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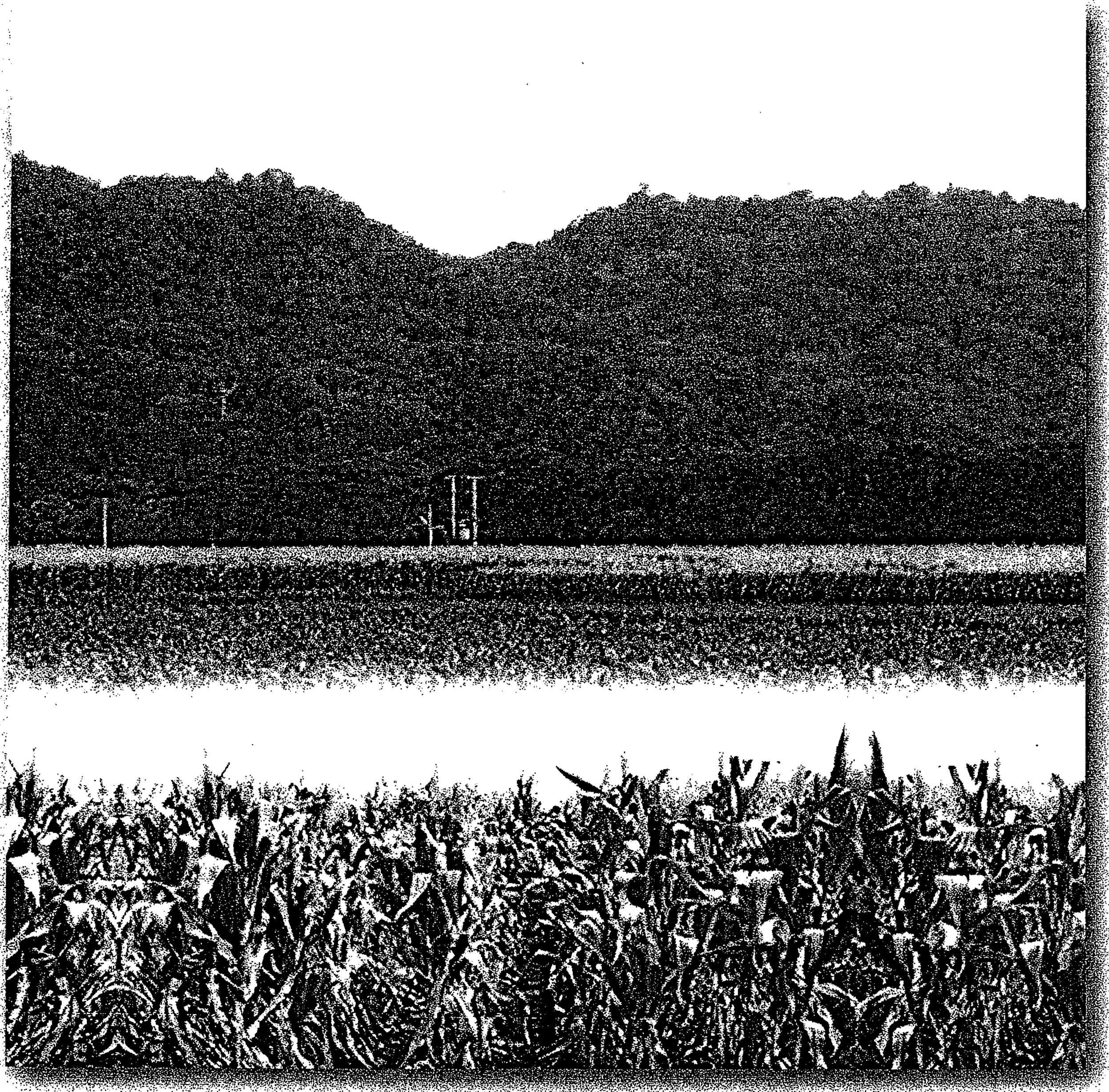

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Sensing soil and plant properties by non-destructive measurements

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Abstract

Drought and nitrogen deficiencies represent major constraints to plant growth worldwide. For an improved adaptation of plants to marginal environments soil conditions as well as plants subjected to stresses should be better characterised. Existing methods of soil and plant analysis however are costly and time consuming in delivering information on the actual and spatially resolved site-specific soil properties as well as the biomass and nutritional status of crops. Non-destructive techniques to sense soil and plant properties could contribute to improvements. In this paper applications and new developments of non-destructive techniques to sense soil and plant properties are presented. Spatially resolved soil information can be gained by electromagnetic induction, near infrared spectroscopy and indirectly by correlating plant stands to soil properties. With such methods soil texture, soil carbon and plant available water in the soil can be characterised. Root water uptake can be traced with non-destructive measurements of soil water contents. Aerial remote sensing and proximal remote sensing allow to determine plant biomass, nitrogen content and nitrogen uptake. The methods tested and further developed included aerial and ground-based reflectance based measurements and tractor based laser induced chlorophyll measurements. Together such methods should allow for optimised management to better adapt plants to marginal environments and for a more efficient screening of cultivars subjected to stresses.

Introduction

Existing methods of soil and plant analysis are costly and time consuming in delivering information on the actual and spatially resolved site-specific yield potential, soil water status as well as biomass and nutritional status of crops.

Soil properties such as clay and organic matter are important factors for soil fertility. Classical methods to determine organic matter and particularly clay contents are lengthy, space consuming, and laborious. More rapid and inexpensive methods would be valuable in obtaining such information. Owing to the rapid progress in data processing during the last decade, the use of near infrared spectroscopy in chemical, biological and agricultural sciences has been enhanced. Near infrared spectroscopy has already been demonstrated as an accurate method to obtain valuable information on soil texture and organic matter

(Stenberg et al., 1995), especially of soils of homogeneous origin (Ben-Dor et al., 1995). Studies of soils encompassing very different origins and composition are rare and are addressed in this work.

Crop growth depends on soil attributes. It should be feasible to use the crop stand condition as a bio-indicator of soil productivity. Biomass is one of the important parameters to differentiate crop stand conditions. For regions with negative water balance during the growing season, the site-specific availability of soil water is the main limiting soil resource. The availability of soil water is expected to strongly correlate with biomass production.

Many applications in fields such as hydrology, meteorology and agriculture require mapping of soil moisture, since the amount and status of water in soils impacts crop growth. This requires reliable techniques to perform accurate soil water content measurements with minimal soil disturbance. Previous research has shown that drought susceptibility is related to rooting depth (Camp, 1996). Rooting depth and knowledge of rooting pattern represent basic information to evaluate drought tolerance of plants. Destructive investigations for rooting density and depth are laborious and time-consuming. Relating rooting activity to depletion in soil water content represents a direct information about the presence and activity of roots with depth and time. Many methods for soil moisture monitoring use permanently installed devices at selected sites in the field; their usefulness is limited because of the high spatial variability of soil moisture. Portable capacitance-type moisture meters represent an attractive alternative for root water uptake studies and were investigated within the scope of this research.

Remote sensing has great potential for characterising the effect of stresses on plants so understanding the factors that influence the reflectance signal will greatly enhance the quality of the data and the potential for detecting stresses (Major et al., 2003).

Previous research has shown that spectral measurements can indirectly describe biomass, nitrogen concentration and nitrogen uptake. In the past mostly hand-held spectrometers were used for this purpose. Reflectance measurements have been widely used in order to estimate the N status of plants. Leaf reflectance in the visible region is driven primarily by chlorophyll absorption, in the near infrared region by leaf structure and in the short wave infrared by water absorption. Primarily leaf reflectance and absorption of light, the amount of leaves and the reflectance of the soil or other background drive canopy reflectance.

Another technique to monitor the nutritional status of plants by means of non-destructive and remote measurements is based on the fluorescence of plant pigments like chlorophyll. The use of chlorophyll fluorescence in plant physiology studies in not new, since this method has been used for many years as a tool for photosynthesis research and for stress detection in plants. Laser-induced chlorophyll fluorescence is the optical emission from chlorophyll molecules that have excited to a higher energy level by the absorption of electromagnetic radiation. Changes in the chlorophyll concentration can be detected based on the basis of changes in the plant's fluorescence spectra. A newly developed sensor has been tested in this work to describe nitrogen content and biomass of crop stands under field conditions.

Absorption of light by leaves is inversely proportional to the leaf water content (Tucker, 1980). As with chlorosis, leaf water deficit will quickly result in cessation of canopy growth and even leaf loss so there is multicollinearity between leaf reflectance and canopy vigour and canopy water will be highly correlated with conventional vegetation indices. Jackson and Ezra (1985) showed that a loss of water results in higher reflectance in the short-wave infrared portion of the spectrum. The water status of plants is thus closely related to the biomass. Several authors have shown that different wavelengths in the SWIR may be correlated with the water status of plants (Bowman, 1989; Carter, 1991). However detection of the water status independent of the biomass would be highly interesting to better characterise the actual water status of plants. This was aimed at in this study.

The overall goal of this study is to investigate and demonstrate the potential to sense soil and plant properties by non-contacting methods.

Materials and Methods

Non-destructive principles to sense soil properties

Mapping soils by apparent electrical conductivity measurements

Electromagnetic induction represents a fast non-contacting method to get information about field heterogeneity of soil texture and soil 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. Measurements of the electromagnetic induction by EM38 were validated on different levels, on the field level, and on the farm level, and a survey was conducted within geographic regions of various origins.

Determination of soil texture and soil carbon content by NIRS

NIR-spectra were obtained by using the Bruker/Vector 22N system (Bruker©, Ettlingen, Germany) equipped with a PbS detector. Models for dried and sieved soil samples were developed based on Partial Least Square regression and cross validation using Opus/Quant2-Software (Bruker©).

Mapping soil surface properties by aerial reflectance measurements

The spatial variability of topsoil texture and organic matter across fields was studied using field-spectroscopy and airborne hyper spectral imagery with the aim of improving soil-mapping procedures. Organic matter and clay content were correlated with spectral properties. Topsoil reflectance (330-2500 nm) was measured in the field using a GER 3700 field-spectrometer and a Lambertian Spectralon reference panel of known reflectivity. The airborne HyMap sensor was used at an early May flight campaign for recording hyper spectral images (420-2480 nm, 128 channels) of bare soil fields. Partial least square regression (PLSR) was applied to develop and calibrate an inverse model that establishes a quantitative relationship between the spectra and soil parameters.

Mapping available soil water by aerial thermography or proximal reflectance measurements

Multi-spectral airborne remote sensing was used to improve the inventory of soil heterogeneity at the field level. Ground measurements of crop parameters were collected from representative soil sites. Spectral information at visible, infrared and thermal wavebands was recorded from the airborne scanner Daedalus AADS 1268 at eleven spectral channels. The spectral information was transformed into soil information using bio-indicative transfer-functions, based on cause and effect relationships of the soil-plant system. Five fields located in Sachsen-Anhalt, Germany, were selected for this investigation. The area is characterised by 450 mm annual precipitation with a negative water balance during the vegetation period. Soil properties, plant development and crop stand conditions were measured on the ground at representative soil sites. The available water storage capacity and the rootability were derived from soil texture and texture changes within the soil profile. Grain yield and biomass of each soil site were determined. Relationships between the investigated parameters were established.

Sensing root water uptake with portable capacitance probes

Experiments were conducted with a hand-held capacitance probe (Diviner, Sentek, Australia). Each unit comprises a data display connected by cable to a portable probe rod with one sensor attached. The portable capacitance sensor measures the soil moisture content at regular intervals of 10 cm down through the soil profile. Readings are taken through the wall of a PVC access tube. Capacitance probe access tubes were installed in 36 plots cropped with wheat providing a snug fit to the soil. Soil water contents were measured weekly. On four occasions the soil was also core-sampled. Linear regressions were developed relating soil moisture content by thermogravimetric method to instrument readings.

Non-destructive tools to sense plant properties

Non-destructively sensing biomass and nitrogen status by tractor based reflectance measurements

A tractor-based radiometer was used to measure the reflectance in field grown wheat and maize plants. The experimental design included different nitrogen applications (0, 90, 130, 170, 210 kg N ha^{-1}). Individual plots were 15 m wide and 50-60 m long.

The radiometer contained two units of Zeiss MMS1 silicon diode array spectrometers with a spectral detection range from 400 to 1000 nm and a pixel distance of 3.3 nm. One unit was linked with a diffuser and measured the sun radiation as a reference signal. Simultaneously the other unit measured the canopy reflectance with an oligo view optic (Lammel et al., 2001). The spectrometer was connected with a four in one light fibre and the signal was optically averaged. The optical inputs were positioned with an azimuth angle of 80° between the front and rear side and 100° between the right and left side of the tractor. The zenith angle was set at 58 ± 6° to minimize the influence of the tractor (Reusch, 2003).

In front of the tractor the sensor system was mounted 1.90 m above the canopy. The field of view consisted of four ellipsoids with 1.23 m in length, together around 4.5 m^2. The reflectance was measured at five wavelengths, which were at 550, 670, 700, 740 and 780 nm. Various reflectance indices were calculated including the REIP, NDVI, IR/R, IR/G, G/R. Spectral indices were related to destructively measured biomass and nitrogen content.

Plants were cut shortly after the spectral measurements to estimate the above ground biomass. Small plots on both sides of the tractor were harvested, 1.5 m in width and around 8 m in length, matching exactly the measured area. A green chopper equipped with a weighing unit was used for this purpose. A separate sub-sample was removed and dried after weighing to estimate the total dry matter. The dried samples were milled and analysed for total N-content with a macro N elemental analyser.

Non-destructively sensing biomass and nitrogen status by tractor based laser induced chlorophyll fluorescence measurements

The reliability of proximal remote sensing measurements of the laser-induced chlorophyll fluorescence to determine chlorophyll and nitrogen content as well as biomass production in field-grown maize and wheat plants was determined with a newly developed sensor. A tractor-mounted fluorescence sensor developed by Planto GmbH company (Leipzig, Germany) was used that detects the fluorescence emitted at 690 and 730 nm. The sensor was mounted at the rear of the tractor at a height of around 3 m above the plant canopy. A laser beam stimulates the emission of fluorescence, which is detected at a distance of approximately 3.3 m between the canopy and the sensor. The canopy is scanned at in a 0.5 m wide strip. Strips of approximately 15 m in length were measured and the total area sensed was around 6 - 7 m^2. The chlorophyll fluorescence ratio F690/F730 was then calculated. Destructive harvests for biomass and nitrogen content were done as described for the reflectance measurements by spatially matching sensor measurements and destructive harvests.

Using spectral reflectance measurements to detect the water status of plants

Canopy reflectance was measured with a GER 3700 hyper-spectral spectroradiometer (Geophysical & Environmental Research Corp., Millbrook, NY, USA) ranging from 330 to 2500 nm. Reference measurements were done using a spectralon white standard. Drought was established under controlled and field conditions by withholding water. Spectral signatures and water status (water potential) were parallel measured. The water potential was determined with a pressure chamber (PMS, Corvallis, USA).

Results and Discussion

Sensing soil properties

Electromagnetic induction measurements to survey the spatial variability of soils

Clay content and water content in 0-90 cm soil depth were the parameters most closely related to the apparent electrical conductivity with similar R^2-values between 0.31 - 0.67 for clay and water content (Schmidhalter et al., 2001a). A further segmentation of the data in different soil groups improved the relationships significantly to R^2-values higher than 0.67 for clay, silt and sand (Heil and Schmidhalter, 2003). By this way soil water content at field capacity could be determined with adjusted R^2-values higher than 0.89. Electromagnetic induction represents a useful method to delineate different management zones in heterogeneous fields.

Determination of soil texture and organic matter content by near infrared spectroscopy

The results obtained demonstrate that NIR spectroscopy is a potential technique for rapid and cost-effective determination of soil texture and organic matter content. Results from our study with soils of very different origin confirmed previous investigations with homogeneous soils (Ben-Dor et al., 1995). Results of cross-validation of NIRS-models for soil texture and organic matter content predicted clay, silt and organic matter accurate. The corresponding regression coefficients were R^2 = 0.91, 0.91 and 0.9 with prediction errors of 11, 15 and 12 % (Wagner et al., 2001). This results are in line with a more recent investigation (Sorensen and Dalsgaard, 2005) and indicate the feasibility of near infrared spectroscopy for rapid non-destructive prediction of soil properties.

Spatial detection of topsoil properties using hyperspectral sensing

Organic matter and clay content could be determined simultaneously from a single spectral signature since organic carbon largely responds to wavebands in the visible range and clay responds to wavebands in the near infrared (Selige and Schmidhalter, 2003). Complexity and auto-correlation between the soil parameters led to the use of multivariate calibration techniques, particularly PLSR. PLSR estimates of the organic matter content and the clay content of top soils indicated R^2-values of 0.82 to 0.92 with RMSECV values of 0.4 for organic matter and 4 - 6 for clay content. It is shown that the clay and organic matter content can be predicted quantitatively using PLSR.

Characterising soils for plant available water capacity and yield potential using airborne remote sensing

The variability of the plant available storage capacity of the root zone accounted for 93 % of the variability of winter wheat biomass at the development stage BBCH 77 (milk ripeness) when the leaves started to become yellow (Selige and Schmidhalter, 2001). The biomass at this development stage indicated also the pattern of the later harvested grain yield. The crop stand condition at this development stage accounted for 96 % of the grain yield variability of winter wheat. This result also suggests that the crop stand condition can be used to forecast yield and its pattern across fields. The correlation between plant available water capacity and grain yield underlines the importance of soil water availability. The thermal emission and its relationship to the transpiration of crops was recognised as most suitable to detect quantitatively soil properties via crop stand conditions of winter wheat.

Sensing root water uptake with portable capacitance probes

Capacitance probes allowed to obtain sufficiently accurate values of root water uptake with depth and time. For many purposes even relative differences in root water uptake will be sufficient and allow screening of cultivars in exploring soil water reserves. To arrive at absolute values capacitance sensors require previous calibration. Suitable calibrations were developed (Geesing et al., 2004).

Sensing plant properties

Sensing biomass and nitrogen status of crops by tractor based reflectance measurements

Close relationships between spectral indices and biomass, nitrogen content and particularly nitrogen uptake ($R^2 > 0.85$) were determined in four seasons from 2001 to 2004 (Schmidhalter et al. 2001a; 2003; Mistele et al. 2003). A good correlation between spectral indices and the final yield was observed as well. Reliable estimates could already be obtained at the 4-leaf stage of maize plants. Consistency in data normally requires that reflectance be measured only when the solar zenith angle provides sufficient irradiance, when sky conditions are uniform and bright and when the sensor view angle is close to nadir (Major et al., 2003). The oligo view optic tested outperformed existing techniques by enabling non-nadir measurements at solar zenith angles with reduced irradiance and non-uniform sky conditions.

Sensing biomass and nitrogen status of crops by tractor based laser induced chlorophyll measurements

The fluorescence ratio F690/F730 and the biomass index were well correlated with shoot biomass and nitrogen uptake in maize across different developmental stages. The fluorescence intensity at 690 nm and 730 nm increased as shoot biomass and SPAD values increased, while the ratio F690/F730 was inversely correlated with N uptake, shoot biomass and SPAD values. N fertilization levels in the field could be differentiated by means of fluorescence ratio measurements.

The goodness of linear fits between nitrogen content, biomass, nitrogen uptake and SPAD values to fluorescence ratio mean was as fallows: 0.78, 0.87, 0.87, 0.88 (Bredemeier and Schmidhalter, 2003). Similar relationships were found in wheat and maize. The system allows to determine independently biomass and chlorophyll density.

Detection of water status by reflectance measurements

The differentiation of spectral signatures in water absorption bands in the SWIR increased with drought stress. Under controlled conditions the best correlation of water potential to reflectance was found at wavelengths of 1450 and 2000 nm. Under field conditions a strong dependency of reflectance on the zenith-view angle, the field of view and the weather conditions was observed (Ruthenkolk et al., 2001). The preliminary observations indicated that further work is required to differentiate between biomass and water status. A newly designed sensor that measures concomitantly reflectance and irradiation should overcome some of the observed limitations. Further combinations with laser induced chlorophyll fluorescence seem promising.

Conclusions

Derivation of relevant soil properties by non-contacting sensor techniques is highly effective and will provide a long-term information for optimised management. Assessment of the nitrogen, biomass and water status of plants by contact less optical measurements is seen to be a promising technique not only for management decisions of farmers but also for breeding purposes. These techniques have the capability of sampling a high number of plants in a short time rather than a single leaf point and allow a fast assessment of the spatial and temporal variability of plant growth.

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