3. Europ. Conference Precision Agriculture, Montpellier, 16.-20.06.01, 349-354 **494**

ESTIMATING SOIL MOISTURE DISTRIBUTION FOR CROP MANAGEMENT WITH CAPACITANCE PROBES, EM-38 AND DIGITAL TERRAIN ANALYSIS

J. BOBERT

Chair of Plant Nutrition, Department of Plant Sciences, Technical University of Munich.
85350 Freising, Germany
E-mail: bobert@toax.de

F. SCHMIDT

Institute for Geodesy and Geoinformatics, Department for Land Cultivation and
Environmental Protection, University of Rostock. 18051 Rostock, Germany

R. GEBBERS

Centre for Agricultural Landscape and Land Use Research. 15374 Müncheberg, Germany

T. SELIGE, U. SCHMIDHALTER

Chair of Plant Nutrition, Department of Plant Sciences, Technical University of Munich.
85350 Freising, Germany

ABSTRACT

A method is described to include digital terrain analysis and two sensor based methods for detection of soil texture and soil water content into the estimation of the soil moisture distribution. Soil moisture was monitored with capacitance probes and by determination of the gravimetric soil water content. With the EM-38 sensor spatial information about the soil texture was obtained. The digital terrain analysis was based on 5 m and 2 m raster DEM. The software package TAPES was used to derive several topographic attributes, including the topographic wetness index $\ln(As/\tan\beta)$. Correlations between $r=0.5$ and $r=0.9$ could be found between wetness indices and soil moisture measurements.

INTRODUCTION

Water is one of the most import factors for the crop growth. In rain-fed agriculture the amount and distribution of precipitation is very decisive for crop yield. Beside the temporal pattern of precipitation the spatial distribution of soil moisture within the field determines the crops water supply. Physical and chemical soil properties as texture or organic C-content are important parameters to estimate the amount of plant available soil water. The influence on field topography for the distribution of soil moisture is another important factor. This article describes a method to combine digital terrain analysis and two sensor-based methods for detection of soil texture and soil water content into the estimation of spatial and temporal soil moisture distribution for site-specific crop management.

MATERIALS & METHODS

Study Sites

The study was carried out on two fields in Germany. The selected plots represent regions with different climatic conditions and soil formation.
Test Site Wulfen: Wulfen is situated in the Eastern part of Germany 100 km southeast from the highland ranges of the Harz. The average precipitation is about 450 mm per year. 12 monitoring sites were selected within a field with very heterogeneous loess soils with texture ranging from sandy to clayey loam. The relief consists of gentle slopes from North to South. At the monitoring sites the volumetric water content was measured with capacitance probes. The probes were calibrated by determining gravimetric water content and bulk density as well as by pedo transfer functions. For validation of the capacitance probes one system was installed in a weighing lysimeter in Berlin. The correlation between the capacitance probe and the lysimeter values was r=0,97. Depending on the calibration function the accuracy of the absolute data vary with different soil types. Nevertheless relative data showed a good correspondence to the volumetric soil water content. Work is on the way to establish calibration functions for a range of German soils. A map of the apparent electrical conductivity (ECa) was produced from the conductivity data of the soil at field capacity. Additionally multi-temporal measurements of ECa were conducted at the monitoring sites.

Test Site Kassow is located in the North-East of Germany, 30 km south of the Baltic Sea. Two sub-areas were monitored. Twenty monitoring sites for multi-temporal gravimetric determination of soil water content extended on a 600 m long catena, ranging from 23 to 30 m and included an east-west and a north-south axis. Sixty raster locations were on an area of the same field that is dominated by short-range variations in relief. The landscape is a slightly undulating ground moraine area, dominated by glacial till, sedimented during the last ice age. The main soil texture is loamy sand; sand and loam are also present. The average annual precipitation is around 550 mm and the mean temperature is 8.2° C

Soil Moisture Measurement

Soil moisture was monitored with capacitance probes and by determining the gravimetric soil water content on the test site Wulfen and gravimetric determinations on the test site Kassow. With the EM-38 sensor, spatial information about the soil texture was derived on both areas and validated with specific soil sampling. The precipitation data were obtained from nearby weather stations. Soil moisture was measured on 17 times between March and July 2000 for Wulfen and three times between March and September 2000 for Kassow.

The Wetness Index Concept

The Wetness Index ln $(A_s/\tan\beta)$ is a so-called compound terrain attribute and consists of the specific catchment area A_s and the local slope gradient $\tan\beta$. The concept was first presented by Beven & Kirkby (1979) and further developed and incorporated into various terrain analysis software in the 1990ies (Moore et al., 1993; Barling et al., 1994; Wilson & Gallant, 2000).
The Wetness Index concept is based on the assumption that topography controls the movement of water in sloped terrain and, thus, the spatial pattern of soil moisture distribution. High values of the Topographic Wetness Index (TWI) will be found in converging, almost flat terrain, low values are typical for steep, diverging areas. The concept is only valid for

areas with significant amount of lateral water movement and uniform vertical flow (i.e. homogeneous distribution of soil conditions). Barling et al. (1994) demonstrate that the hydraulic conductivity declines with depth and thus even in gently sloped areas the piezometric head can be assumed as parallel to the terrain surface. Wetness indices tend to concentrate high values close to calculated flow channels in the bottom of valleys. Whereas this is true for the hill slope scale with high relief, for areas with low relief, a low-pass filter can make the pattern look more realistic. Some variations of the Wetness Index can consider varying soil conditions by additional parameters like the saturated hydraulic conductivity that mainly controls vertical flow. If no detailed soil maps are available, the simple steady-state Wetness Index $\ln (A_s/\tan\beta)$ can predict areas of first soil moisture saturation and dry zones best.

For the calculation of the TWI, the only base data is a digital elevation model (DEM). Since wetness indices are sensitive to small variations in convergence and divergence of terrain, especially in flat areas, a high quality DEM is needed (see Schmidt, this issue). For the results presented in this study, the height accuracy of the DEM is around 10 cm in a 2 m grid (based on a laser scanning campaign for Kassow) and a 5 m grid (based on a RTK-GPS survey for Kassow and Wulfen) respectively. The terrain attributes presented here were derived with the TAPES-G package (Wilson&Gallant 2000).

Further data sources

Aerial and near infrared photos support the interpretation of the results. Yield data were obtained by mapping the yield during harvesting as well as with manual sampling at specific locations.

RESULTS

Study Site Wulfen

Fig. 1(a) shows the relative potential soil moisture distribution as predicted by the TWI. The high values indicate converging parts of the terrain and depressions (as shown by the contour lines of the DEM). Pearson's correlation coefficient was used as an indicator for the goodness of the Wetness Index prediction. The highest correlations with soil moisture measurements were found at a depth of 20-60 cm (Fig. 2), especially in the first 3-4 days after high rainfall. The topsoil shows huge variations in the quality of the fit since it is strongly dependent on the

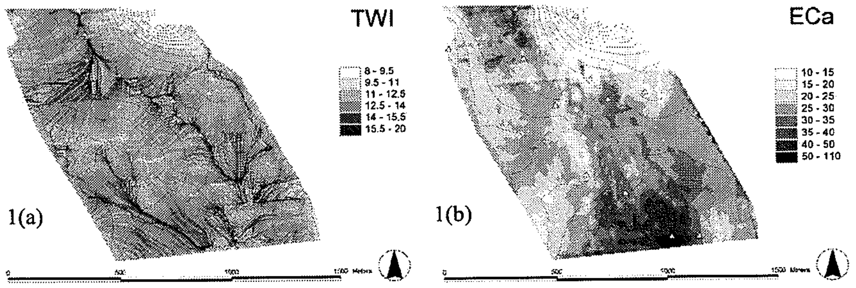

Fig. 1: Spatial pattern of TWI (potential soil moisture distribution, 1a) and electrical conductivity (1b). The isolines are the 1 m elevation contours. The North-South extension of the plot is approx. 1.2 km. The white triangles are the 12 sample points.

actual precipitation (temporal resolution of 1-2 days). The topsoil moisture content can only be predicted in early spring when the soil is almost saturated. No correlation could be found for shallow soil samples in June after some dry days. Deeper samples show a rather stable correlation coefficient of 0.6-0.8 since there is a less significant influence of the actual precipitation. Effects of infiltrating water occur with delay and are levelled to a large amount.
The correlation coefficient of ECa and TWI for the 12 sample points was r= 0.52. For a wide range of locations, similar patterns can be found for electrical conductivity and Wetness Index. Since the ECa value is dominated by both soil texture and soil moisture, the Wetness Index can help to interpret the ECa-map. Tab. 1 shows the correlation of ECa value with clay, silt and clay + silt content and how the correlation coefficient can be improved by extracting the drift caused by soil moisture taken from the Wetness Index map (TWI5).
Tab. 2 shows the correlation between the biomass at the monitoring sites close to maturity of the plants and the ECa data at different times of the vegetation period. The ECa determination of the nearly saturated soil at April 3 shows the best correlation with the yield.

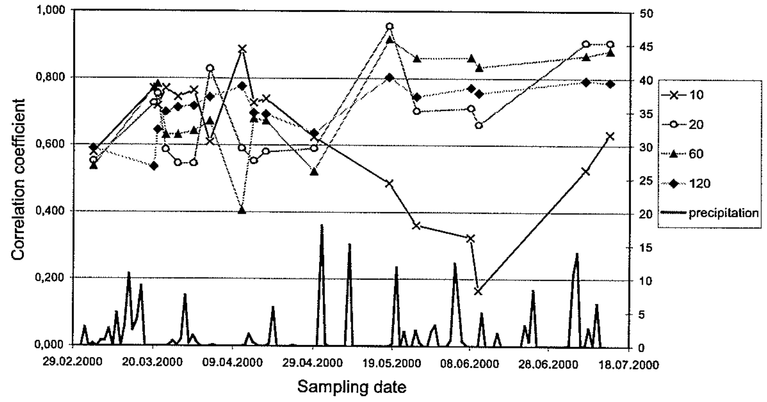

Fig. 2: Temporal pattern of the correlation between the Topographic Wetness Index (TWI) and soil moisture. precipitation [mm] is additionally indicated.

Tab. 1: Correlation coefficient r of ECa-values with soil texture before and after extracting the TWI trend (ECa_corr) at Wulfen. The data presented in Tab. 1 are based on 12 monitoring points.

r	Silt+clay	silt	clay	TWI5
ECa	0.50	0.38	0.53	0.52
ECa_corr	0.84	0.70	0.73	

Tab. 2: Correlation coefficient r of ECa values at different times of the vegetation period with the biomass close to maturity at the 12 monitoring locations in Wulfen.

	ECa	ECa	ECa	ECa
Date	03.04.00	29.04.00	24.05.00	09.06.00
Biomass 26.06.00	r = 0,94	r = 0,92	r = 0,92	r = 0,88

Study site Kassow

The results of the two sub-areas of the study site vary significantly in terms of correlation quality between the gravimetric soil moisture content and the Wetness Index. The catena presented in Tab. 3 is based on 20 monitoring points each representing a typical landform position along a sloped surface including different exposition. The Wetness Index gives a good representation of the spatial pattern of soil moisture when calculated from a 2 m DEM ("TWI 2"; height accuracy 10-15 cm). The QDWI, a quasi-dynamic wetness index derived by Barling et al. (1994), includes the spatial variation of hydraulic conductivity k_{sat}. However, these data are difficult to estimate due to enormous small-scale heterogeneity. Unless there are clearly defined areas of k_{sat} variation, the correlation cannot be enhanced.

Tab. 3: Pearson's Correlation Coefficient (Kendall's Rank Correlation) of gravimetric water content and ECa or Wetness Indices for 20 monitoring points.

Soil moisture (depth in cm)	ECa	TWI 2 (LS)	TWI 5 (GPS)	QDWI 2	QDWI 5
17.03.00 (0-30)	0.55 (0.364)	0.63 (0.09)	0.29	0.28	0.33
17.03.00 (60-90)	0.72 (0.343)	0.60 (0.343)	0.16	0.06	0.17
22.06.00 (0-30)	0.87 (0.600)	0.48 (0.095)	-0.03	0.12	0.16
22.06.00 (30-60)	0.75 (0.589)	0.57 (0.295)	0.13	0.12	0.10
22.06.00 (60-90)	0.60 (0.253)	0.67 (0.274)	0.38	0.17	0.23
TWI2	0.45	1.00	0.67	0.37	0.28

As for the study site Wulfen, the correlation coefficients decline from March (field capacity) to June. In June, the prediction is better for lower soil horizons that are not as strongly influenced by actual precipitation.

The adjacent study area with 60 raster sample points is dominated by small-scale variations in soil texture and short hill slope lengths. Here, no good correlation could be found between TWI and soil moisture. Again, the TWI based on the 2 m laser scanning DEM proved to be superior to the 5 m GPS-DEM. However, ECa gave a better representation of soil moisture. It can be said that for short, irregular hill slopes, soil moisture is determined mainly by texture and to a lesser degree by relief. Linear statistics is not suited for this type of data. Extremely low or high values are common in pedological data. They strongly influence Pearson's Correlation Coefficient. Kendall's rank correlation provides a better comparability of data. More work is under way with non-linear and fuzzy correlations and the CART approach (classification and regression trees).

DISCUSSION

The soil moisture content is strongly variable in time and space. For the temporal pattern, precipitation data is needed to assess the distribution. The spatial pattern can be assessed well with the Wetness Index in sloped landscapes and depending on the degree of texture heterogeneity with the apparent electrical conductivity (ECa value, e.g. determined by EM38). A combination of both methods is possible to improve the quality when a correlation between ECa and the Wetness Index is found. Best results were reached for the depth 20-90 cm. Only weak correlations were found in topsoils. Probably disturbance by tillage and/or other agricultural activities lead to heterogeneity of important soil properties like porosity, compaction, soil organic matter content and influence the measurements whereas in greater depth, the undisturbed soil profiles are less sensitive to the described impacts.

Correlations up to r=0.9 were found between TWI and soil moisture measurements. With ECa-maps and terrain analysis, the effort of soil sampling can be reduced. More sophisticated Wetness Indices are described in the literature. However, they request more detailed base data such as k_{sat} maps. An approach for precision farming cannot afford such detailed data.
Knowledge of the most likely distribution of soil moisture within a region or field during specific conditions is a very important prerequisite for decision-making in precision agriculture. The correlation of the ECa signal at field capacity and the biomass at the monitoring sites in Wulfen was up to r =0,94. This relation as well as the Wetness indices can provide useful information for optimum sowing density or site-specific fertilisation strategies.

CONCLUSIONS

The conducted work shows the potential of the Topographic Wetness Index in combination with apparent electrical conductivity mapping and soil water measurements to determine the spatial soil moisture distribution depending on relief and soil texture. This system may be helpful to classify management zones for precision agriculture. The simple steady-state Wetness Index ln (A_s/tanß) can support determination of spatial soil water distribution with soil-water models. Concerning the application of more complex wetness indices further investigation is necessary.

Acknowledgements
This research was supported by the Bundesministerium für Bildung und Forschung (BMBF), Bonn, Germany (project No. 03397401).

REFERENCES

Barling, R.D., Moore, I.D., Grayson, R.B. (1994) A quasi-dynamic wetness index for characterizing the spatial distribution of zones of surface saturation and soil water content, *Water Resources Research, Vol.30, No.4, p. 1029-1044*

Beven, K.J., Kirkby, M. (1979) A physically based, variable contributing area model of basin hydrology, *Hydrological Sciences Bulletin 24, S.43-69.*

Chaplot, V., C. Walter and P. Curmi (2000) Improving soil hydromorphy prediction according to DEM resolution and available pedological data, *Geoderma 97, pp. 405–422.*

Durlesser, H. (1999) Bestimmung der Variation bodenphysikalischer Parameter in Raum und Zeit mit elektromagnetischen Induktionsverfahren, *Shaker-Verlag, Aachen, FAM-Bericht; Bd. 35, dissertation Technical University of Munich.*

Moore, I.D., Gessler, P., Nielsen, G. & Peterson, G. (1993) Soil Attribute Prediction using Terrain Analysis, *Soil Science Society America Journal, Vol.57, S. 443-452.*

Paltineau, I.C., Starr, J.L. (1997) Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration, *Soil Sci. Soc. Am. J. Vol. 61, November-December 1997.*

Wilson, J.P., Gallant, J.C. (Eds.) (2000) Terrain Analysis. Principles and Applications. Wiley, New York.