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Mapping of soil surface crusts using airborne hyperspectral HyMap imagery in a Mediterranean environment

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Abstract. Soil surface crusting is a common but unfavorable process in Mediterranean environments. Soil surface crusts hamper infiltration of water into the soil and stimulate surface runoff, erosion and flooding downstream. Furthermore, crusts hinder germination of seeds and settlement of plants. Surface crusts develop within minutes during high intensity rainfall typical for arid and semi-arid environments. The raindrops destroy the soil aggregates and the aggregates disintegrate into the basic particles clay, silt and sand. Crusts are formed at the surface by compaction or by infilling of the inter-aggregate pore space. The objective of this study was to determine the spectral and physical properties of surface crusts in the field and to investigate the possibilities of hyperspectral airborne imagery to map soil crusts and to identify crusts types. Results show that the differences in some physical properties between crusted and non-crusted surfaces are significant while others show only marginal variation. Infiltration capacity is largely reduced by crusting. Spectral differences are small. Crusted versus non-crusted spectra differ mainly in albedo values (8 to 40%). No consistent changes are found in absorption features in the spectra of crusts and non-crusted surfaces. Some of the crusts show stronger absorption features in the clay mineral absorption bands at 2200nm. Spectral feature fitting and linear spectral unmixing algorithms were applied to HyMap images to evaluate the mapping of surface crusts. The presence of crusts could be mapped for fallow, agricultural lots but in case of natural badland areas the spectral response of the fragmented landscape was too complex to map the presence of crusts.

Keywords: Hyperspectral remote sensing, soil surface crusts, spectra, physical crust properties.

1. Introduction

Hyperspectral remote sensing or imaging spectroscopy register sunlight by the earth surface reflected in many, narrow contiguous spectral bands. The spectral signature and the absorption features in the spectra allow us to identify and to map certain soil properties and minerals present at the earth surface. Imaging spectroscopy was developed in the late eighties and has developed into a full grown, near-operational quantitative mapping technique (Van der Meer & De Jong, 2004). Here we investigate the possibilities of identifying and mapping soil surface crusts using airborne imaging spectroscopy.

Soil surface crusting and sealing are common processes on unstable soils in arid and semi-arid regions. Soil crusts and seals are thin layers with high bulk density, higher shear strength and finer pores compared to the underlying soil. Crusting is the response of the soil surface to intense rainfall causing the consolidation of surface particles. Sealing is the disintegration of structural elements by slaking or dispersion leading to infilling of the inter-aggregate pores or by welding aggregates into larger units. Crusting and sealing are unfavorable processes for a number of reasons (Bresson et al., 2006; Cerdan, 2001; Stolte et al., 1997; De Jong, 1992):

- they reduce the infiltration capacity of the soil and consequently stimulate surface runoff, rill and gully formation downhill and may contribute to flooding downstream;
- they hamper germination of seeds and the settlement of plants;

- they reduce the water retention capacity of the top soil;
- they reduce soil aeration and may hamper proper root functioning.

In this study we investigated the process of soil crusting, comprising both crusts and seals, in a Mediterranean area in southern France and the possibilities of using earth observation techniques to determine the spatial extent of the crusts. The objectives of this study were:

1) characterizing the physical and hydrological properties of the soil surface crusts compared to the non-crusted soil;
2) identifying the spectral characteristics of the crusted soil surface and non-crusted soil surface in the spectral range from 400 to 2500 nm using high resolution field spectra;
3) investigating the possibilities of mapping the spatial distribution of surface crusts using airborne, hyperspectral HyMap images.

The crusts that develop in our Mediterranean study area should not be confused with the biological types of crusts, biological crusts have in part similar unfavorable effects but their formation process is entirely different and their spectral properties are different due to their chlorophyll content.

2. Soil surface crusts

Aggregate stability plays a key role in the development of surface crusts. Strength of soil aggregates is influenced by a wide range of aspects like texture, organic matter content, calcium and iron content and moisture (Hillel, 2004; Roth and Eggert 1994; Le Bissonais, 1990; Farres, 1985). Rainfall or irrigation water may destroy soil aggregates by two processes: slaking and raindrop impact. Slaking is the breakdown of soil aggregates into smaller sized micro-aggregates when immersed in water. The second process that may destroy aggregates is the hammering impact of falling raindrops. This is a form of mechanical breakdown of soil aggregates. If a raindrop hits the surface, its kinetic energy, obtained by the falling velocity, breaks down the aggregate in several smaller aggregates or even discrete singular grains. Aggregates can also be broken down by swelling of clay minerals. Le Bissonais (1990) concludes from rainfall experiments that two different situations occur during rainfall: 1) if aggregates are saturated before rainfall, breakdown intensity is due to contact between water and aggregates, and the most important processes are slaking and micro-cracking, and 2) when aggregates are dry before rainfall, the breakdown intensity is due to rainfall kinetic energy and the most important process is mechanical breakdown or splash erosion. Under field conditions, morphological degradation of the soil surface is related to soil particle displacement by rainfall. The loose particles, resulting from aggregate breakdown by raindrop impact or slaking, are partially moved by splash erosion and carried into the soil mass by the infiltrating water where they fill the voids between other aggregates. This process is called 'washing in' and was already described by McIntyre (1958). When the majority of aggregates at the surface has been broken down, the impact of the raindrops hardens the surface crust. Boiffin (1985) refers to this as a structural crust. After the rainstorm a layer of variable thickness of particles, mainly clay that was in suspension during the rainstorm, is deposited on top of the skin seal. Boiffin (1985) calls this a depositional crust. Rainstorm characteristics like rainstorm intensity or frequency of raindrop impacts, are important for aggregate breakdown. The total rainfall energy and the total volume of rainfall are of minor importance.

3. Soil spectra

The spectral reflectance curve of a soil in the solar part of the spectrum (400 to 2500 nm) has a concave shape and is mainly determined by factors such as moisture content, organic matter content, texture, structure, iron content, mineral composition, type of clay minerals, and surface conditions of the soil (Van der Meer & de Jong, 2004; Ben Dor et al. 1999; De Jong, 1994, 1992). The spectral resolution is important because when soil spectra are measured at high spectral resolution (15 nm or less) with a large number of bands several diagnostic absorption features of minerals become apparent. This prerequisite limits the suitability of conventional satellite sensors such as Landsat TM and SPOT-XS for soil property mapping because their spectral resolution is too low (80 nm or more) and the number of spectral bands is too limited.

The hypothesis that a crusted soil will have a spectral signature different from that of a non-crusted soil is based on the idea that particle segregation does occur on the soil surface (Goldshleger et al., 2001) and that color and brightness differences are observed between crusted and non-crusted surfaces. The segregation process results in either chemical (minerals) or physical (particle size) differentiations which are both correlated to reflectance properties of soils.

4. Study Area and Field Methods

Our study area is located 60 km west of Montpellier in southern France and is characterized by various geological substrates. A large part is situated in the Lodève Basin consisting of Permian, continental fluvial-lacustrine, red and grey sediments (shales), local tuff deposits and small basalt outflows (Bonfils, 1993). The soils developing on these substrates are Regosols, Lithosols, Brown Soils, Calcareous Soils and Andosols on the basalt plateaus. These soils are shallow with an A-R or A-C profile and have low organic matter content. The climate in the area is a sub-humid Mediterranean climate with a long dry summer. Average annual rainfall is around 750 mm with a large inter-annual variability. Rainfall is concentrated in autumn (October and November) and in spring (April and May) but short severe storms with high intensity rainfall are quite common in the summer (Sluiter, 2005; Bonfils, 1993).

Airborne hyperspectral images collected by the HyMap sensor are available for the study area. The HyMap sensor is owned and maintained by HyVista (HyVista, 2008) and collects images in 126 spectral bands between 450 and 2500 nm with a spectral resolution of 15 to 20 nm and a spatial resolution of approximately 5 by 5 meters. An on-board D-GPS (Differential Global Position System) and INS (Inertial Navigation System) are used to automatically deliver geo-correct products. Airborne flights are carried out by the German Aerospace Establishment (DLR). The images were converted from radiance to reflection and orthorectified by DLR using the ATCOR4 software (Richter and Schläpfer, 2002) and PARGE software (Schläpfer and Richter, 2002). An ordered image acquisition campaign for the summer of 2007 unfortunately failed due to technical problems. Therefore HyMap images collected during an earlier campaign on 13 July 2003 were used in this study.

Quantitative information on the characteristics of crusts and the underlying soil and on their spectral signature was collected during a field campaign in the Salagou study area in the summer of 2007. A total of 107 plots of five by five meters were visited and described. An initial field survey yielded an overview of areas most prone to crusting. For each soil type a minimum of 10 crust samples was described for physical characterization. In addition, at least three infiltration experiments were carried out as well as a determination of aggregate stability and of the average spectral curve for crusted and non-crusted surface by a field spectrometer. At each location the following observations for crusted and non-crusted surfaces were made: soil type, land use, land management, thickness of the crust, cohesion of the crust and underlying soil using a Torvane, strength of the crust using a mini-penetrometer (Geotest, 2008), color of the crust and underlying soil, crust type, stone coverage, stone size and vegetation coverage, and in the case of crusts, number of cracks, average length and width of cracks. Infiltration capacity between crusted and non-crusted surfaces was determined by applying a constant flux by means of a Mariot bottle until steady-state infiltration was achieved (pre-wetting extending for at least 20 minutes). The constant flux over the steady infiltration surface area provides the infiltration capacity of the soil. Similarly, the infiltration capacity of the soil under the crust was determined to which end the crust was removed with a knife and the surface leveled to allow for an even distribution of water from the Mariot bottle and, consequently, vertical infiltration.

Field spectra of crusted and non-crusted soil samples were measured using an ASD Fieldspec Pro FR spectroradiometer (ASDI, 2008), covering the 350-2500nm wavelength region with a sampling distance of 1.4nm and a band width of 2nm. At each location a crusted surface, a non-crusted surface (if possible) and a soil sample where the upper crust was manually removed were measured for three locations within 1m^2. Per location an average of 50 spectra was taken. The manual removal of the crust was done to accurately measure and determines soil conditions of crusted and non-crusted samples. The spectra were measured using a soil probe, carrying its own light source of known strength and wavelengths. By covering the samples with the soil probe the measured samples were excluded from atmospheric interference. A white spectralon reference panel was used before each field measurement to calibrate the reflectance measurements.

5. Results

The field campaign showed that soil surface crusting is abundant in the study area in southern France. At the 107 sampling plots, large crusted areas were found on natural slopes with sparse vegetation cover, on bare agricultural fields and on agricultural fields with exposed soil such as vineyards and cereals. Although farmers frequently remove crusts by harrowing or plowing, surface crusts were almost ever-present, which suggests that crusts develop very fast after each rainfall event. Crust thickness did not differ between agricultural fields and natural areas despite the intuitive expectation that crusts in natural areas would be thicker as they are undisturbed and have unlimited time to develop. Both structural and depositional crusts were found in the area but the structural crusts were far more common. Depositional crusts were generally thicker than the structural crusts (average of respectively 4.2 and 3.4 mm) but spatial variability of crust thickness is very high, changing over short distances (decimeter-scale). No significant differences of crust thickness were found between the soil types or for land cover types.

Infiltration capacity, the soil characteristic most susceptible to crusting, differed significantly between the crusted and non-crusted soils and between soil types. On average, infiltration capacity was reduced by a factor 3 to 7. The infiltration capacity dropped most significant for Andosols. During the field experiments the importance of cracks on the infiltration capacity was noted. Cracks strongly stimulate infiltration at the beginning of the rainfall event but they close within a few minutes of intensive rainfall due to swelling or compaction. Twenty additional measurements were done to quantify the effect of cracks on the infiltration capacity. A significant positive relation was found between surface crack density and infiltration (r^2= 0.61). A significant negative relation was found between infiltration rate and crust thickness (r^2= -0.36). These findings confirm the importance of soil crusting in the generation of Hortonian overland flow because of the reduced infiltration rate.

Visual inspection of the spectra revealed that crusted surfaces show a higher albedo compared to non-crusted soil surface (between 8 and 40%). The higher albedo is most probably caused by lower moisture content and the finer texture of crusts. Furthermore, it was noted that when cracks develop in the crust, the albedo decreases, up to 25% compared to crusts without cracks (figure 1). The decrease in albedo is caused by the shades and dark areas of the cracks and the increased roughness of the surface. Main absorption features visible in the spectra are the major water absorption features at 1900 and 1400 nm. The minor water absorption feature around 1040 and 960 are not visible due to the dry conditions of the crusts and soils.

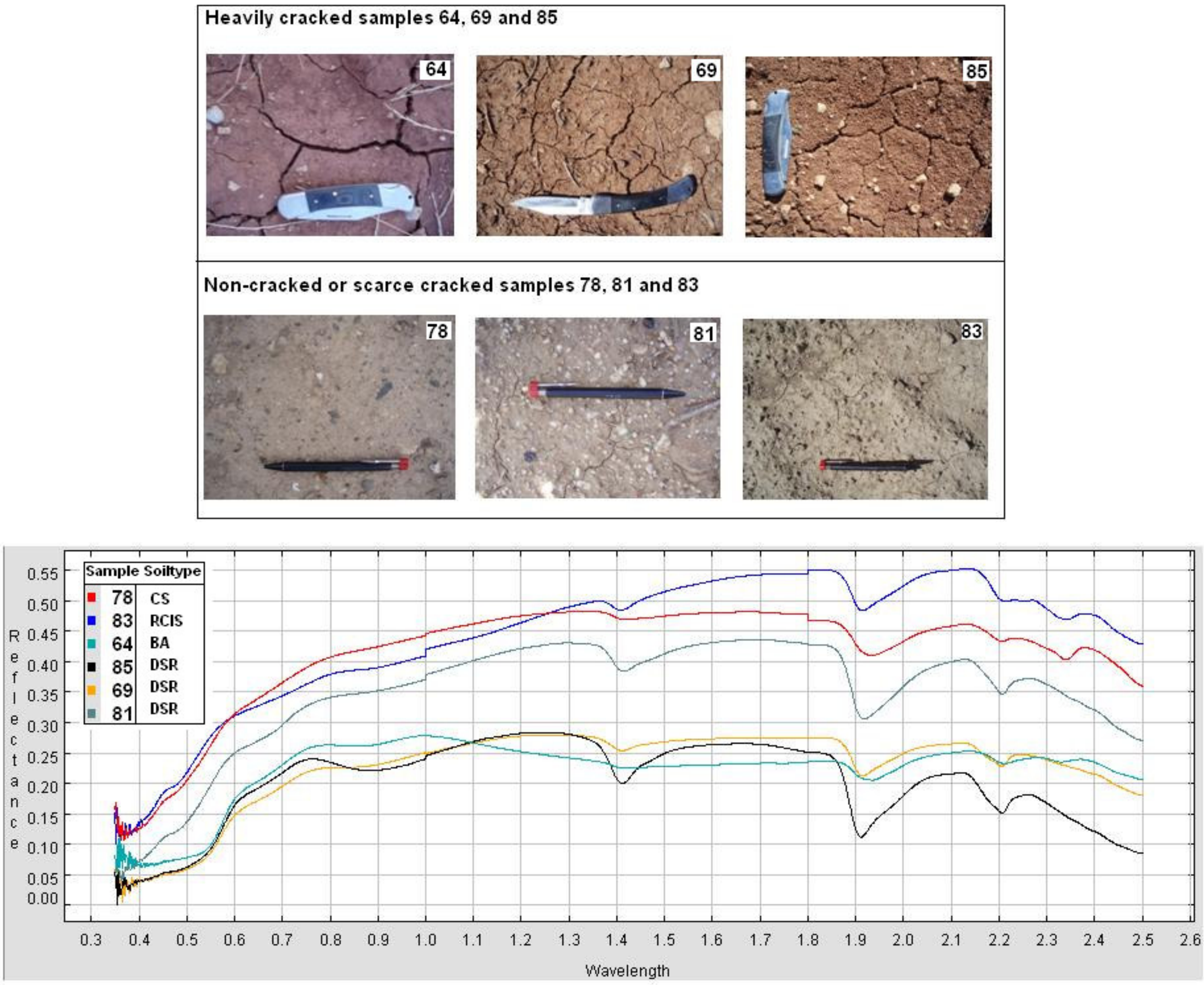

Figure 1: Photos of crusted soil surfaces with and without cracks (above) and their spectra (below). Note the decreased albedo of the crusted soil surfaces with cracks.

Other visible absorption features in the spectra are the iron features around 900 nm, clay mineral absorption bands around 2200 nm and calcite features around 2315 nm. Goldshleger et al. (2001) describe the relative enrichment of fine particles (mainly clay) by the aggregate destruction and crusting process and the resulting increased absorption around 2200nm in the spectra. To investigate this effect on spectra of crusted and non-crusted soils in our area, we applied a continuum removal algorithm (convex hull) to the soil spectra. The upper convex hull is calculated as an enveloping curve over the maxima of the spectra. Next, the hull-quotient of the spectra is computed by taking the ratio between the spectra and the envelop and used to characterize the absorption features in the spectra in terms of spectral position, depth, width and asymmetry (Van der Meer & De Jong, 2004). Absorption features at 2200 nm were found for crusted and non-crusted soils indicating the presence of clay minerals. The ratio between the 2200 nm absorption bands was computed for the crusted and non-crusted soil spectra. When relative enrichment of fine particles is detectable this would yield a ratio value above 1.0 for crusted surfaces. 58% of the soil samples showed stronger absorption for the crusted surfaces at 2200 nm, but differences were not significant. Spectra of crusted and non-crusted soil surfaces differ mainly in terms of overall average reflectance (albedo). These differences are mainly caused by color differences and moisture differences of the surface.

Next, we evaluated the possibilities of using airborne hyperspectral HyMap images acquired over the study area to determine the spatial distribution of crusted and non-crusted surfaces. The approach followed was to use the accurate, high spectral resolution field spectra as reference for detailed spectral analysis of the HyMap image. Two algorithms were evaluated and successfully applied: linear spectral unmixing (LSU) and spectral feature fitting (SFF). Linear spectral unmixing assumes that the reflectance of an image pixel is a linear combination of the reflectance of the materials (surfaces) present within that pixel like bare soil, crusted soil, vegetation, crop residues (Adams and Gillespie, 2006). LSU aims at unraveling the image pixel spectra by using the reference spectra, sometimes also referred to as endmembers. These reference spectra can be collected from the HyMap image itself, or from spectral libraries, but we preferred to use our detailed field spectra of the soil surfaces and other targets. Spectral feature fitting (SFF) is an algorithm that matches absorption bands in image spectra to reference spectra collected in the field or laboratory (Van der Meer and De Jong, 2004; Clark et al., 1990). Continuum removed image spectra are used and compared to continuum reference spectra. A least-squares fit is calculated band by band between reference spectra and the HyMap image spectra. SFF results in maps giving the similarity of absorption feature depth between image and reference spectrum.

Only the results of the SFF are presented here in figure 2 for a subset of the study area. The figure shows the original HyMap image in a color infrared combination on the left and on the right the SFF product of the HyMap image with the crusted Red Lithosol spectrum used as endmember. Red tints indicate the best match, blue and purple a poor match and black areas are masked out due to a very poor fit. LSU and SFF identify the same lots as crusted but do not correspond in the degree of crusting within and between the lots.

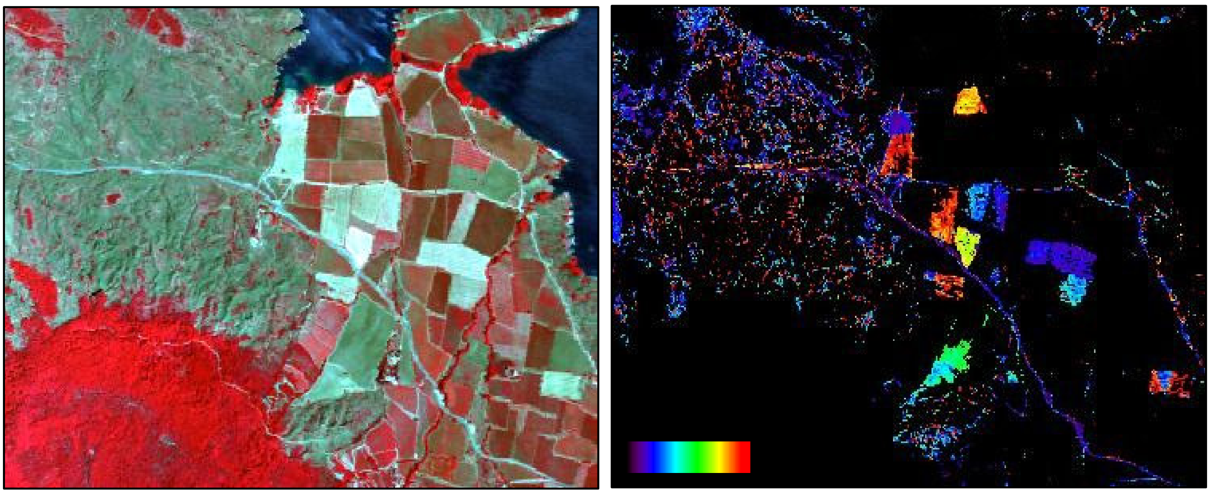

Figure 2: Left the original HyMap image in a color infrared combination and right the result of the Spectral Feature Fitting algorithm using the crusted Red Lithosol reference spectrum. The rainbow color palette indicates the match of the absorption feature between the field reference spectrum of the crusted Red Lithosol and the image spectra. From Red to purple: good to poor match.

6. Discussion and Conclusions

In this study the occurrence and properties of soil surface crusts was investigated in a Mediterranean study area in France. Soil surface crusting is a common but unfavorable process because it stimulates runoff and erosion and hampers vegetation development. Soil surface crusts are abundant in the area on agricultural soils but also on natural bare or sparsely vegetated soils. Both crust types, depositional and structural, occur in the area. Structural crusts are most common. Crusts are formed in minutes at the beginning of a rainfall event, dry out and crack within hours after the rain ceased. For various soil types physical properties of the soil surface crusts and the underlying soil were determined. Crust thickness and strength show a high spatial variability. Crust characteristics may drastically change within decimeters. Infiltration capacity of a soil may be reduced by a factor 3 to 7 by the presence of a surface crust.

The suitability of hyperspectral earth observation for mapping soil crusts was investigated. Accurate field spectra of non-crusted and crusted soil surface revealed differences in albedo (overall reflectance). No significant differences in absorption band depth or position was found. The spectral mapping techniques linear spectral unmixing and spectral feature fitting were applied to airborne, high resolution hyperspectral HyMap images of the study area. We collected the field spectra that were used as reference spectra. Although the spectral differences of crusted versus non-crusted soil surface are small, it was possible to identify spatial patterns within and between agricultural fields having surface crusts and having no surface crusts. The spectral unmixing algorithm is superior over the spectral feature fitting. For the natural areas, bare or sparsely vegetated, it was not possible to map surface crusts due to the complexity of the landscape and the resulting noisy spectral response of these areas in the HyMap imagery. Although the use of hyperspectral imagery seems promising, the results should be used with care because the spectral differences between the soils and between the crusted and non-crusted surface are subtle and accurate validation of the mapping results is complicated due to the spatial (sub-pixel) and temporal variation of the crusts .

Future studies may investigate the suitability of using object-based remote sensing mapping methods. Such methods group pixels together in objects of similar spatial and spectral properties and will enhance the subtle differences between the various soil surfaces.

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