range of the data from 11.6 mS/m^2 (raw data) to 2.1 mS/m^2 (screened data), the structure of those lines was still visible in the resulting EC-maps. This raises the question, if distorted EM38 measurements are usable at all.

The electrical resistivity data (Veris 3100) showed only weak correlations with the pH-values of the test site. Also the spatial pattern was very different compared to the EM38 measurements. But the spatial structure followed the borders of a fertilisation trial that has been performed on plot FV 36. This might be a first hint that electrical resistivity data is much more sensitive to different fertiliser levels. This will be examined in the near future.

5 Conclusion

The use of EC-maps as an indicator for variability is not a trivial topic. Most farmers and advisors neither have the statistical background nor the technical facilities and of course not the time to produce correctly interpolated EC-maps.

In this experiment a very homogeneous field has been measured. Due to the low variability in texture and the small range of EC values a high correlation between texture and EC values could be computed. Further analysis in more heterogeneous fields is needed to see, if EC measurements are suitable to map in-field texture variation. Using the raw data directly for field management could lead to false interpretation in the simplest case, or to severe economical and ecological risks (e.g. wrong application of fertilizers) in the worst case.

The electromagnetic (EM38) and electrical resistivity (Veris 3100) techniques delivered different information; in the research work presented here the results of the electromagnetic measurements (EM38) were affected by texture (keeping in mind the variability was very low), whereas there are first hints that electrical resistivity data could deliver information on soil chemical composition, but further research is needed.

EC measurements as base information for precision agriculture should be used very carefully, since the signal to parameter relation are not clear by now. The range of the measurement values of the resulting maps need to be watched closely, since many mapping programs produce a standard number of classes (e.g. 5 classes). Maps produced from a data set with a small range of the EC-values will pretend much more variability than is present in reality.

Acknowledgement

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