APPLICATION OF HYPERSPECTRAL IMAGING FOR THE QUANTIFICATION OF SURFACE SOIL MOISTURE IN EROSION MONITORING AND MODELLING

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ABSTRACT

The focus of this paper is the prediction of moisture rates for different soil classes from spectral features. The main goal hereby is to find robust spectral features that are not severely influenced by other heterogeneous soil properties (i.e. mineralogy, organic carbon, roughness, crust, others).

Soil samples from a recultivation mining area at Welzow/Cottbus in Eastern Germany were taken and analysed in the laboratory. Results were used to set up an appropriate model to be applied with HyMap data acquired over the area.

In the laboratory some 100 different spectral features could be found to quantify soil surface moisture rates for homogeneous soils with regression coefficients above 0.95. Only few spectral features proved to be applicable under field conditions. The ratio of reflectance values at 1255 and 1515 nm was among the best results to predict surface soil moisture for the given substrates.

For two HyMap images taken in July 2004 in different moisture states, surface soil moisture maps were deduced and compared to field measurements using FDR devices. Overall results of deduced soil moisture rates for the test area showed good conformances with in-field-measurements. The vertical distribution of soil moisture in the upper centimetres of the column could be used to explain underestimations by the regression function. Remaining inconsistencies can be partly related to soil crusts present in the test area.

INTRODUCTION

Erosion models are a suitable means for the simulation and prediction of present, past and future erosion states. In the case of soil moisture, due to the local variability of this parameter, it is necessary to rely on measured data that cover the whole area of interest rather than interpolating discrete measurements.

Quantitative high spectral resolution remote sensing (imaging spectroscopy) can dramatically increase the accuracy of erosion monitoring. In terms of erosion, soil moisture is crucial since it directly influences infiltration rates and runoff values. In recent years much focus was put on the extraction of accurate soil properties and mineralogical parameters that can be obtained only from reflectance measurements with high spectral resolutions (i). Soil moisture is one of these parameters of interest (ii, iii). However, most research is done in the confined environment of a laboratory. The resulting correlations were rarely tested with hyperspectral images in the field.

The overall objective of this interdisciplinary study is to monitor, understand and model the dominant processes of runoff and erosion in a small catchment of 4 ha in size. The focus of this paper is the prediction of moisture rates for different soil classes. The main goal hereby is to find robust spectral features that are not severely influenced by other heterogeneous soil properties, and which can be used with remote sensing data.

STUDY AREA

The Study area is a small catchment (4 ha) being part of a bio-monitoring recultivation zone in the lignite mine Welzow-Süd near Cottbus, Germany. This subsequent landscape is left over from the

Niederlausitzer mining industry. Undisturbed conditions, a relatively harsh climate and the lack of vegetation make this area ideal for the research on soil parameters. Since the area undergoes unusual local dry conditions and has a distinct slope from north to south, land degradation processes take place and can be accurately measured and controlled throughout the years. Weather stations and erosion plots measure the physical parameters that are linked to the remote sensing results.

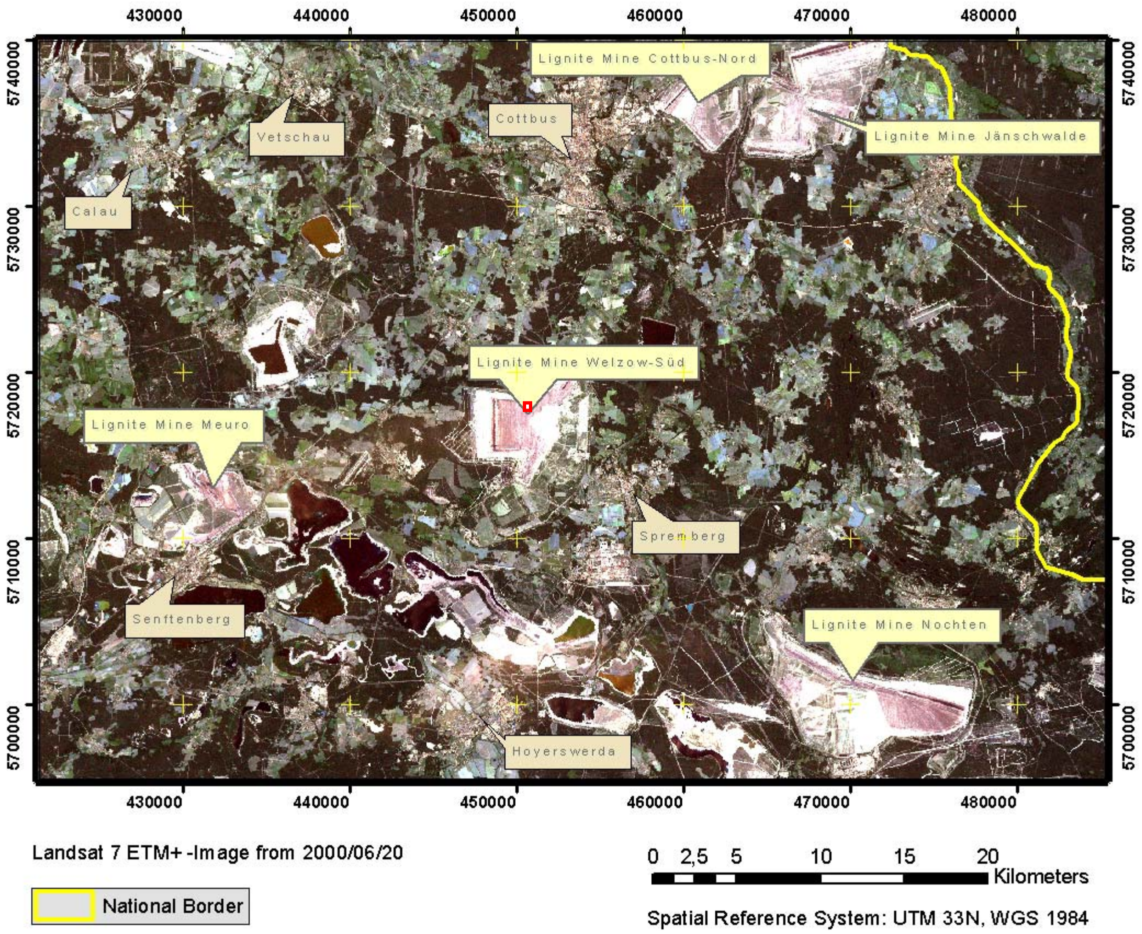


Figure 1. Location of the study site at lignite mining area Welzow-Süd (red square).

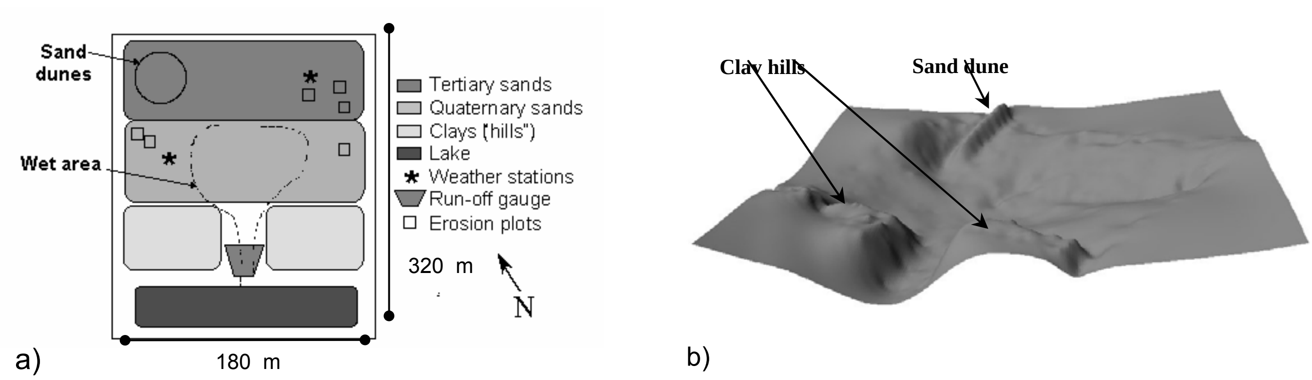


Figure 2: a) Schematic map of the study site at lignite mining area Welzow-Süd, b) DEM of the test site (10 times vertically exaggerated) (M. Kuhnert, personal communication, 2004).

In the year 2002, the whole recultivation area has been overburden with several different substrates. Generally speaking, there are three different types of soils present. The northernmost part is covered with tertiary sand. This substrate is characterised by its bright-greyish colour. The relatively large grain size gives it a poor water storage capability (field capacity). Due to its low pH-value (iv), vegetation is very sparse on this ground. From the spectra taken in the field, this substrate has very little organic matter content, no carbonate, and is kaolinite-rich (v). This part of the recultivation area is the uppermost in terms of elevation, so all discharge takes place in a southward direction (see Fig. 2b).

In the adjacent area quaternary sand is predominating. The slightly basic character and small to moderate field capacity of the soil lead to a temperate vegetation in summer (herbages, minor shrubs). However, no vegetation is present in the confined plots that are measured regularly in the field (see Fig. 2a).

South of the quaternary sand, two clay hills have been land filled on the western and eastern border, respectively. Due to its small grain size, the clay acts as a rigid barrier to the water masses flowing in a southerly direction. Thus, the gap between these hills forms a valley lying 3 to 4 meters below the top of the hills and therefore formed a drainage channel. In contrast to the sandy substrates, the clayey hills exhibit distinct vegetation.

METHODS

In order to determine soil moisture rates from spectral features, a multilevel approach was accomplished. In this context, two types of soil were considered: tertiary sand and quaternary sand.

First of all, subsets of two totally dry soil samples from the field (tertiary and quaternary sand, respectively) were prepared in order to receive a well-defined soil moisture percentage. For both types of soil, five subsets of the initially dry samples were wetted using a spray bottle and the fractions of water put onto these samples were determined by measuring the masses of the dishes, samples and water amounts using a balance of 10 mg accuracy. The soil moisture was calculated in mass of water per mass of soil matrix. The soil samples were put in covered petri-dishes in the fridge for 24 hours to gain a constant soil moisture over the whole sample. Afterwards, the masses were measured again. Spectra were acquired over the wetted samples using an ASD spectroradiometer FieldSpec Pro FR (www.asdi.com) and multiple spectral features were evaluated: band means and standard deviations, band ratios and spectral feature surfaces. Since all sub-samples of one type of soil originate from the same sample and only differ in their rate of soil moisture, a direct effect of this parameter could be analysed.

In a next step, spectra of field soil samples in natural field conditions with varying moisture rates (e.g. before and after rainstorm events) were measured under laboratory conditions and correlated with the parameter of interest. In contrast to the first approach the sub-samples did not originate from the same sample. Thus, other physical and chemical parameters affected the spectra as well and complicated the determination of soil moisture. However, in order to gain stable methods, these factors have to be taken into account. For the correlation of spectral features with soil moisture, the appropriate values were measured by our project partners at the BTU Cottbus applying conventional methods: the soil samples were put into a drying chamber for 24 hours at 105 °C. The decrease in weight represents the initial mass of water in the sample.

Finally, spectroradiometers were also taken to the field for measuring the same parameters under natural conditions and to monitor interannual surface reflectance changes. When measuring in the field with the sun as the light source, the stronger water absorption bands are masked due to atmospheric absorption. Therefore, the methods developed in the lab have to take into account that certain regions in the spectrum (e.g. around 1.4 µm and 1.9 µm) cannot be used under outdoor conditions.

The remote sensing monitoring includes yearly acquisitions of hyperspectral airborne images with the HyMap scanner (http://www.hyvista.com/hymap.html). In summer 2004, two acquisitions were conducted. Hereby, the spatial integration over a pixel size of ~16 m² and the atmospheric correction are further challenges to be addressed. In a last step, the results gained in the laboratory and from field measurements were evaluated in the context of hyperspectral images.

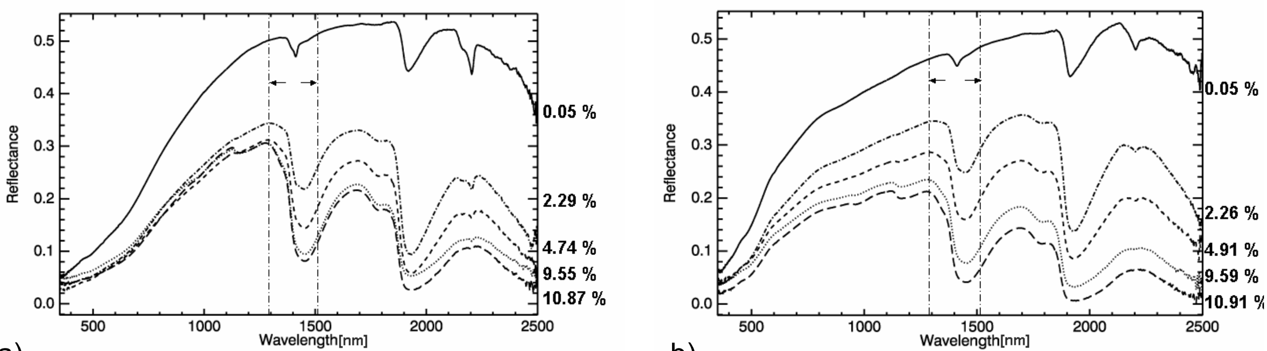
RESULTS

Laboratory analysis of samples with artificial soil moisture

For the tertiary sand and quaternary sand, five sub-samples with different soil moisture rates were measured, respectively. Hereby, the moisture rates range from air-dried to fully saturated samples (~11 % in mass). Due to the higher signal-to-noise ratio of the spectra for laboratory acquisitions and absence of atmospheric absorption, the results are smooth spectrum curves as can be seen in figure 3. The deep absorption bands in the regions around 1.4 and 1.9 µm are due to absorption by OH- and H2O and are therefore a promising region to quantify soil moisture.

First results of the conducted analysis show that certain band ratios in this region can be correlated to soil moisture with R^2-values as high as 0.99 for the ten samples.

For example, the ratio of the two bands 1288 nm and 1515 nm was calculated (see dashed lines in figure 3). The linear regression curve shown in figure 4 depicts the strong correlation (R^2 ~0.94) of this ratio with the soil moisture. Though the correlation coefficient is not optimal, its transferability to other samples proved to be very good.



a) b)

Figure 3: Laboratory Spectra of soil samples with different moisture percentages: a) tertiary sand and b) quaternary sand. The dashed lines indicate the wavelengths for the ratio calculation.

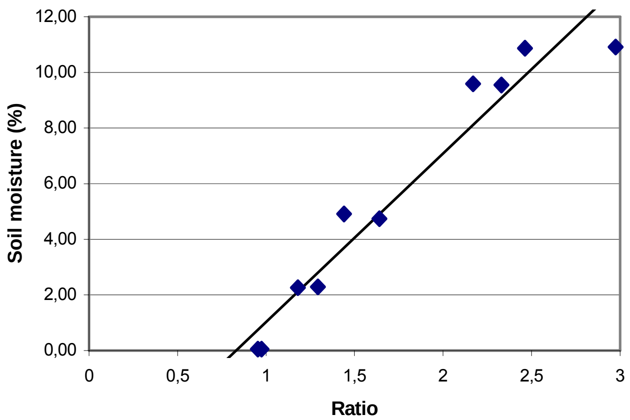


Figure 4: Regression plot for band ratio (1288 nm vs. 1515 nm) applied to homogeneous tertiary and quaternary sand samples in the laboratory. Regression function: -5.04+6.06•(r_{1288}/ r_{1515}), R^2=0.94

Through all the spectral analyses conducted, more than 100 ratios of bands could be found with very high correlations (R^2 >0.96). Many of the bands correlated are directly in the overtone absorption bands of 1.4 or 1.9 µm or considering too narrow band intervals and can therefore not be used with remote sensing images.

Laboratory analysis of samples with natural field soil moisture

The results from the artificially wetted samples are promising for the correlation of soil moisture and absorption features. However, soils are mostly not only differing in their moisture content, but also in other parameters like colour, crust, density, organic matter etc. It is therefore necessary to find features that are robust enough to eliminate these side effects while still correlating significantly with the soil moisture percentage. In order to choose which of the correlation developed is the best predictor for soil moisture, the transferability of the features was analysed.

For the tertiary and quaternary sand, multiple samples were taken from the field using a 5cm diameter soil core of 5cm depth. The samples were subdivided into five layers of 1cm depth and reflectance was measured for all layers. The layers have different properties in terms of the parameters mentioned above (grain size, mineralogy) and are therefore considered heterogeneous. The samples were taken in the field between May and August 2004. The maximum soil moisture percentage of these samples was about 2.6% (gravimetric soil moisture).

The same ratio feature was calculated, the resulting linear regression curves are shown in figure 5.

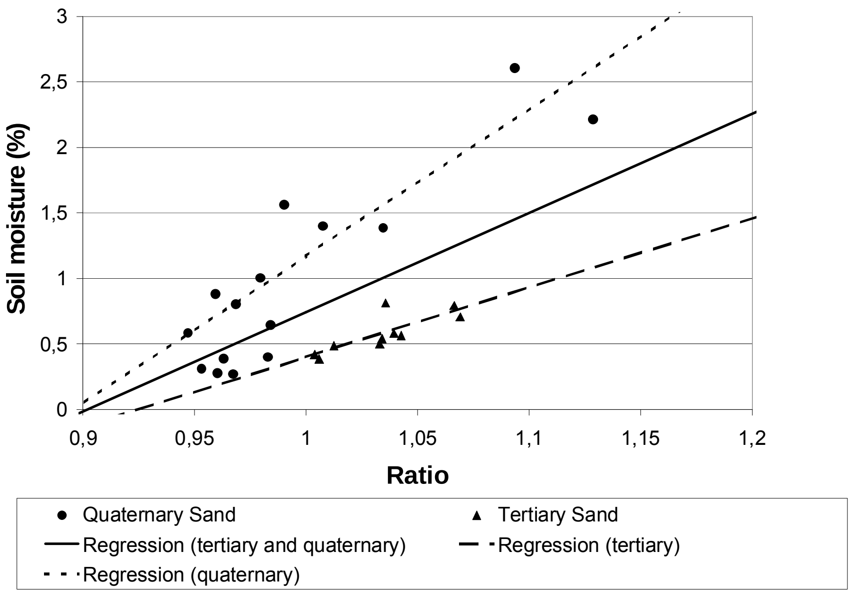


Figure 5: Regression plots for band ratio 1288nm vs. 1515nm (functions for all samples as well as for tertiary and quaternary sand samples separately).

Regression functions: -6.83+7.57•(r_{1288}/ r_{1515}), R^2= 0.36 (all samples), -9.95+11.12•(r_{1288}/ r_{1515}), R^2= 0.79 (quaternary samples) and –4.88+5.28•(r_{1288}/ r_{1515}), R^2= 0.65 (tertiary samples).

- The correlation coefficients were significantly lower than for the homogeneous samples measured in the first step. When regarding all samples in a single regression function, the correlation coefficient turned out to be very poor (R^2=0.36).
- Therefore, for the two substrates two different regression functions were calculated and led to much better correlation coefficients (0.79 and 0.65, respectively). It is therefore necessary to distinguish between soils when relating reflectance to moisture.
- Soil moisture determination from HyMap Image
- Based on the results of the laboratory studies, spectral features were also applied to airborne HyMap images in order to determine soil moisture states. An image of the test site is provided in figure 6.

Figure 6: HyMap image from July 30th 2004 (RGB from bands 13/7/2). The red line depicts the boundaries of soil moisture measurements in the field, and is associated with the area shown in figure 7.

On the day of the overflight in July 2004, field measurements on soil moisture were conducted at various spots. The resulting discrete mesh of measured values was then interpolated in order to deduce soil moisture states for the whole area. Although local heterogeneities in terms of vegetation, surface topography, soil types and crusts make the interpolation approach error-prone, it provides an impression of the overall surface moisture distribution. The field measurements averaged volumetric moisture coefficients for the upper five centimetres of the soil using a Frequency Domain Reflectory (FDR) probe. Figure 7a shows the distribution of soil moisture in the sandy parts of the test site resulting from these measurements.

The results from laboratory analyses correlating spectral features with soil moisture showed that ratio features are suitable to detect soil moisture coefficients for the different soil classes. Thus, for the HyMap image, different ratios were calculated for each pixel of the whole image. The resulting distribution of the same ratio value as applied above between wavelength bands 1288 and 1515 nm is exemplarily provided in figure 7b. Due to the atmospheric windows, other ratio features used in the laboratory (e.g. 1802 nm vs.1455 nm) were not applicable for the HyMap image.

Since the FDR device measures volumetric instead of gravimetric soil moisture values, a conversion factor of 1.7 (average bulk density of the quaternary sand, in g/cm³) was applied to transform HyMap-derived gravimetric into volumetric soil moisture rates.

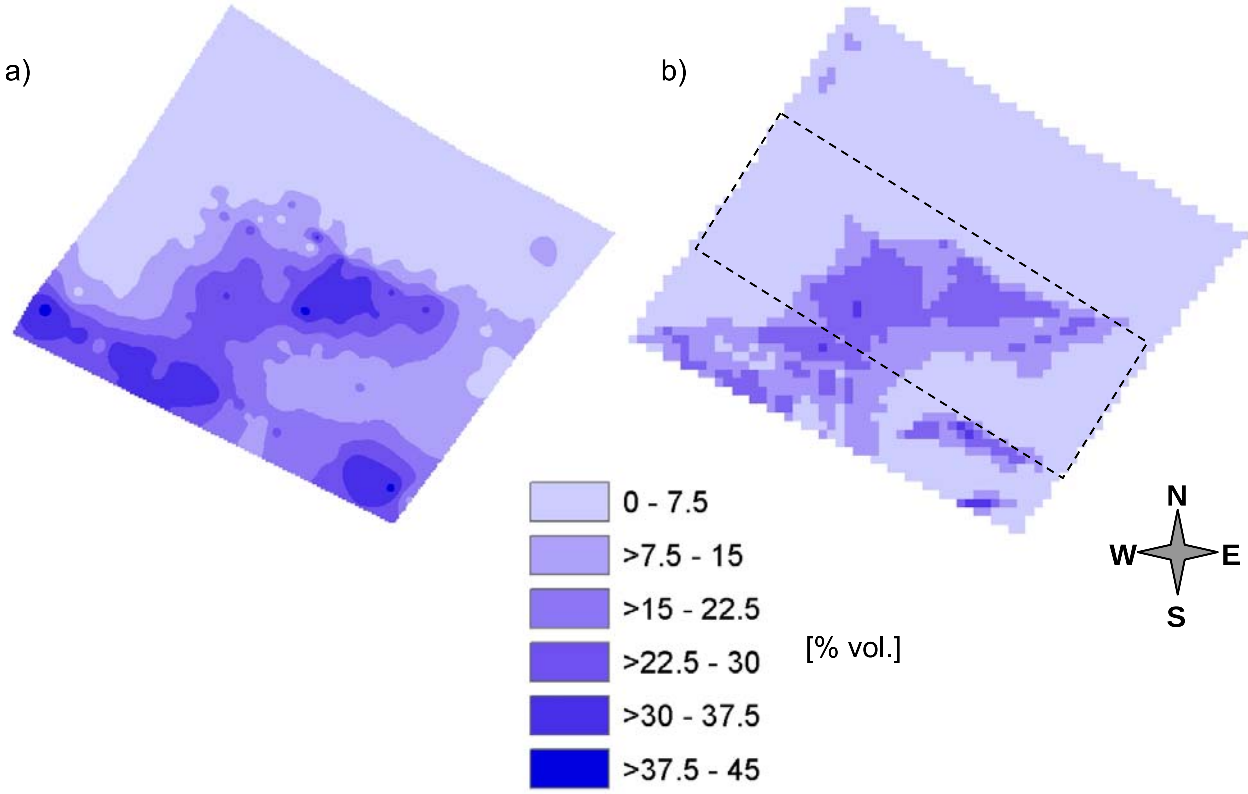


Figure 7: Surface soil moisture from July 30th 2004 determined from (a) FDR field measurements and (b) HyMap-based ratio calculation (1288 vs. 1515 nm) based on the regression function for quaternary sand. The dashed line shows the part of the area being covered with quaternary sand.

The comparison of the two resulting soil moisture maps shows that the resulting ratio feature image from the HyMap data (Fig. 7b) provides schematically an overall good conformance with the distribution of field soil moisture values (Fig. 7a). However, the soil moisture values deduced from the remotely sensed image are only valid for the area which is covered with quaternary sand, since the regression function was fitted to these samples only in order to receive more accurate results. Thus, the quantification is only valid for the area in the middle, which is bounded by the dashed line in figure 7b. Nevertheless, apart from minor variations, the northern area fits into the quantification scheme of the ratio-based approach as well. The southern parts of the images in figure 7 are covered with clays, so the ratio feature applied here significantly underestimates soil moisture values.

Generally, the range of values in figure 7b is slightly underestimated with respect to the field measurements. This effect is due to the heterogeneous soil water distribution in the upper five centimetres of the soil. Figure 8 shows the vertical soil moisture distribution for some exemplary samples taken in the dry period some days before the HyMap campaign. This figure shows that the deeper layers contain larger amounts of water than the upper surface layers at this specific date. Thus, measuring the soil moisture at the surface using remote sensing data cannot be compared directly to the measurements of the upper five centimetres undertaken in the field using FDR devices, but the additional information on vertical moisture distribution helps to interpret the results correctly.

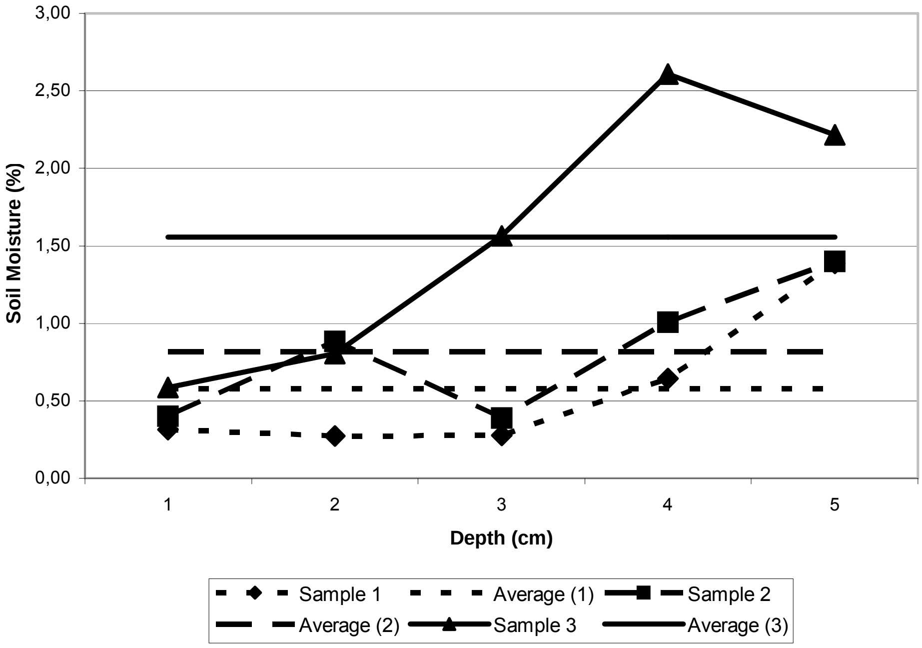


Figure 8: Soil moisture distribution in the upper five centimetres of three representative field samples.

Some of the remaining inconsistencies between the two images can be due to the presence of top-crusts in the field. Another potential source of error is the sparse vegetation in the lower part of the image. Additional techniques (e.g. linear spectral unmixing) must be applied to take these effects into account.

CONCLUSIONS

For the important issue of monitoring the erosion relevant parameter soil moisture, imaging spectroscopy techniques can make a major contribution. This paper shows that certain spectral features hold not only under laboratory conditions, but also in the field and for imaging spectroscopy approaches from airborne sensors.

This research is still in the validation phase and its robustness has still to be improved. Further spectral features will be surveyed and validated in the laboratory and field (vi). In order to apply the results to other types of soil, further research is necessary. The question has to be solved, if only one parameter brings up satisfying results. Confusion factors like surface roughness stated in other papers (vii) have to be taken into account more systematically and a sophisticated quantification model must be set up.

Since optical remote sensing can only be used to gain information on the uppermost surface, further information about the vertical moisture distribution is necessary for estimating parameters to be used in erosion models. Therefore, rainfall data in the field together with empirical information about soil specific infiltration rates will be taken into account in a next step.

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