Monitoring infiltration rates in semiarid soils using airborne hyperspectral technology

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Abstract. Loss of rain and irrigation water from cultivated fields is a matter of great concern, especially in arid and semi-arid regions. The physical crust that forms on the soil surface during rain events is one of the major causes of increased run-off and reduced water infiltration into the soil profile. Based on previous studies that showed significant correlation between crusted soil and soil reflectance properties, we performed a systematic study over Loess soil from Israel, in order to map the infiltration rate from a remote distance, using Hyperspectral (or Imaging Spectroscopy, IS) technology. First, we simulated rain events under laboratory conditions, using the selected soil and varying rain energy treatments. After measuring the reflectance properties of the crusted soils, we developed a spectral parameter for assessment of crust status. The parameter, Normalized Spectral Area (NSA), uses the area under a ratio spectrum across the VIS-NIR spectral region (calculated from the ratio of the crusted (treated) soil spectrum to the non-crusted soil spectrum). The correlation between the NSA and infiltration rates values provided a significant calibration equation. Based on these results, we conducted an airborne campaign, employing the AISA imaging scanner adjusted to 30-channel data in the VIS-NIR, and established control plots (crusted and non-crusted soil) on the ground, to examine the NSA parameter for mapping the infiltration properties of Loess soils. Reasonable agreement was obtained between the two datasets (laboratory and air), suggesting that infiltration rates can be estimated remotely. Further research is necessary to expand the analysis to other areas and conditions (e.g. diverse CaCO₃ and moisture content of soil). The paper shows that spectral reflectance information in the VIS-NIR region can be used to assess soil infiltration affected by the soil crust, in both laboratory and air domains. It is strongly suggested that future study in this regard use the full optical range (VIS-NIR-SWIR-TIR), as well as a spectral library of crusted soils collected in or within the rain simulator environment.

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1. Introduction

Soil erosion by water runoff is a matter of great concern in both bare and agricultural lands. This process may lead to significant effects such as loss of water to the soil profile, decline in soil fertility and productivity, and increased peak stream flow, as well as associated floods. The main cause of the runoff from rain and overhead irrigation water is the structural crust (a term coined by Hillel 1959) that develops over bare soils during rainfall or irrigation events and significantly reduces the soils’ infiltration rate. The hydraulic conductivity of this crust is a few orders of magnitude lower than that of the underlying soil (e.g. McIntyre 1958, Morin and Benyamini 1977). Whenever the hydraulic conductivity of the crust is lower than the rainfall intensity, ponding, runoff and soil erosion will occur.

The structural crust is formed by two complementary mechanisms (Agassi et al. 1981): (a) physical disintegration of aggregates at the soil surface, rearrangement and compaction of the disintegrated soil particles forming at the ‘skin’ seal; and (b) physico-chemical dispersion of the clay minerals and migration of the fine particles into the soil with infiltrating water, clogging pores immediately beneath the surface and forming a layer of low permeability termed the ‘washed in zone’ (McIntyre 1958, Onofiok and Singer 1984).

Most of the available methods for assessing the physical crust status use disturbed soil samples, which do not represent exact field conditions (Keren and Singer 1989, 1991) or simulation techniques, which cannot mirror exact field conditions (Agassi and Bradford 1999). Consequently, mapping and predicting soil structural crust processes are of great interest and importance to soil scientists and farmers. Apparently, crust potential mapping is not a straightforward matter, and to the best of our knowledge, this technique has never been employed.

Recent studies by Goldshleger et al. (2001, 2002) and Ben-Dor et al. (2003), based on the first works of this type (De Jong 1992, Metternicht 1998), have revealed a significant relationship between selected wavelength readings and infiltration rates, when measured under controlled laboratory conditions. Furthermore, these recent studies were able to create a spectral library that contains spectra of three soils from Israel, in varying rain energies and crust positions, and to show that a different correlation existed for each soil.

In general, remote sensing using reflected solar radiation provides rapidly and effectively a wide spectral and spatial view of areas. In this respect, hyperspectral remote sensing (also known as imaging spectroscopy (IS) technology), which provides a near-laboratory-quality reflectance spectrum of each pixel, may bridge the gap between the laboratory spectral knowledge and quantitative soil mapping applications. IS is rapidly gaining recognition as a tool for precise and quantitative analysis of the atmospheric-terrestrial systems from far distances, which allows identification of objects based on their well-known spectral absorption features (Clark and Roush 1984, Goetz and Curtis 1996, Ben-Dor et al. 1999). Because significant spectral changes occur within the soil surface as a result of raindrop impact (see Goldshleger et al. 2002), it is assumed that the IS technology will capture the spatial variation within a rain-affected field and provide a real-time spatial overview of related properties of the soil crust (such as soil erosion and infiltration).

To the best of our knowledge, a comprehensive spectral study combining the capability of reflectance radiation (to detect the physical crust status in the laboratory) and IS technology (to collect high quality spectral data on a spatial domain) has not yet been conducted or considered. Thus, the purpose of this study is to examine the effectiveness of IS technology, combined with careful laboratory
and field measurements, in identifying soil properties that are related to the structural crust formation and status of agricultural soils in Israel.

2. **Materials and methods**

The area selected for this study consists of the fields of the Gilat experimental farm station, located in the Negev area of southern Israel (see figure 1). The soils in this area are Loamy Loess, defined as *Loess* by the local Israeli definition system (Dan and Raz 1970) and calcic haploxeralf according to the USDA definition (Soil

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![Figure 1. Location of the research area.](image-url)
Survey Staff 1975). The mechanical composition is 28% clay, 47% silt, and 25% sand; the mineralogy of the soil, estimated by XRD is ≈14% montmorillonite, ≈50% kaolinite, ≈27% illite, and ≈17% calcite. The area is relatively dry, having annual precipitation of about 200 mm, concentrated mostly during December through April. Some of the area is used for intensive agriculture activity, irrigated both artificially and naturally. The particular area selected for this study is a mixture of vegetation in several growing stages of beans, wheat, and barley, and bare Loess soil in several crusting stages, from ploughed to heavily crusted soil.

2.1. The AISA overflight

The airborne sensor selected for this study, the Airborne Image Spectrometer for Applications (AISA) (Makisara et al. 1993), is a programmed computable push broom airborne imaging spectrometer with wavelength range between 400 and 900 nm. The size of the CCD detector array is 384 by 286 pixels and the spectral bandwidth is >1.5 nm (max. 186 channels), which can be summed up to 9.6 nm. The swath width is 384 pixels and the IFOV is 1 mrad, enabling a pixel size of 1 m from a 1000-metre altitude where the FOV is 22°. The integration ('exposure') time is 4 ms, and the pixel data are digitized to 12 bits.

On 24 March 2001, the AISA sensor was mounted onboard a twin-engine piper Aztec aircraft and flown over the study area at an altitude of 3000 m (providing about 3 m pixel size and 1.2 km swath) with 30 spectral bands (421–888 nm) characterized by Full Width Half Max (FWHM) ranging from 1.55 nm to 1.71 nm (see table 1 for more details). The band configuration was selected to capture vegetation and soil signals from the ground. The signal-to-noise ratio of the sensor over a 50% albedo target provides reasonable values, ranging around a value of 90 (maximum 125, minimum 20). During the flight, a cosine receptor was mounted on the aircraft roof, to collect the down-welling radiation. In addition, an INS-GPS combined system was used to record geo-positional data of the aircraft for the purpose of future geometric rectification. The raw data were radiometrically converted into radiance using laboratory calibration file provided by the SpecIm company, which were collected prior to the flight. The radiance data were corrected into reflectance units using an ACORN code (Atmospheric CoRrection Now, ACORN 2001) polished by ground reflectance spectra of four soil samples that were taken during the overpass on the ground, using the Empirical Line (EL) methods (Roberts et al. 1985). ACORN is a program that uses MODTRAN 4 code

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to derive scaled reflectance data of IS images by modelling the scattering and absorption effects of the atmosphere. A hybrid strategy that combines relative (e.g. EL) and absolute (e.g. ACORN) methods is known to provide better results than each of them separately (Clark et al. 1993); this justifies the procedure employed for the retrieval of the reflectance data described below.

2.2. Laboratory study

2.2.1. Rain simulator

Soils were collected from a nearby field, brought to the laboratory, air-dried, and then passed through a 4-mm sieve. Two experiments (several months apart) were conducted using two batches of soils, in order to determine the relationship between the spectroscopy and the infiltration rate of the soil in the laboratory. The soils in each experiment were identically packed into 30 cm × 50 cm perforated soil boxes, 4 cm deep, over a 6 cm layer of coarse sand. Four runs (two for each experiment) were employed. For each run, the boxes were placed on a soil-box carousel, five boxes per run, at a 5% slope, and were subjected to a simulated rainstorm, using distilled water (Morin et al. 1967). In each experiment, in the first run, the simulated rainstorm provided a fog-type rain (no energy), with an intensity similar to the soil-infiltration rate. The storm lasted until the measured rate of percolation (in this case, also infiltration) reached that of the measured intensity of the simulated rainstorm. Then the rainfall was stopped and the soil boxes were left to rest until drainage from all the boxes ceased. One soil box was randomly taken out and photographed. In the next stage, the rainfall energy was changed to \( \sim 22.3 \text{ joule mm}^{-1} \text{ m}^{-2} \). The carousel was rotated again with the four remaining soil boxes, which were subjected to rainstorm intensity approximately similar to the initial infiltration rates of the soil. First, the storm was continued until \( \sim 3.5 \text{ mm} \) of rainfall had been applied (equal to \( \sim 70–80 \text{ joule} \)), during which time the infiltration rate was continuously measured. Then one box was randomly removed and photographed. This procedure was repeated several times until \( \sim 89 \text{ mm} \) of rainfall had been accumulated (see table 2 for more details). After the rainstorm was stopped, the soil boxes were oven-dried for 48 h at 35°C and then at room temperature for a week. Table 2 also includes the equivalent infiltration rates measured for each rainstorm event, the accumulated quantity of rain, and the corresponding energy. Without disturbing the soil crust, 15–20 soil samples were taken from each box, for spectral reflectance measurements in the laboratory. These measurements were carried out using an ASD spectrometer with a portable light source, which measures soil samples under a constant halogen illumination and reflectance geometry conditions across the VIS-NIR-SWIR region (0.4–2.4 \( \mu \text{m} \)). The reflectance of the soil samples was measured against Halon, and the final spectrum of each measurement was calculated relative to this reference. An average spectrum for every rain treatment was calculated, using the samples taken from each soil box. The spectra were stored and later processed to analyse the spectral-infiltration relationship.

2.2.2. Chemical analysis

In several locations around the study areas, samples were collected from an area of about 5 m\(^2\) at the surface (the upper 1 cm). These were brought to the laboratory and analysed for CaCO\(_3\), using the gasometric method (Jackson 1979), in which a soil sample exhausts CO\(_2\) into a closed system, based on the reaction with HCl. The
CO₂ is measured and compared to the CO₂ volume exhausted by a standard CaCO₃ powder of the same weight. Three replications were conducted for each soil sample and the average was used for interpretation. Soil colour was determined using the Munsell colour chart (Munsell Color Company, Inc., 1975) under diffused (shade) radiation on a sunny day.

2.3. Field study

During the overpass, soil samples were collected from several targets in the area to enable rectification of the radiometric measurements into relative reflectance. Also, sun photometer data was acquired for future atmospheric correction of the AISA data. Four soil-control plots in the agricultural fields of Gilat farm were selected to study the crust spectral response from the air. The plots were characterized by a noticeable crust, which had formed during a prolonged period of rainstorms over the last two months (100 mm). Each plot was divided into two subplots: (a) the ‘non-crust’ plot, composed of bare soil, with the thin crust broken by gentle ploughing of the upper soil layer 24 hours before the flight, and (b) a ‘crusted’ plot, composed of crust soils (formed by natural rain) with noticeable crust occurrences. The last rain event in the area (affecting the ‘crusted’ plots) was reported on 10 March 2001 (2 mm) suggesting that the soil maintained a basic hygroscopic moisture capacity which was measured to be around 4%.

3. Results and discussion

Figure 2 is a flow chart of the stages of the complex study. Figure 3(a, b) provides a grey scale subset image (band 14, 576 nm) that was sampled from the entire flight line image and covers the study area. In addition, the selected control plots and exact locations of the soil sampling for CaCO₃ are also overlaid on this image (a). The study area is rather flat, characterized by vegetation (beans, barley,
and wheat) alongside the bare soil plots (with and without organic residual). The soil plots are marked 1–4 in Figure 3(b) for the purpose of further discussion. As mentioned earlier, each soil plot was divided into two subplots, one non-crusted and one crusted. The image reveals that albedo variation occurred within the selected plots 1–4, as well as in other areas. One of the major factors of soil brightness in an arid environment is CaCO$_3$ content. This component can be assessed simply with IS technology, by using the strong absorption feature at 2330 nm (Gaffey 1986). However, since the AISA sensor does not cover the SWIR region, this information cannot be extracted from the current database and hence cannot be used to confirm or reject the above brightness assumption. To examine this, we conducted a field study in which 18 samples from the areas (for the exact locations, see Figure 3) were randomly sampled and analysed in the laboratory for CaCO$_3$ content (see §2 for more details). The plots of the CaCO$_3$ content versus the albedo parameter of each ground target (calculated from the area under the spectral curve, between 489 and 888 nm) are presented in figure 4. As shown, poor and non-significant correlation is obtained between the two parameters, suggesting that the albedo tone variation may have emerged from another source.

One of the possible sources for albedo (and colour) changes in bare soil fields is physical crusting. In this process, the finer particles that migrate to the soil surface (Chen et al. 1980) change the reflectance properties of the soil, so that soil colour variation is visible to the naked eye (De Jong 1992). This thesis is based on the well-known phenomenon in which fine particle size increases the overall reflectance value of a given material (Clark 1999). In the present research, the crusting process may be the reason for this variation in tones. From ground truth observation, bright
Tone areas are located along plots characterized by physical crust, whereas dark tone areas are located in areas that represent non-crusted soils (either gently or heavily ploughed).

Figure 3. A grey-scale image (band 14, 576 nm) of the research area, the location of the ground soil sample (for CaCO$_3$ content analysis) (a) and the control plots (crusted and non-crusted) (b).

Figure 4. The relationship between CaCO$_3$ content and albedo (the area under the spectral curve between 489 to 888 nm) of the samples shown in figure 3.

tone areas are located along plots characterized by physical crust, whereas dark tone areas are located in areas that represent non-crusted soils (either gently or heavily ploughed).
Figure 5 presents a ground overview of one of the field plots (plot 3 in figure 3) after breaking the soil crust with a discus (non-crusted) 24 hours before the flight; some slightly crusted areas are visible at the edge of this plot. The photo also shows a close nadir view from 80 cm. To the naked eye, a soil colour change from bright to dark tones can be seen within the soils, which corresponds to the degree to which these are crusted. Examination of a Munsell colour chart (Munsell Color Company, Inc., 1975) before and after the crusting process revealed changes within the soil chroma from 7/5 YR 5/4 (bulk) to 7/5 YR 5/2 (highly crusted), respectively. Although the differences are not marginal, the slight visible colour change does suggest that spectral changes occurred within the soil surface, and soil spectroscopy might be used as a tool for assessing the crusting status.

Extracting the spectra of each plot (calculated from an average of about 40 pixels) shows that the spectral base line (and hence the soil albedo) is higher in the crusted soils than in the non-crusted soils. Figure 6 shows the spectral reflectance of the selected plots, with and without the crust layer. The crust plots are higher than the non-crusted plots, by about 3–6% (reflectance units) or about 30% (in relative values.)

In order to explain the relationship between the spectral parameter of the crusted soils and the raindrop impact and other related properties, we spectrally analysed the data obtained from the rain storm simulation in the laboratory. Figure 7 provides an overview of the soil in the laboratory tray after applying a rainstorm at energies of 613 and 1842 joule m\(^{-2}\) (taken from the first experiment). The bulk soil with no rain energy (non-crusted soil) is also presented. This figure clearly reveals that albedo changes occur precisely as observed in the field, that is, when the raindrop energy is high, the soil is brighter, and when the raindrop energy is low (or nonexistent), the soils are darker. To test this observation objectively, we
measured the reflectance of each rain treatment, and positioned them on the same plot for all runs of both experiments (figure 8(a, b)). Figure 8(a, b) also reveals a noticeable spectral sequence, going from low raindrop energy (slightly crusted) to high raindrop energy (highly crusted) in both experiments. These values are equivalent to high and low infiltration rates, respectively, as measured simultaneously during the rainstorm event. This is presented in table 2. The overall reflectance changes observed in the laboratory were similar to those revealed in the image: 3% in the lower energies and 8% in the highest energy levels. As shown, the

Figure 6. The reflectance spectra of the control plots in both crusted and non-crusted position. Dotted lines represent the crusted soil (light tones in figure 3(b)) and solid line, the non-crusted soil (dark tones in figure 3(b)).

Figure 7. Three images showing the crust position after the rain simulator treatments in three different rain energies: (a) 0, (b) 613 joule m$^{-2}$, and (c) 1842 joule m$^{-2}$.
shape of the spectra is constant with rain energy (no new spectral features or slope changes occur when going from one rain energy to another), and the only significant spectral change is the reflectance offset. It is interesting to note that Goldshleger et al. (2001) found that in the SWIR region, not only albedo changes, but changes in the spectral features positions and intensity, as well, are also noticeable. This is based mainly on the specific spectral information of OH in clay minerals across the SWIR region, which is not active in the current AISA VIS-NIR spectral region.

Although the VIS region is less informative than the SWIR region, the albedo changes observed in the laboratory treatments suggest a possible quantitative relationship between spectral parameters and the crusting phenomenon. In order to explain such a relationship, we suggest using a new spectral indicator that is compatible with other datasets (either airborne, field, or laboratory measurements). This indicator, termed a Normalized Spectral Area (NSA), which is the area under the ratio curve, is generated by using a crusted soil (test) spectrum against standard non-rusted soil (reference) spectrum.

The advantages of this NSA parameter are that it does not depend upon any certain wavelength absorption features, it eliminates systematic noise that appears in both the tested and reference samples, it can mimic non-visible features, and it enables the comparison between different spectral datasets.

Applying the suggested transformation of the original laboratory data provides the ratio spectra series shown in parts ‘a’ and ‘b’ of figure 9 for the two experiments, respectively. As the figure illustrates, the area under the ratio spectra increased as the rain energy increased and the infiltration rate decreased. Also noticeable is the featureless spectral curve obtained in the entire ratio spectra, confirming the assumption that no significant VIS spectral features changes occur in the current soil population. Plots of the area under the ratio curve against the infiltration rates for all samples from both experiments are presented in figure 10. A significant relationship between the two parameters (infiltration rate versus the NSA) was obtained ($r^2 = 0.91$, $n = 19$). Based on the normalized strategy and the previous field observation, we assume that the linear equation obtained in the laboratory experiment represents well the crust status in the field and hence may be applied to the ‘soil’ pixels for estimating the crust-related properties in a spatial overview.
The next stage was then to apply the crust spectral-based calibration extracted from the laboratory measurements to the image data. To do so, we processed the reflectance image data in the same way that the laboratory spectral data were processed. For this purpose, we selected a polygon from a selected ‘non-crusted’ subplot of plot 3 (see figure 3) and used it as a reference in which the NSA could be calculated for every pixel in question.

Figure 11 provides the ratio spectra derived through this procedure for all four control plots presented in figure 5. The selected ratio spectra indicate a similar trend to the laboratory spectra, that is, a straight line with minor spectral changes.
throughout the entire spectral region and higher reflectance of crusted soils (in terms of ratio values) than of non-crusted soils.

The non-crusted soils hold ratio values around unity, with a weak spectral feature at around 680 nm that may be attributed to chlorophyll remaining in each of the plots. It is interesting to note that this feature was barely noticeable in the original spectrum, and hence demonstrates the ability of the spectral ratio technique to mimic small spectral changes. On the basis of the spectra of the four plots (crusted and non-crusted), it is possible to estimate the current crust status position of each plot, by extracting the infiltration rate and using the calibration curve in figure 10. In figure 12 we plotted the NSA values of the 18 soil samples (see figure 5) against the CaCO$_3$ content of each soil (taken from the image). As the figure illustrates, no correlation between the two variables is obtained, suggesting that the NSA parameter is not sensitive to the CaCO$_3$ variation in the area. Based on the fact that the soils were relatively dry and the moisture content has no significant variation in the area, the tone’s variation, and hence the NSA parameter, can be attributed confidently to the crust status. The NSA values of plots 1–4 demonstrate how the NSA parameter can spot qualitative shade on the crust status: plots 1–3 maintain low NSA values, while plot 4 shows relatively high NSA values, even in its ‘non-crust’ condition. Checking the records of plot 4 reveals that the non-crusted soil was lightly crusted, as it was not broken prior to the flight, but about a month before. During that time, several rainstorm events occurred, developing a physical crust in these soils, so that it differed from non-crusted areas in plots 1–3.

In order to apply the calibration equation obtained in the laboratory to the...
entire area, and not only to the controlled plots, it was important to mask out all non-soil pixels. The ratio spectra of several vegetation targets shown in figure 13 demonstrate that the ratio technique still maintains spectral identification of non-soil targets. This capability can therefore be used to mask out the non-soil pixels from the analysis, in order to estimate the infiltration rate (InR), pixel-by-pixel only, on all of the soil. To do so, we ran the SAM classifier (Kruse et al. 1993) on the ratio image using a threshold angle of 0.01 mRad and two end members from the image, representing high and low chlorophyll content (dense and poor vegetation respectively), as already shown in figure 13. Following this, we applied

Figure 12. The relationship between the CaCO₃ content versus the NSA parameter of the samples shown in figure 3.

Figure 13. The ratio spectra of two vegetation end members (against a spectrum of selected soil that represents non-crusted area), applied to mask out the vegetation pixels from the soil crust analysis.
the linear equation given in figure 10 to the vegetation-masked image on every ‘soil’ pixel. The result is an image with a colour ramp representing the ‘infiltration rate’ (InR) values (figure 14).

In the processed image, several areas holding high and low InR values can be seen. The low InR area (marked as A on the image) is a ploughed (dry) field, which exhibits NSA values within the detection limit of the InR calibration curve. Based on the NSA values of this soil, it is assumed that the current plot is holding a good (non) crust condition, in which the soil infiltration potential is high and the erosion risk is minimal. The high InR areas (marked as B, C, and D) are holding InR values that are outside the calibration range. Area B represents a dirt road enriched with high CaCO₃ content (27%) lime, which is relatively higher than the average CaCO₃ content of the entire population of 13.8% (SD 5%). Area C also consists of high CaCO₃ content (30%), is thus not expected to be crusted under the current analysis. Area D consists of CaCO₃ content of 14.6%, and hence represents a significantly crusted area. In practice, when CaCO₃ may affect the tones values of the crust status, a discreet segregation should be applied to the data using the spectral channel at 2330 nm for point detection of CaCO₃ content (Gaffey 1986). Then, different calibration equations for several CaCO₃ intervals may be examined in the laboratory and applied to the data in steps. In this respect it should also be noted that as the OH assignment at 2200 nm is correlated with the crust status (Ben-Dor et al. 2003), this wavelength may be also applied to the analysis in all future IS-crust analysis. For that purpose, however, an IS sensor that covers the entire VIS-NIR-SWIR region is necessary. Apparently, the current AISA sensor does not go beyond 900 nm and hence the masking procedure has to be manually applied. Another factor inherent in the calibration results is the soil moisture status.
(wet or dry), which also can change the soil colour tones. This parameter can also be masked out by using the SWIR or TIR spectral region, as shown by Bowes and Hanks (1965). Another variation in the soils is remaining organic matter, which can be also masked out in the VIS or even by the SWIR spectral region (Ben-Dor et al. 1997).

In the current area, the CaCO₃ maintained similar values, with limited exceptions, which have already been discussed. The soil moisture was also similar in the area, as all soils were similarly dried after the last rain events. Thus, the InR image presented in figure 13 provides a reasonable overview, confirming the field observations. As discussed previously, adding the SWIR (and, one hopes, the TIR, as well) region into similar analysis may yield a better and more confident InR map. It can mask out problematic pixels and provide more spectral information about other factors in the scene.

Further study in this direction is necessary in order to improve the accuracy of crust mapping and perform it totally independently of field information. The spectral information suggests that there is a significant potential to do so in more complex soils systems. For this purpose, a comprehensive spectral library of crusted representative soils should be built, and better sensors should be used (in terms of signal to noise and spectral coverage that consist of the VIS-NIR-SWIR-TIR spectral region). This paper, to the best of our knowledge, is a pioneer in the direction of extracting factors such as infiltration and erosion potential from IS data. We hope that it will serve as a precursor for further study in this direction. The importance of the paper lies in its demonstration that IS technology can be used to extract reliable spatial information about soil crust-related problems. For farmers in arid and semi-arid environments, such information, provided in a real-time mode, offers a highly valuable way to preserve their lands.

4. Summary and conclusions

The main conclusion of this study is that reflectance properties of Loess crusted soils have a systematic relationship with the crust status. In the soil examined, the albedo parameters across the entire VIS-NIR region correlate significantly with raindrop energy, and particularly with infiltration rate. A normalized spectral curve, using a non-crusted soil spectrum as a reference, was found to be a reliable database in which spectral information from one sensor to another can be compared. Doing so enables the utilization of the laboratory spectral relationship with those which IS provides. The spectral variation among the selected plots in the field remained within the confidence range provided by the laboratory experiment. The pixel-by-pixel calculation for InR in the soil provided a reasonable picture for the selected area and their surroundings. High InR values mapped outside this area were suspected to reflect high CaCO₃ content, generating further consideration of the use of IS in SWIR regions. Although the VIS-NIR spectral region is limited, the results show that it is possible to map crust-related problems from the airborne platforms combined with careful laboratory work. Further study in this direction, based on the present results, is strongly recommended. The creation of a comprehensive spectral library of many other soils in varying rain energy regimes, and use of IS sensors that cover the entire VIS-NIR-SWIR-TIR region are the issues that warrant further investigation. We hope that more ideas and thoughts on how to further apply IS further in this direction will be presented by additional researchers.
Acknowledgment

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Monitoring infiltration rates in semiarid soils


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