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CALIBRATION OF ELECTROMAGNETIC INDUCTION MEASUREMENTS TO SURVEY THE SPATIAL VARIABILITY OF SOILS

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ABSTRACT

Measurements of the electromagnetic induction by EM38 were validated on three field sites and on the farm level with detailed investigations of soil texture, soil water content and the electrical conductivity of the soil solution. Calibration was performed for individual soil horizons. Clay content and water content in 0-90 cm soil depth were the parameters most closely related to the apparent electrical conductivity with r^2-values between 0.31-0.67 for clay and 0.31-0.64 for water content. Other soil parameters like silt and sand content or the electrical conductivity of the soil solution were in general not related to the apparent electrical conductivity. Values of the electrical conductivity in the horizontal and vertical mode correlated with each other (r^2=0.93). The results point out that relevant information for site-specific management can be obtained by this non-contacting method.

INTRODUCTION

Electromagnetic induction represents a fast non-contacting method to get possibly information about the field heterogeneity of soil texture and water content. Measurements of the apparent electrical conductivity represent the influence of several factors, including soil texture and organic matter content, soil salinity, soil water content and soil bulk density. Detailed calibration work has been performed in the last three years to further develop the application of this technique which has previously been used mainly for salinity mapping. Whereas the influence of salinity plays normally a minor role under temperate conditions, information about clay content (de Jong et al. 1979) and water content (Kachanosky et al. 1988) can be derived. This study aimed at a better understanding of the contribution of individual factors to the apparent electrical conductivity.

Calibration work was performed on different levels, on the field level, and on the farm level, and a survey was conducted within the framework of a nation-wide German project in geographic regions of various origins as presented in our companion paper (Neudecker et al. 2001). This paper addresses the point- and site-specific calibration obtained by comparing measurements of electromagnetic induction in the horizontal and vertical mode with detailed measurements of soil texture, soil water content, soil solution salinity, soil bulk density and derived parameters as available water content in the rooting zone.

MATERIALS AND METHODS

The investigations were carried out on field sites in the tertiary hills of Bavaria, Germany. The study sites are part of on-going multidisciplinary Precision farming projects (IKB, FAM). The first study included heterogeneous fields of three different sites, Kleinbachern, Krohberg and Sieblerfeld, 1.8, 5 and 4.5 ha in size, nearby Freising in Bavaria, and the second study involved a farm situated in Scheyern where representative raster points were selected covering an area of about 100 ha.

On the Kleinbachern field 88 grid points were chosen for an extensive soil sampling in three soil depths 0-30, 30-60 and 60-90 cm. Soil samples were taken with an automatically driven auger, three cm in diameter. Soil samples were analysed for soil texture according to the German classification (clay, silt and sand, subdivided in the following fractions <2, 2-20, 20-63, 63-200, 200-630, 630-2000 μm) by the pipette analysis and sieving, gravimetric water content by weighing before and after oven-drying at 105 °C, soil solution salinity was approximated by measuring the electrical conductivity in a 1:1 dry soil/water solution extract. Measurements of the apparent electrical conductivity were performed with an EM38 (Geonics Limited, Mississauga, Ontario) in the vertical and horizontal mode. Details of the method are described in other studies (McNeill 1980). Precautions were taken to avoid any warming up of the sensor by encapsulating the sensor and frequent re-calibration. Previous work showed a significant possible influence due to the warming up of the sensor. This aspect has not received the necessary attention in other studies and needs specifically to be considered in the warmer season. Soil temperature which varies only insignificantly during measurements was recorded in 30 cm soil depth on selected grid points and converted according to Durlesser (1999) in a depth-averaged temperature. Results were expressed on a 25 °C basis. Measurements of the apparent electrical conductivity were obtained in different seasons in 1998 and 1999 at different degrees of soil water saturation. Comparable investigations were carried out on the other two fields, Sieblerfeld (n=21) and Krohberg (n=34) in 1999. Gravimetric results were also converted to volumetric values based on detailed soil mapping at selected sites. Correlation results between soil texture and EC_a, however were not improved.

The second study was conducted on representative sites of the farm Scheyern. On this site detailed soil investigations have been carried out on a 50x50 m grid on more than 500 grid points. For the purpose of our study 49 sites were chosen representing the range of soil texture. The available information included detailed information about soil texture, organic matter content, and apparent soil bulk density. Values of soil water content and soil solution salinity were determined in April and June 2000. In contrast to the previous study salinity was directly determined in the soil solution with a Sigma probe (Delta-T Devices Ltd., Cambridge, UK). This is an accurate way to obtain information about soil solution salinity in temperate regions (Hilhorst and Balendonck, 1999). Linear regressions between the investigated parameters and the apparent electrical conductivity were calculated with the JMP program (SAS Institute Inc., Cary, NC, USA) and were expressed as coefficients of determination (r^2). Detailed analysis were conducted for the differing soil depths, averaged depths, and the soil information weighted according to the sensor signal distribution. Semi-mechanistic or empirical relationships between the influencing variables and EC_a have been described in the literature and were tested for their validity. This included equations according to Günzel (1994) and Auerswald (2000, personal communication). The latter is a simple empirical relationship which considers the soil information on a volume basis.

RESULTS

Measurements of the apparent electrical conductivity in the horizontal and vertical mode correlated strongly (r^2=0.93) with each other. The depth weighted values of clay, silt, sand, and water contents from July 1998 (n=94) and March 1999 (n=88) varied between 7-32%, 4-

53%, 28-79%, 11-24%, and 14-24 %, respectively. Clay content (r^2=0.38) and gravimetric water content (r^2=0.39) averaged over 0-90 cm soil depth were best correlated to ECa measured in the horizontal mode in July 1998 (TABLE 1). Results were slightly better than for the vertical mode. Similar results for clay contents averaged over 0-90 cm soil depth (r^2=0.38) were found for the March measurements in 1999 (r^2=0.41).

TABLE 1. Correlation (r^2) between the apparent electrical conductivity of the soil measured in the vertical and horizontal mode by Em38 and various soil parameters (clay, silt, sand, water content, EC soil solution) measured in three different soil depths at Kleinbachern in July 1998 (n=94). Correlation values were also calculated for averaged values of the 0-90 cm soil depth and the clay content averaged over 0-90 cm depth according to the depth distribution function of the measurement device (0-90w). Levels of significance are indicated. *,**,***, n.s. Significant at P<0.05, 0.01, 0.001, and non-significant, respectively.

Date Soil depth	Mode	Clay ($\%_g$)	Silt ($\%_g$)	Sand ($\%_g$)	Water content ($\%_g$)	$EC_{soil\ solution}$ ($mS\ cm^{-1}$)
July 1998						
0-30	Em_v	0.13^{***}	$0.04^{n.s.}$	0.16^{***}	0.22^{***}	
	Em_h	0.38^{***}	$0.01^{n.s.}$	0.08^{**}	0.05^{***}	
30-60	Em_v	0.17^{***}	$0.03^{n.s.}$	0.11^{**}	0.16^{***}	
	Em_h	0.12^{***}	$0.02^{n.s.}$	$0.00^{n.s.}$	0.14^{***}	
60-90	Em_v	0.22^{***}	$0.03^{n.s.}$	0.08	0.18^{***}	
	Em_h	0.08^{**}	$0.02^{n.s.}$	$0.00^{n.s.}$	0.07^{*}	
0-90	Em_v	0.33^{***}			0.26^{***}	0.11^{**}
	Em_h	0.38^{***}			0.39^{***}	0.07^{*}
0-90w	Em_v	0.27^{***}			0.27^{***}	
	Em_h	0.35^{***}			0.34^{***}	

Depth weighting according to the signal distribution of the sensor did not enhance or improved only slightly the relationship. In 1998, a comparable relationship of EC_a measured in the horizontal mode was also observed for the clay and gravimetric water content measured in 0-30 cm soil depth. Silt and sand content and the electrical conductivity of the soil solution were not correlated to EC_a. Non-linear regression showed that this relationship could partly be improved, e.g. for the water content in 0-90 cm soil depth to r^2=0.51. EC_a measurements were correlated to available water capacity with r^2=0.31. Yield showed only a weak correlation to EC_a in 1998.

Similar results with partly improved relationships were obtained on the other fields, Krohberg and Sieblerfeld (TABLE 2). The depth weighted range of clay, silt, sand and water content used for the correlation to the vertical mode of the apparent electrical conductivity varied between 8-36%, 19-60%, 12-70%, and 9-36 % in Krohberg, and 5-27 %, 12-57 %, 21-83 %, and 9-37 % in Sieblerfeld, respectively. EC_a, measured in the horizontal mode, and clay content in 0-90 cm depth correlated with r^2=0.67 in Krohberg and r^2=0.59 in Sieblerfeld. Expressing the clay content on a volume basis improved slightly the relationship on the Sieblerfeld (r^2=0.72). Inclusion of other soil texture classes in multiple regression equations did not improve the relationship. Sieblerfeld was the only site where a relationship to the single parameters silt or sand was found. Water content in 0-90 cm depth was best correlated to EC_a measured in the horizontal mode (r^2=0.64) in Sieblerfeld, no such relationship was observed on Krohberg. The electrical conductivity measured directly in the soil solution was not related to EC_a.

Results from the second study on farm Scheyern are given in TABLE 2. Depth-weighted clay, silt, sand contents varied from 12-42 %, 14-71%, 6-75 %, and water contents in April and June from 15-33 % and 11-31 %, respectively. The following relationships between EC_a measurements, conducted in the vertical mode in April 2000, and soil parameters in 0-90 cm soil depth were found and are indicated in brackets: For clay (r^2=0.43), sand (r^2=0.33), gravimetric water content (r^2=0.34) and for soil solution salinity (r^2=0.55). The correlation was weak for the June measurements except for the water content (r^2=0.34).

The two approaches tested to describe more mechanistically based on soil information the output signal of the sensor showed in general comparable results. The goodness of fit for EC_a measurements in the horizontal mode based on the equation of Günzel (1994) was for the site Scheyern in April, r^2=0.54, for Scheyern in June, r^2=0.29, for Sieblerfeld, r^2=0.38, and for Krohberg, r^2=0.07. For these sites and the measurements conducted in the same mode the equation proposed by Auerswald (2000, personal communication) gave r^2=0.50, 0.32, 0.45, 0.15, respectively. A better fit to the vertical mode measurements was found on Sieblerfeld with r^2=0.69 and r^2=0.72 for the two equations. Expressing the parameter cation exchange capacity in the Günzel equation simply by the clay content resulted in a significant improvement for Scheyern in April (r^2=0.65) and in June (r^2=0.49), whereas the results were not changed on the other sites.

DISCUSSION AND CONCLUSIONS

Measurements of the apparent electrical conductivity can be used to indicate the spatial and depth variation in clay contents and water contents. Coefficients of determination of linear regressions between clay content in 0-90 cm soil depth and EC_a in the vertical mode were on the field level in Kleinbachern in July 1998, r^2=0.38, in Kleinbachern in March 1999, r^2=0.44, in Sieblerfeld in April 1999, r^2=0.44, in Krohberg in April 1999, r^2=0.39, and on the farm level in Scheyern in April 2000, r^2=0.42, and in June 2000, r^2=0.20. Whereas no significant difference between temporal measurements was found in Kleinbachern, drier conditions in Scheyern in June 2000 most likely resulted in a weak relationship. A comparable goodness of fit was found for the water content in 0-90 cm soil depth in Scheyern in April and in June 2000 (r^2=0.34 and 0.38), and in Kleinbachern in July 1998 (r^2=0.39). No relationship to the water content was found on the other two fields in Sieblerfeld and Krohberg measured in the horizontal mode by EM38. These results might be influenced by the range of variation and the number of samplings. The number of investigated points varied between n=21 to n=94. The results are probably also influenced by the frequency of composite soil samplings per investigated grid point. In this study the number was limited to n=2. The inherent small scale variability influences the degree to which point samplings can reflect information on the scale of the electrical conductivity probe which is influenced by the distance the electrical coils are separated at.

In general, all other investigated soil parameters (silt, sand) were found to be non-significantly related to the measurements of the apparent electrical conductivity. A significant relationship was found between EC_a and the electrical conductivity in the soil solution in Scheyern. Better relationships are to be expected if the range includes higher salinity values. On this site the range varied between 0.9 to 2.3 mS cm^{-1}, whereas the values were rather lower in the other field studies.

Measurements of the electrical conductivity performed in the horizontal and vertical mode were in general strongly related to each other. Multi-temporal measurements indicated that the general pattern did not vary on the individual field sites or the farm level, however eventually the correlation to the soil parameters was altered.

TABLE 2. Correlation (r^2) between the apparent electrical conductivity of the soil measured in the vertical (Em_v) and horizontal (Em_h) mode by Em38 and various soil parameters (gravimetric or volumetric content of soil texture, gravimetric and volumetric soil water content, electrical conductivity of the soil solution at different sites. The number of measurements (n) and the significance level is indicated. *,**,***, n.s. Significant at $P<0.05$, 0.01, 0.001, and non-significant, respectively.

	Scheyern April 2000		Scheyern June 2000		Sieblerfeld April 1999		Krohberg April 1999	
Number of measurements	49	49	49	49	21	21	34	34
Mode of measurement	Em_v	Em_h	Em_v	Em_h	Em_v	Em_h	Em_v	Em_h
Clay ($\%_g$)	0.43^{***}	0.38^{***}	0.21^{**}	0.13^{*}	0.44^{***}	0.67^{***}	0.39^{***}	0.59^{***}
Clay ($\%_v$)	0.35^{***}		0.13^{**}		0.47^{***}	0.72^{***}	0.28^{**}	0.47^{***}
Clay+fine silt ($\%_g$)	0.45^{***}		0.23^{***}		0.48^{***}	0.70^{***}	0.15^{*}	0.35^{***}
Silt ($\%_g$)	0.20^{**}	0.27^{***}	0.11^{*}	0.10^{*}	0.46^{***}	0.60^{***}	$0.01^{\text{n.s.}}$	$0.11^{\text{n.s.}}$
Sand ($\%_g$)	0.34^{***}	0.37^{***}	0.18^{**}	0.13^{*}	0.49^{***}	0.69^{***}	0.12^{*}	0.30^{***}
Water content ($\%_g$)	0.34^{***}	0.32^{***}	0.38^{***}	0.49^{***}	$0.19^{\text{n.s.}}$	0.64^{***}	$0.04^{\text{n.s.}}$	0.16^{*}
Water content ($\%_v$)	0.35^{***}		0.38^{***}		0.19^{*}	0.64^{***}	$0.04^{\text{n.s}}$	0.16^{*}
$Ec_{\text{soil solution}}$ (mS cm^{-1})	0.54^{***}†		0.29^{***}†		0.23^{*}‡	$0.16^{\text{n.s.}}$	$0.00^{\text{n.s}}$‡	$0.05^{\text{n.s.}}$‡

† electrical conductivity determined in soil solution
‡ electrical conductivity determined in 1:1 soil/water extract

Our further calculations indicated an interesting potential of a modified version of the Günzel equation to describe the relationship between EC_a and relevant soil parameters. There is a strong need to develop better and more mechanistically oriented models for this purpose. Our current achievements focus on on-site investigations of the soil water content by TDR principles. Volumetric soil samples are obtained with a recently developed automatic auger which may further indicate the soil bulk density after oven-drying. However, a sensitivity analysis did not yet indicate a need for volumetric soil water content measurements, whereas such information on a volume basis may be desirable for clay content as used in the model calculations. Measurements of soil solution salinity could be performed on-site with a Sigma probe. Current achievements focus on simplified determinations of the clay content in the laboratory and in the field by Near Infrared Spectroscopy. This may lead to the development of on-site measurements of all relevant parameters.

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