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Analysis of vegetation heterogeneity as sensor for soil moisture patterns using remote sensing

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Abstract: Soil moisture patterns are key parameters when it comes to controlling and managing process-pattern interactions in processes relating to soil, vegetation, landscape, climate and the ecosystem Soil pattern heterogeneity is hard to determine in European landscapes using direct procedures, which are used on soil with little or no vegetation, because the soil is often covered with vegetation all year round. The goal of this study is therefore to develop indirect procedures to analyze soil moisture patterns, which “use the biochemical-biophysical characteristics of plants as sensors and indicators” for soil moisture heterogeneity. For this research, geoelectrical methods which include electromagnetic induction (EMI) via a mobile geoplatform with a tractor) and the helicopter electromagnetic method (HEM) are used in the two test areas to quantify model information for soil moisture patterns. At the same time, in both study areas the suitability of optical airborne and satellite remote sensing data (hyperspectral AISA-DUAL, Modis, Landsat TM) will be examined to predict the connection between the spectral response of biochemical- biophysical vegetation characteristics and underlying soil moisture patterns. The first results show the best univariate models for predicting electrical conductivity for the vertical dipole EM38DD V with an $R^2=0.54$ based on the spectral information NPCI (Normalized Pigments Reflectance Index). To predict the horizontal dipole EM38DD H with the spectral index NPCI an $R^2=0.65$ was achieved. The combination of variables including the geographical elevation was tested as the input for a multivariate regression analysis. An improvement could be made to explain the variance of EMI measurement signals by combining elevation and spectral information.

Keywords: Vegetation heterogeneity; soil variability, soil moisture patterns; electromagnetic induction (EMI); Helicopter-borne electromagnetic (HEM)

1. INTRODUCTION

Soil moisture is a key variable in controlling a wide range of hydrological as well as climate and other ecosystem processes (Vereecken et al., 2008). To determine soil characteristics and moisture patterns i) direct and ii) indirect measurements are used. Direct procedures are used if the soil has no vegetation or just a little vegetation. Direct procedures for quantifying soil characteristics include electromagnetic techniques like electromagnetic induction (EMI) and gamma ray (Fig. 1a) which are taken with the help of a mobile geophysical platform involving a tractor or helicopter (Werban et al. 2009; Lausch et al., 2013a; Stadtler et al., 2014).

Direct remote sensing techniques include passive L-band microwave observations from airborne sensors (PLMR) (Pause et al., 2012, 2014, Montzka et al. 2013) as well as the active L-band radar system (Robert et al., 2008) which are capable of retrieving soil moisture patterns with high spatial resolution (<100m).

Optical remote sensing techniques are also used for directly measuring soil characteristics. Geringhausen et al. (2012) use airborne image spectrometer data to study soil properties and soil patterns. Jarmer et al. (2005) use simple optical remote sensing sensors like Landsat TM to assess soil inorganic carbon in the Judean Desert. Using remote sensing techniques to record soil heterogeneity is often very limited in European regions because vegetation covers the soil seasonally. Moreover, the limited number of very good sunny days, a requirement for optical satellites, restricts the possibilities to take images. For this reason, methods are needed to measure and assess the distribution and pattern of soil properties and soil moisture patterns using indirect methods. When it comes to obtaining information on soil characteristics and moisture patterns, indirect measurements are take of various biochemical characteristics of the vegetation which are used to determine specific soil traits and moisture patterns. The vegetation acts as a sender or indicator of soil moisture characteristics.

The underlying hypothesis for this research is that soil moisture heterogeneity leads to changes in the biochemical-biophysical characteristics of plants and vegetation. These changes correlate with the spectral reflectance of plant species and vegetation communities and can be recorded with remote sensing imaging techniques. This paper investigates the usability/feasibility of remote sensing data from the vegetation canopy to characterize, describe and model physical-chemical and hydrological components and characteristics of the underlying soil moisture characteristics. The goal of the study is to provide an operational method for taking surface images of soil heterogeneity and moisture patterns based on remote sensing data as input size for different soil-landscape model approaches.

2. STUDY AREAS

The studies were performed in two test areas, “Roßlauer Oberluch” and “Staßfurt-Egelner Sattel”, which are situated in Saxony-Anhalt in Germany. Both areas are part of the TERENO long-term monitoring region (Terrestrial Environmental Observatories, www.tereno.net, Zacharias et al., (2011). The region “Roßlauer Oberluch” is an ancient floodplain and is made up of various flood channels, floodplain forests and wet meadows. From a geological perspective the study site can be assigned to the Holocene floodplain which features the moraines of the Saale River to the north and is bordered by the Elbe River to the south.

Since 1852, the research area “Staßfurt-Egelner Sattel” has been characterized by the extraction of evaporated salt in underground salt mines. Due to insufficient technical experience and risks associated with mining there were a number of drownings and uncontrolled freshwater flooding in the open-pit mine. The subrosion processes caused by the flooding and the partially collapsed deformations in the cavities led to subsidence and sink holes on the surface in the 19th century (Wolf, 2011). This, in turn, caused severe subsidence measuring in some cases seven meters, which resulted in the regions becoming very waterlogged.

3. DATA AND METHODS

3.1 Measuring soil characteristics

For analyzing soil moisture in both test areas, geoelectric methods were used. In “Roßlauer Oberluch”, electromagnetic induction (EM) was used on a mobile geoplatform with the help of tractor. In “Staßfurt-Egelner Sattel”, moisture characteristics were recorded using the helicopter electromagnetic method (HEM).

Electromagnetic induction (EM) for very near surface exploration is usually done using a two-spool system, which by producing magnetic fields in electrically conductive areas underground creates eddy currents. EM procedures are therefore very suitable for making qualitative assessments of the conditions of electrical conductivity. Electrical conductivity in soil is influenced by a combination of chemical and physical soil properties. Most notably, these are electrical conductivity, soil water content, organic matter, clay content, bulk density, texture and structure as well as temperature (Ben-Dor et al., 2002; Li et al.; 2011, Robinson et al., 2012). According to Meerfeld and McDonnell (2009), EM-based conductivity measurements are linearly related to soil moisture patterns. The electrical conductivity ($б_a$) is an indicator of the plant-soil status in terms of moisture or salt stress (Li et al.; 2011).

A main objective of HEM (Helicopter-borne electromagnetic) surveys is to conduct rapid and comprehensive mappings of the upper hundred meters of the subsurface. The investigations are used extensively for mineral and groundwater exploration and a large number of environmental investigations. Electromagnetic-induction prospecting methods use man-made primary electromagnetic fields. An alternating primary field (generated in the transmitter coil) induces insignificant eddy-current field in the ground depending on the averaged electrical conductivity in subsurface. These eddies generate a secondary magnetic field which is picked up by the receiver coil and related to the primary magnetic field.

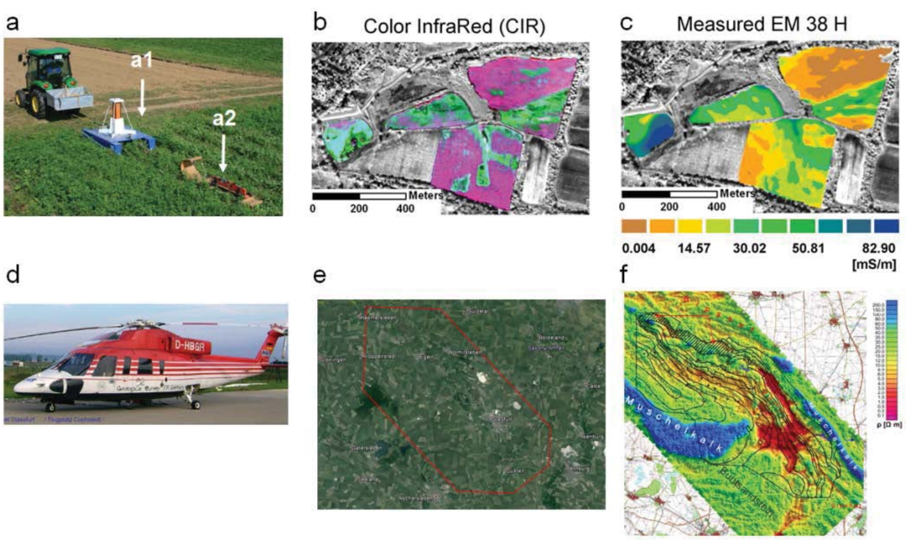

Figure 1. (a-c) Study area “Rosslauer Oberluch”, Measurement arrangement of (a1) Gamma-ray spectrometer and (a2) EM38DD, (b) Color Infrared image (CIR) - taken from the hyperspectral sensor AISA-EAGLE/HAWK, 400 - 2500 nm, 2 m ground resolution, 461 spectral bands, date of recording 2010-09-23 with a Cessna 207, (c) Measured and interpolated electrical conductivity – EM38DD H, (d-f) Study area “Staßfurt-Egelner Sattel”, (d) Helicopter for HEM (Helicopter-borne electromagnetic) surveys from the BGR, (e) study area “Staßfurt-Egelner Sattel”, (f) electrical conductivity based on HEM,

In the typical frequency domain HEM system both the transmitting coil set and the receiver coil set are housed in a rigid boom or "bird" that is towed beneath the helicopter. The BGR’s standard helicopter-borne geophysical system consists of electromagnetic, magnetic, GPS and laser altimeter sensors housed by the bird, a cigar-shaped 9 m long tube, which is kept at about 30-40 m above ground level. The gamma-ray spectrometer, additional altimeters and the navigation system are installed into the helicopter. The base station records the time varying parameters diurnal magnetic variations and air pressure history. The sampling rate is 10 Hz except for the spectrometer (1 Hz), which provides sampling distances of about 4 m and 40 m, respectively, taking an average flight velocity of 140 km/h into account (Siemon, 2009). A typical airborne survey consists of parallel profile lines covering the entire survey area and several tie-lines. Results of HEM prospections are generally presented as apparent resistivity maps and vertical resistivity sections.

3.1 Remote sensing data

In order to study soil moisture characteristics in both test areas, different remote sensing data was used. The specific airborne and satellite remote sensing data used is recorded in Table 1.

For the test site “Roßlau Oblerluch”, three flight campaigns were carried out in 2010 and 2013 using the imaging hyperspectral Sensor AISA-DUAL (Lausch et al., 2013a). Once the airborne AISA-DUAL raw data had been recorded, it underwent radiometric correction according to the CaliGeo procedure (SPECTRAL IMAGING LTD; Mäkisara, 1998) operated under ENVI (ITT VISUAL INFORMATION SOLUTION, BOULDER, CO, USA). After radiometric correction, an image-driven, radiometric recalibration and rescaling method was implemented to reduce ocular linear and non-linear miscalibration in the hyperspectral data (ROME; Reduction Of Miscalibration Effects, Rogaß et al., 2011). Atmospheric correction was performed using ATCOR4 software (Richter and Schläpfer, 2002). A digital elevation model (DEM) was used together with the CaliGeo geocoding procedure for the orthorectification of the airborne hyperspectral image. After pre-processing, the hyperspectral data could then be georeferred to as ground reflectance data with a spatial ground resolution of 2m (Lausch et al., 2013a).

For the “Staßfurt-Egelner Sattel” test area, remote sensing data MODIS, Landsat-TM, as well as SPOT from 2007 was included in the analysis. The atmospheric correction of the data was performed using ATCOR4 software (Richter and Schläpfer, 2002).

Table 1. Specification of remote sensing data for the test areas “Rosslauer Oberluch” and “Staßfurt-Egelner Sattel”

Testsite	Remote Sensing Data	Recording Date	Ground Resolution [m]	Spectral Resolution Wavelength	Platform
Rosslauer Oberluch	Hyperspectral AISA-DUAL	2010-23-09 2013-05-06 2013-07-07	2	400-2500 nm	Airborne, Piper
Staßfurt	MODIS	2007	250	V/NIR, SWIR, TIR	Satellite
Staßfurt	Landsat-TM	2007	30	V/NIR, SWIR, TIR	Satellite
Staßfurt	RapidEye	2009	5	V/NIR, SWIR	Satellite
	EMI / HEM				
Rosslauer Oberluch	EMI	2009-08	-	15-20 mS m-1	Tractor
Staßfurt	EM	2007-06/07/08	-	386, 1.822, 8.339, 5.489, 41.485, 133.350 HZ	Helicopter

3.3 Model approach for soil process – vegetation pattern analysis

In the study areas several spectral indices and index types based on the remote sensing data were calculated and tested in terms of their suitability to predict vegetation patterns as a function of soil water conditions. The spectral vegetation indices (VI) used were divided into different categories: (I) *Reflectance VI,* (II) *Spectral VI:* 70 vegetation indices from literature and (III) Spectral derivate. The calculation for all spectral indices, spectral published indices and index derivate of imagine hyperspectral data were carried out using IDL/ENVI, v. 4.9.

The statistical analysis aims to investigate the predictive power of spectral and spatial vegetation patterns as an indicator of soil and soil water measurement conditions taken with EMI and of plant availability water evaluations. The predictive power of spectral and spatial vegetation patterns with regard to underlying soil and soil water conditions was assessed in a statistical analysis. Univariate and multivariate linear regression models were used to develop the respective transfer functions. We used a resampling framework to account for the large sample size and randomly resampled 1000 responses and their respective predictor variables 1000 times from the original data for each spectral indicators, spectral derivatives and spectral bands separately. These were used in a robust regression framework to down-weigh the influence of potential outliers. For each of these 1000 models per predictor, the calculated coefficients and their respective standard errors, *t* values and error probabilities were recorded. Finally, mean values were calculated.

3. FIRST RESULTS AND DISCUSSION

In the “Roßlauer Oberluch” test region, studies were done to examine the extent to which the spectral heterogeneity of plants and vegetation as an indicator of soil properties and moisture characteristics can be simulated and measured with electromagnetic induction.

The correlation studies between moisture patterns and vegetation patterns based on each spectral wavelength resulted in the highest correlation in the wavelength range from 695-700 nm with an R^2 of ca. 0.3 (RMSE = 11.33 mS/m^{-1}) for EM 38DD H (Fig. 2a and b). EM38DD H compared to EM38DD V and EM31 has the shallowest penetration depth and the highest sensitivity to the very near surface soil properties. Lower linear correlations exist for the electrical conductivity measured by EM38DD V and EM31 V with an R² of max. 0.26.

For modeling soil properties and moisture pattern based on 70 well published and tested spectral indices, which can simulate the "vitality" of the vegetation according to following criteria: changes in photosynthetic pigments in plants, photosynthesis activity, water status and content, content in lignin and cellulose and transpiration of plants and vegetation.

Table 2. Best model fits for univariate regression between EMI spectrometry measurements and spectral vegetation indices derived from the imaging hyperspectral sensor AISA-DUAL, recording date 2010-23-09, 2m spatial resolution, in test region "Rosslauer Oberluch"

Spectral Indices [no dimension]	**EM38DD H** R² RMSE [mS/m^{-1}]	**EM38DD V** R² RMSE [mS/m^{-1}]	**EM31 V** R² RMSE [mS/m^{-1}]
PSRI - Plant Senescence Reflectance Index (R_{680}-R_{500}) / R_{750}) Group: *Pigment activity/Light use efficiency* Merzlyak et al. (1999) Sims and Gamon (2002)	**0.39** **[10.65]**	0.39 [12.22]	0.28 [13.46]
CAI - Cellulose Absorption Index (0.5 (R_{2000}+R_{2200})−R_{2100}) Group: *Leaf content* Daughtry et al. (1996)	0.39 [10.63]	**0.40** **[12.17]**	0.27 [13.64]

The results showed that with the Plant Senescence Reflectance Index (PSRI, Merzlyak,1999) for EM 38 H and EM 38 V the best model fits were achieved. The PSRI (R680-R500) / R750) is designed to maximize the sensitivity of the index to the ratio of bulk carotenoids (e.g., alpha-carotene and beta-carotene) to chlorophyll (Table 2). Merzlyak et al. (1999) indicates an increase in PSRI, an increase in canopy stress (carotenoid pigment), the onset of canopy senescence and plant fruit ripening. The PSRI is therefore often used in vegetation health monitoring and plant physiological stress detection (Liew et al., 2008; Stagakis et al., 2010; Clark et al., 2011). The Cellulose Absorption Index (CAI, Daughtry et al., 1996) also provided a reasonable fit for EM38DD H with an *R*2 of 0.39. Furthermore, the CAI predicts EM38DD V with an *R*2 of 0.40 (RMSE 12.17 m Sm-1).

The results show that the target value for electrical conductivity measured with EM 38 H generates a good model prediction with an *R*2 of 0.655 (RMSE 8.06 m Sm-1). A considerable improvement in the explanation of the model variance for the EM 38 H, EM 38 V as well as EM31 V measurement signals was nonetheless still achieved by considering the relief (Table 3).

Table 3. Best models for univariate and multivariate regression between EMI and spectrometry measurements and variables in the "Rosslauer Oberluch", derived from the imaging hyperspectral sensor AISA-DUAL, recording date 2010-23-09, 2m spatial resolution.

Predicted Variable	Best model fits	R²	RMSE
EM38DD H	Y = 164,994 – 1,971 * Elevation	0.637	8.26
	Y = 158,179 – 1,972 * Elevation + 16,393 * NPCI	**0.655**	**8.06**
EM38DD V	Y = 163,241 – 1,848 x Elevation	0.419	12.10
	Y = 142,522 – 1,850 * Elevation + 49,836 * NPCI	**0.540**	**10.76**
EM31 V	**Y= 171,351 – 2,014 * Elevation**	**0.485**	**11.54**

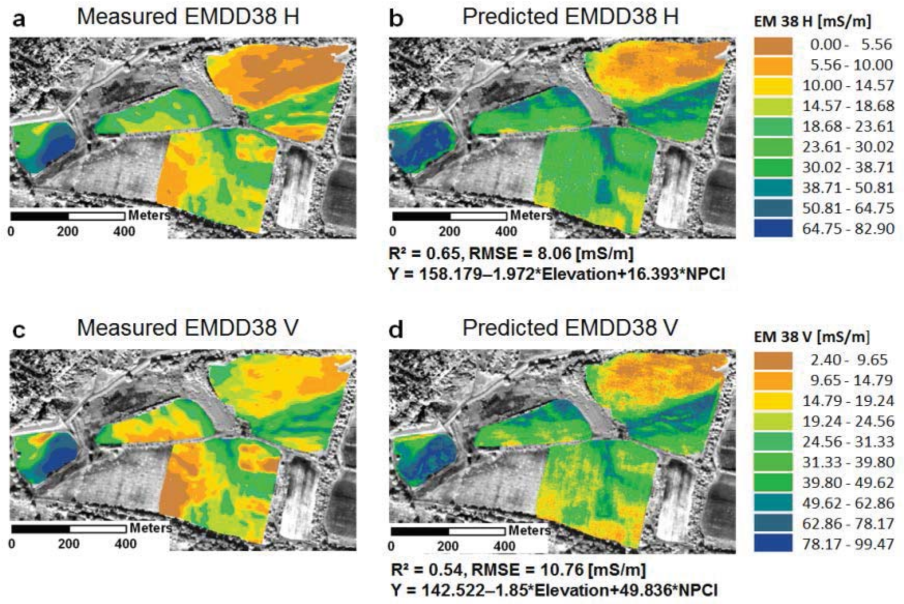

Figure 2. The best model fits for mulitvariate regression between EM38DD H, EM38DD V and information from hyperspectral bands of the imaging AISA-DUAL sensor, (a) measured - EM38DD H, (b) Predicted - EMDD38 H, (c) measured - EMDD38 V, (d) Predicted - EM38DD V, derived from the imaging hyperspectral sensor AISA-DUAL, recording date 2010-23-09, 2m spatial resolution, (modified after Lausch et al., 2013a).

The relief looks at soil conductivity indirectly via the relief dependency of the substrate as well as of the soil moisture pattern. Studies by Zippich et al. (2001) and Sommer et al. (2001) confirm this as well. This is reflected by the EMI and gamma-ray measurements.

The EM31 V could only be predicted with the variable elevation with an *R*2 of 0.49 (RMSE = 11.54). The best prediction was obtained for EM38DD H with an *R*2 of 0.65 (RMSE = 8.06) as well as for EM38DD V with an *R*2 of 0.54 (RMSE = 10.76). Elevation and the spectral indicator NPCI improve the model fit (Table 3, Fig. 2).

4. CONCLUSION

Functional reactions in plants and vegetations are controlled and influenced by a combination of soil properties including characteristics like texture, salinity, pH- levels, chemical composition, soil moisture patterns and temperature (Meerveld and Mc Donnell, 2009; Li et al. , 2011; Schmidtlein et al., 2012). This condition influences the biochemical–physical properties in vegetation as a result of adaptation or plant stress or the distribution of vegetation structures (Lausch et al., 2012, 2013a).
Initial results from the “Roßlauer Oberluch” study reveal that hyperspectral remote sensing is a suitable tool to describe and analyze biochemical vegetation characteristics in relation to underlying soil moisture characteristics.

The existing and still relatively small correlations among spectral information, spectral reflectance values of vegetation and soil moisture patterns show that there still are a number of unanswered questions and several problems to solve. Further studies will provide answers to the following questions.

The hyperspectral flight data used in the first study was collected on 2010-23-09. At this time there was, on account of the senescence of the vegetation, overlapping of this with the biochemical-biophysical signals based on different soil moisture patterns. To minimize these effects, hyperspectral flight campaigns were performed at other points on 2013-05-06 and on 2013-07-07 for “Roßlauer

Oberluch”. The “Roßlauer Oberluch” area is covered with natural vegetation. The variability of different plant species in geometry and biochemical-biophysical vegetation characteristics makes it difficult to correlate underlying soil moisture heterogeneity. This is why more test areas will be included in the analysis which have homogenous agricultural crops.

The existing soil process – vegetation pattern interactions are nonlinear processes. For this reason, we intend to test classification approaches such as SVM, PLSR and cluster algorithms in subsequent steps. This will also include additional spatial information of descriptive soil-related site characteristics such as soil water budget information. In addition, other indicators like the wetness index are to be included in the overall analysis.

With the help of helicopter electromagnetic (HEM) surveys and other optical remote sensing data like MODIS, Landsat TM, SPOT and RapidEye, the connection between vegetation heterogeneity as a result of soil moisture patterns will be studied over large areas.

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