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CHARACTERIZING SOILS FOR PLANT AVAILABLE WATER CAPACITY AND YIELD POTENTIAL USING AIRBORNE REMOTE SENSING

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Abstract

Multi-spectral airborne remote sensing was used to improve the inventory of soil heterogeneity at the sub-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. The spectral information was transformed into soil information using bio-indicative transfer functions, based on cause and effect relationships of the soil-plant system. This procedure enables the spatial detection and the quantification of soil properties. The available water capacity of the rooting zone accounted predominantly for the heterogeneity of crop stands and yield formation of winter wheat. At specific development stages the crop stand conditions were identified as sensitive bio-indicator of the plant available soil water capacity. 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. The soil map derived from remote sensing and bio-indicative transfer functions explained the pattern of nitrogen uptake and yield formation. Maps as developed in this study will support farmers and agricultural advisors to practice precision farming using site-specific management.

Introduction

Precision farming is the challenging technique for the future of agriculture. Site specific decision support systems require detailed information about the natural resources as they vary across a field. The variability and the spatial pattern of crop growth within fields depend on the variability and the spatial pattern of soil properties. Hence, detailed information about the spatial pattern and the functional properties of the soils is required to enable site specific management.

In this study, remotely sensed imagery was used to enable the digital mapping of soil resources with high resolution and timely flexibility. Remote sensing technologies are not able to view into the soil profile, but record the spectral characteristics of soil-crop surfaces. The conception of this research is capitalizing on these cause-effect relationships of the soil-plant-sensor system. It takes advantage of crop stand characteristics as indicators of soil profile characteristics. The mapping process derives soil quality via the spectral response from crop stand conditions.

Materials and Methods

The investigated area was located in Sachsen-Anhalt, Germany. The area is characterised as a slightly undulated plain at 70 m altitude with intensive arable farming. With 450 mm mean annual precipitation and 9°C mean annual temperature, the region has a negative water balance during the vegetation period. Chernozem is the predominant soil type.

The remote sensing device used for this study was the airborne line-scanner Daedalus AADS 1268 ATM. The scanner records wavebands of visible, near, middle and thermal infrared wavelength at 11 spectral channels. The investigation area was recorded with 5 m geometric resolution. Five fields cultivated with different winter wheat varieties were selected for this paper. Soil properties, plant development and crop stand condition were measured on the ground at representative soil sites. The available water storage capacity (AWC) and the rootability (rz) were derived from soil texture and texture changes within the soil profile. Grain yield and biomass of each soil site were determined. Nitrogen content of straw and grain yield was measured using elemental analyser techniques.

Results

Soil-Plant-Interactions

Detecting soil quality by remote sensing has to consider that soil is predominantly covered by vegetation and its surface is most of the time not visible. Furthermore, essential soil properties can not be discerned from soil surface appearance. However, it is well known that crop growth depends on soil attributes. Hence it should be feasible to use the crop stand condition as a bio-indicator of soil productivity and regulatory functions.

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. Apart from groundwater and lateral water, plants can only utilize the available water storage capacity of the root zone (AWCrz). This soil parameter has been recognized to be the central regulatory attribute of the soil productivity function. AWCrz correlates highly with crop biomass (Fig. 1). Additionally the effects of groundwater uptake and lateral water are included in the crop stand condition. This allows an improved derivation of soil productivity via crop stand conditions compared to classical soil core samplings. In this study, the variability of the plant available water storage capacity of the root zone (AWCrz) accounted for 93 % ($R^2 = 0{,}93^{***}$) of the variability of winter wheat biomass at the development stage EC 77 (milk ripeness) when the leaves started to become yellow.

The biomass at this development stage indicates also the pattern of the later harvested grain yield (Fig. 2). The crop stand at development stage EC 77 accounted for 96 % ($R^2 = 0{,}96^{***}$) of the grain yield variability of winter wheat. These results suggest that the crop stand condition can also be used to forecast grain yield and its pattern across fields.

The correlation between plant available water capacity and grain yield (Fig. 3) underlines the important role of water availability as the main soil resource to be considered in site specific management.

Plant-Sensor-Relationships

The Normalized Differential Vegetation Index (NDVI) is widely used to differentiate crop stand conditions (e.g. crop vigour maps). This relationship is shown in Figure 4 for the winter wheat data of this study. The NDVI correlates strongly with the biomass fresh weight (R^2= 0.89***). But biomass ranging from 30 to 50 t/ha does not cause significant differences in the NDVI. From the non-linearity of this correlation follows that higher biomass of winter wheat can not be differentiated properly when using the NDVI relationship.

Different wavebands and spectral indices were tested for the usability to differentiate crop stands. The statistical analysis identified the thermal emission as the spectral range with the best linear correlation to the biomass fresh weight. The surface temperature of crop stands differentiates synchronously with the biomass (R^2 = 0.90***) caused by the surface cooling effect of transpiration (Fig. 5). The linearity of this relationship enables us to differentiate even higher biomass and to map soil resources of sub-fields over a wider range and more precisely than using the NDVI relationship. The thermal property of the soil-plant surface should be used to distinguish soil qualities and productivity on the sub-field level. Other spectral wavebands and indices were found to be much less sensitive.

Based on the transfer function, soil resource maps of winter wheat fields were calculated (Fig. 6). Classes with width of 50 mm AWC could significantly be delineated. The results were found to be non-sensitive to the five different winter wheat varieties that were used in this study.

The map of AWC was also used to calculate the efficiency of site specific nitrogen fertilizing. The relevant data sets of three representative soils are listed in Table 1. The data emphasize the role of water availability for improving site specific N-efficiency. Low available water capacity limited the yield formation significantly and large amounts of N-surplus remained in the soil. The AWCrz was found to determine the N-uptake by grain (R^2 = 0.90***). The biomass at EC77 already reflects the spatial heterogeneity of grain N-uptake quantitatively (R^2 = 0.94***).

Nitrate leaching to groundwater may occur under such conditions. The efficiency of uniform high N-supply will often be low on fields that are characterised by high variability of available water capacity. The efficiency of N-supply can be reduced dramatically as the data in Table 1 show. This study proved that under conditions of negative water balance during the growth season, the map of available water capacity forms the best process-oriented basis to apply site specific management of N-fertilization. It is also expected from this input map to serve as a basis for decision systems of seed density and crop stand management in general.

Table 1. Data set of three representative soil sites for nitrogen balance and calculation of N supply efficiency

		Sand	Sandy Loam	Loamy Silt
AWCrz	(mm)	40	140	220
Grain yield	(t/ha)	1.1	4.9	8.3
Grain N-uptake	(kg/ha)	35	125	192
N-supply	(kg/ha)	180	180	180
N balance	(kg/ha)	+145	+ 55	- 12
N-efficiency	(%)	19	69	106

Conclusion

The pattern of crop stand conditions at specific "indicative“ development stages reflected soilborne heterogeneity's within fields. The most indicative stages of plant development to derive soilborne crop stand conditions and site properties were identified for winter wheat. Differences in crop stand conditions were correlated with their spectral response.

The plant available soil water capacity and the rooting depth were identified as the most important soil attribute for yield formation in the investigated region. The relationship of the soil-plant-sensor system enabled us to derive soilborne site properties from multi-spectral and remotely sensed imagery via scanning crop stand conditions.

The soil map derived from remote sensing and bio-indicative transfer functions explained the pattern of grain yield formation and enabled grain yield forecast. It provides a process-oriented basis to apply site specific N-supply with high efficiency. This enables cost reductions in fertilizing and ecological sound management.

The combination of a few ground check plots and multi-spectral remote sensing provided a flexible and operational technique to detect quantitatively the spatial pattern of soil properties at the sub-field level for extended regions. The presented procedure will support site specific farming with basic information about the soilborne yield potential. This enables a site specific crop and risk management with targeted resource application of seed, fertilizer and growth regulator.

Acknowledgement

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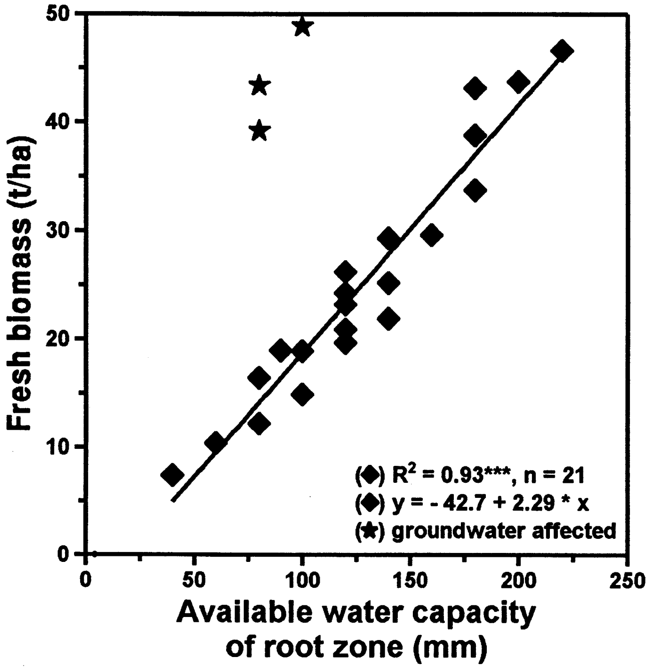

Figure 1: Relationship between plant available water capacity of the root zone and the winter wheat biomass at the development stage of early yellowing

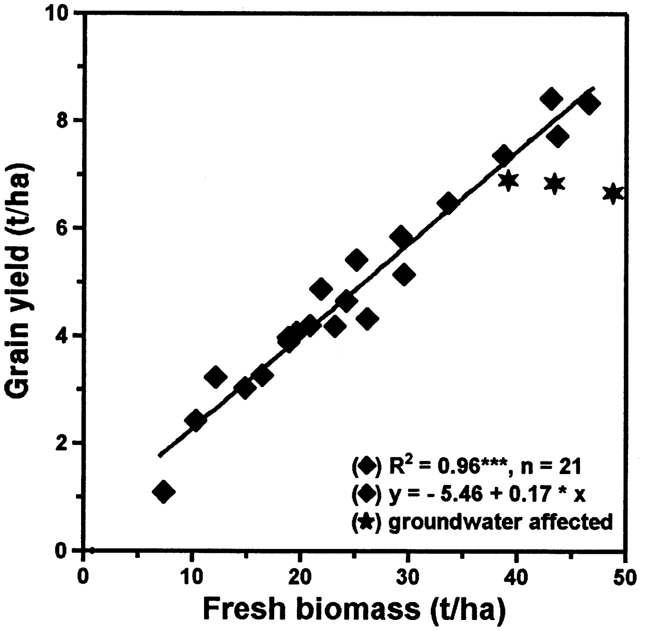

Figure 2: Relationship between winter wheat biomass at the development stage of early yellowing and the grain yield

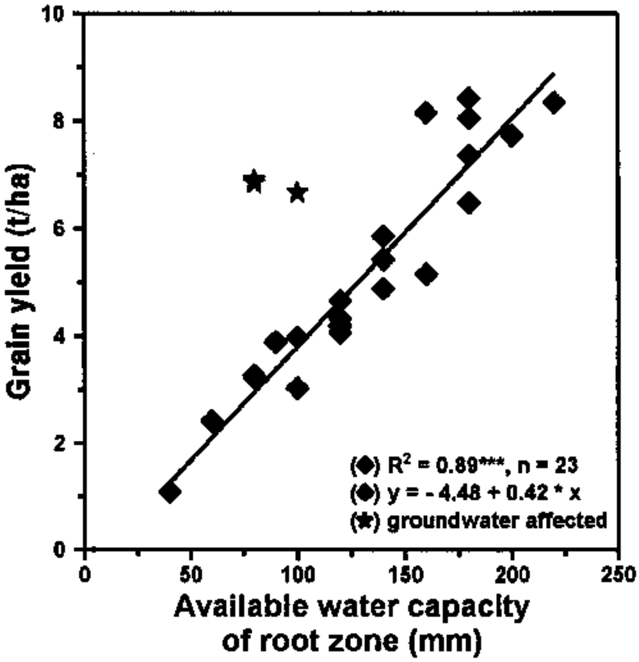

Figure 3: Relationship between plant available water capacity of the root zone and the grain yield of winter wheat

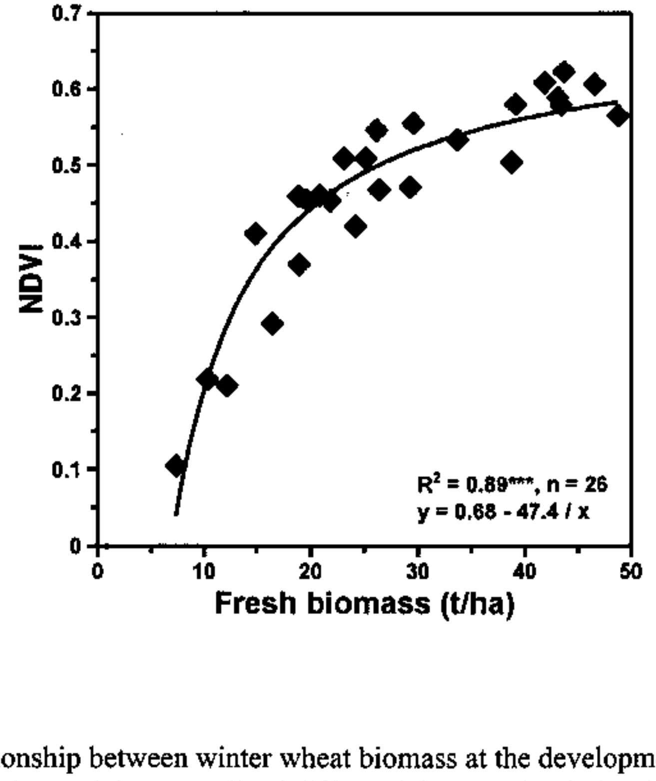

Figure 4: Relationship between winter wheat biomass at the development stage of early yellowing and the normalized differential vegetation index (NDVI)

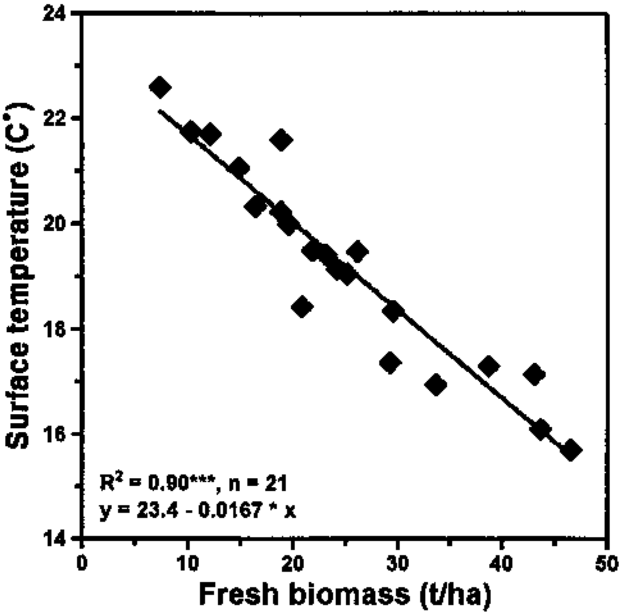

Figure 5: Relationship between winter wheat biomass at the development stage of early yellowing and canopy surface temperature

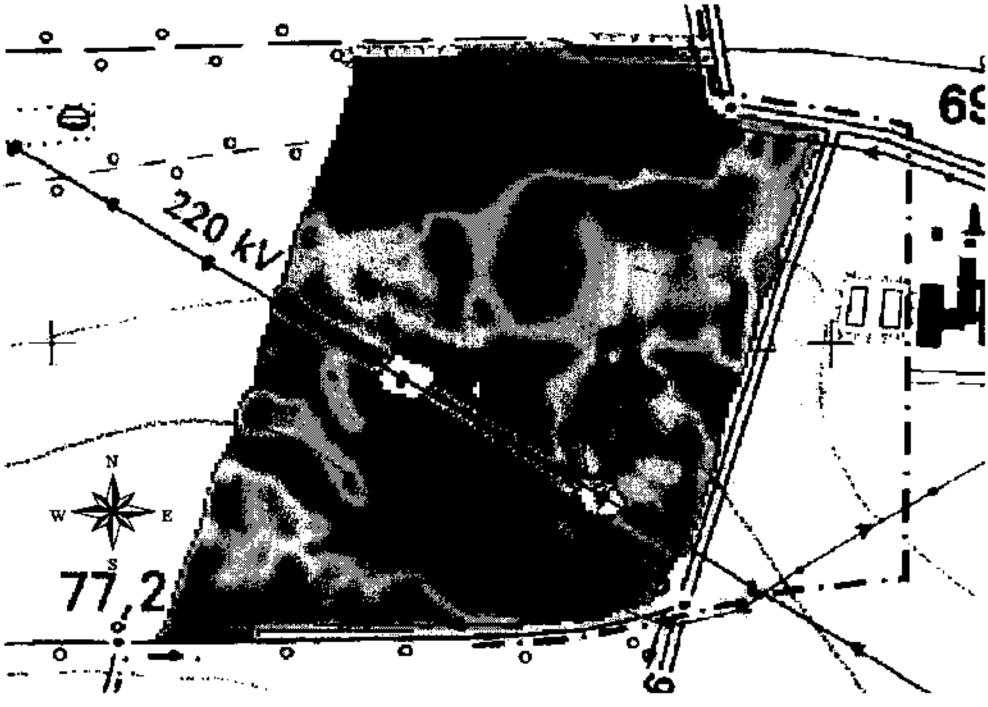

Figure 6: Map of plant available water capacity of the root zone as it varies across the reference field 1 (<50 mm = dark red to >250 mm = dark blue)