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MAPPING SOILS WITH VISIBLE AND INFRARED REMOTE SENSING TECHNIQUES

Abstract - Traditionally, pedologists have used aerial black and white photographs to address soil surveys in the field and speed the process of making soil maps.

The high cost of color photographs produced its non use even when they could have provided more accurate information. Nowadays, satellite and imaging spectrometer data are becoming more and more available as well as software to interpret these data. The capacity of recognizing patterns of soils or features that can be related with the pattern of soils in an area make these techniques attractive to pedologists, especially in those countries that require a more affordable way of knowing their environment than slow and too expensive field surveys.

The purpose of this paper is to analyze the capacity and accuracy of the visible and infrared remote sensing techniques applied to classify and map soils based on some of the latest advancements done in this field.

Riassunto - *Cartografia pedologica mediante l'uso del telerilevamento del visibile e dell'infrarosso*. Per tradizione i pedologi hanno sempre usato per le loro interpretazioni fotografie aree in bianco e nero per la realizzazione di carte pedologiche.

Il costo elevato delle foto a colori è sempre stato un ostacolo per il loro uso, anche se avrebbero potuto fornire informazioni più accurate e dettagliate dell'area di studio. Attualmente i satelliti e le informazioni fornite dalle immagini spettrometriche sono sempre più alla portata dello studioso così come i softwares di interpretazione dei dati.

La capacità di poter riconoscere tipi di terreni o particolari caratteristiche pedologiche che possono essere messe in relazione con tipi di suoli particolari, specialmente in quelle regioni che richiedono uno studio ambientale accurato e nelle quali un rilevamento sul terreno si rivelere troppo lento e costoso.

Il proposito del lavoro è l'analisi della capacità e dell'accuratezza dello studio mediante l'uso di tecniche di rilevazione remote attraverso lo spettro del visibile e dell'infrarosso, applicato alla classificazione e alla realizzazione di carte tematiche basate sulle ultime scoperte realizzate in questo settore.

Parole chiave: Cartografia pedologica, telerilevamento, spettro visibile e infrarosso.

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HISTORICAL REVIEW

Remotely sensed data applied to soil mapping has already a large history. Aerial photographs were used to prepare a soil survey in Jennings County, Indiana, in 1929. The results showed a improvement over the traditional methods and the use of black-and -white aerial photographs spread as a tool for soil mapping in a fast way.

The use of color and color-infrared photography proved to be even more useful to differentiate between soil units and soil processes during the sixties, but the high cost of color photography has been a big impediment for their application until now. Around the same years, a extensive research of films was done in order to match tonal qualities with land features which were described as a combination of vegetative cover and soil background reflectance.

Soils were generally described then as not very reflective in the short infrared, high reflective in the thermal-infrared and variable in the visible part of the spectra (ASRAR, 1989).

The use of optical-mechanical multiple aperture overlaid images and first single-aperture mu

ltiple-channels scanners improved the capacity of recognizing Earth features.

Concerning pedology, Alfisol and Mollisol soils were separated even in places where their reflectance properties could have been affected by human activities, and soil parameters such as type, texture, color, moisture, and organic matter proved to be separable using numerical analysis of aircraft scanner data. During the seventies it was hypothesized that multispectral scanners would be able to provide the capacity of mapping soils at the family or association level in suitable places such as deserts, grasslands or areas with minimal tree coverage.

However, the possibility of mapping soils to the extent of the series level seemed to be a non possible target because there was no way of getting information about the original material of soils from most of these surfaced sensed data (ASRAR, 1989).

The launch of Landsat satellite in July of 1972, meant the existence of a big new resource of data available for soil mapping purposes. Data from the Landsat Multispectral Scanner System (MSS) provided information in the visible and near-infrared portion of the spectrum with a larger view than an aerial photograph (LILLESAND and KIEFER, 1987). These data were used successfully to classify soils at the association level for single counties.

Thereafter, some studies were done adding physiographic boundaries to the MSS images. These boundaries were those of the parent-material of the soils. This was done because the scanner only collected data about spectral surface properties. Classification techniques were applied to areas with only one parent material correlating spectral properties with soil properties at the series level of soils (SCHMIDT, BERNSTEIN, 1975). The activity of stratifying data proved to be an useful method in generating general soil maps and in providing preliminary mapping and map-unit design.

This technique also aided in increasing the accuracy and confidence of soil surveys. At the same time, some efforts were done to relate spectral properties with soil types by means of overlaying spectral data with thematic maps and enhanced images. Advantages of the satellite data compared to previous aircraft methodologies were: increased multispectral and multitemporal available data with a near-orthographic quality, and the potential capacity of giving information about pattern of soils, slope effects and drainage patterns ASRAR (1989).

In 1984, a significant advance in resolution of satellite data was done with the launch of the Thematic Mapper (TM), aboard Landsat 4 (KAHLE, 1984). Advantages of this sensor were higher spatial resolution (30 m against the 80 m of MSS), and additional spectral bands formed by six bands in the visible and shortwave IR (LILLESAND and KIEFER, 1987). It was hypothesized then that this capacity could provide enough information to draw soil boundaries even under intensively cropped areas.

At this point in time, the computer-aided analysis of satellite multispectral scanner could aid field soil scientists to prepare soil-association maps, to significantly speed soil surveys at the soil-order level, to recognize patterns of soils, to quantify map-unit homogeneity in an area, to determine percentages of inclusions within soil-maps units, and to prepare soil single-feature maps such as drainage and organic matter content ASRAR (1989).

Other interesting advancement was the launch of the first SPOT satellite in February of 1986. New interesting properties that could help for soil classification purposes were the high resolution visible (HRV) sensor of 10 m of resolution in the panchromatic band and the capacity of the sensors to be pointed off nadir for the acquisition of stereoscopy imagery (LILLESAND and KIEFER, 1987). In fact, simulated SPOT data were soon applied for the identification of geomorphic features in a desert (PETERSEN *et al.*, 1987).

NEW ADVANCEMENTS FOR SOIL MAPPING PURPOSES

a - The use of thermal data to help soil surveys: the heat capacity mission.

a-1. The importance of thermal data for soil mapping purposes.

The heat capacity mission (HCMM) was part of a plan to place satellites designed to collect unique types of surface information in special orbits. The purpose of this mission was to use thermal infrared data to measure maximum and minimum daily surface temperatures. Concerning soils, temperature is an important factor determining their chemical, physical and biological properties as well as geographic distribution.

The temperature regimes of soils are determined by their Mean Annual Soil Temperature (MAST). MAST is not an easy value to determine: it can be accurately determined by measuring soil temperature at four equally spaced times throughout a yearly period at levels bellow the depth of diurnal temperature fluctuations or from a single bore hole measurement at a depth bellow the level of seasonal fluctuations. Because of its impracticality, MAST is normally estimated for soil surveys from least squares regression models based on geographic location, topographic position, surface cover and moisture conditions or from weather stations and vegetative cover type.

An interesting study using this type of data was reported by Peterson and his collaborators in 1989. In their study, they applied HCMM data to measure apparent soil surface temperature in desert areas and evaluate relationships between surface temperature variability and surface physiography; they also wanted to map soils based on their MAST regimes.

Platform and sensor characteristics

The HCMM satellite was launched the 26th of April of 1978 by a Scout launch vehicle into a sun-synchronous circular orbit inclined 97.6 grades. retrograde to the equator and collected data for over two years. It had a sun-synchronous orbit that could provide coverage surface between 85 grades north and south latitudes every 16 days.

This entire area received diurnal coverage at approximately 12-h intervals. The nominal ascending crossing time of 2:00 p.m. produced north middle latitude crossing times of 1:30 pm and 2:30 a.m.

The HCMM satellite contained a two-channel Heat Capacity Mapping Radiometer (HCMR) that was a modified version of the surface composition mapping radiometer (SCMR) flown on Nimbus 5. The visible near-infrared band corresponded to a broad band equivalent of the Landat MSS and had a resolution of 500*500 m. The TR band had a resolution of 600*600 m with a noise equivalent temperature difference of 0.3 Kelvin grades at 280 Kelvin grades (PETERSON *et al.*, 1987).

Application of HCMM data to mapping soil activities

Peterson reported that satellite data about the Canyonlands of the Colorado Plateau Physiographic Province had been analyzed. The data were HCMM daytime and nighttime TR data sets for five dates in a year. They spatially registered and overlaid these data. First, they calculated the daily temperature average for each one of the dates. Then, these values were used to build a sine curve for each one of the pixels. They estimated MASTS as the point where the curve was divided symmetrically.

The result was a map of the distribution of MAST for the region. Even when these were the only results they had, it is a valuable one because it can be used to distinguish temperature regimes used to classify soils at the family level. However, they noticed the following relations:

MAST was related with topography: the higher was the elevation, the cooler was the average temperature value and vice versa.

MAST was related with aspect: at the same elevation, escarpments are cooler than flat-lying surfaces.

MAST was related to moisture: irrigation or proximity of rivers produced cooler temperatures.

MAST was related to material density and composition: patterns of relatively cool temperatures coincided closely with soils derived from marine shale deposits and they were separable from sandstone-derived material and adjacent rocks that had a higher associated value of MAST. However, the sandstone-derived material was not separable from the bedrock because the had a different oscillation of temperature centered at the same mean.

Soil survey personnel reviewed these results and verified that they had a good agreement with the geographic distribution of temperatures of soils that they had observed. Furthermore, they found that the satellite image had even provided information the mappers knew but did not included due to scale considerations. The soil survey personnel concluded that these data could be very useful as a tool during the initial stages of a soil survey to delineate areas that could require detailed field observation to identify soil types.

The use of TM data for remote sensing of surface soil color.

ESCADAFAL and GIRARD (1989) studied 84 samples of soils all over the world. They estimated the hue, the value and the chroma for these soils based on the Munsell system (a numerical way of describing soil colors recommended by the U.S. department of Agriculture) and their reflectance curves in the visible part of the spectrum. Following the CIE methodology (Commision Internationale de l'Eclairage, 1931) they computed the Red, Green and Blue components for the soil spectral curves and Munsell colors.

They considered the differences between the results as slight even when the precision of the color estimation from the Munsell methodology cannot be as good as the one that can be done with reflectance curves in the visible part of the spectrum. The red, green and blue components that they calculated were strongly related with the digital values of TM 3, 2 and 1 bands respectively.

Thus, they believe that TM data of arid lands can directly produce a color soil map and help to point out where to do the surveys in order to produce a soil-type survey of these regions. However, to reach these desirable applications, the effect of rugged terrain should be determined separately as well as the effect of different illumination conditions. These effects could be modeled separately with the help of radar measurements and digital terrain models for the rugged terrain and different illumination conditions respectively. It might be that the most useful application of their research is to remove soil noise from vegetation indices having the color soil map of the studied region from field surveys manipulating the digital values of TM 3, 2 and 1.

NEW ADVANCEMENTS IN THE ANALYSIS OF SPOT AND TM DATA TO PERFORM ACCURATE CLASSIFICATION OF SOILS

Use of training polygons.

BUTTNER and CSILLAG (1989) reported that the use of SPOT images to classify soils by means of training statistics has shown results different that units of genetic soil classes. However, they were able to infer the following useful results from their studies:

1 - Bright spots were coincident with areas of salinization, thin humic layers, eroded soils, or sand dunes.

2 - Overmoist areas caused by temporary ponds were displayed as dark spots.

3 - Boundaries between two different soil brightness or within field soil/vegetation interfaces mark boundaries between different soil types.

4 - Scattered soil pixels within a vegetated field indicate large spatial variability of underlying soil, exceeding the homogenizing effect of agrotechnics.

They also had the chance of comparing SPOT and Landsat data TM images taken with 2 days of difference for the same area. They applied the same training procedure for TM as they did with SPOT. Their conclusions were the following:

TM bands 2-3-4 had the worse value to represent accurately the different units of the landscape of the area while TM 3-4-5 combination were the best. SPOT X 1-2-3 were between of these combinations concerning its capacity to draw accurate field units based on sensed spectral variability. These results showed the importance of middle-IR for general class separability and recognition

2 *Principal component analysis applied to SPOT and TM images merged with DEM models*

A work done by Su and collaborators (1990) showed more optimistic results for classifying soils with the help of satellite digital data. They worked over a tallgrass prairie near Manhattan, Kansas, with data collected on March the 20th, 1987. They registered these data and corrected the geometric distortion with the help of a USGS 7.5 min topographic map.

They also registered DEM data to this data set where the information of elevation, slope and aspect was treated as more bands. After this, they located five known areas of different family soil types on the satellite digital data. Then, they determined multiple training samples for these areas taking into account knowledge of a soil survey information and a soil sampling report that allowed them to relate the different soil families with characteristic DEM values.

Once they had all their training pixels with the values of all the bands (SPOT and DEM bands) associated with them, they performed a canonical transformation with the purpose of finding out which of the involved bands were the more useful to accurately distinguish the five families of soils.

Finally, they also found that SPOT band 1 as well as DEM elevation and slope were able to explain almost all the variability they had.

Practicing a divergence test analysis, they also found that the SPOT band 1 and the DEM elevation data were enough to perform a good classification of soils. This combination could explain the variability of the studied spectral image better than any other two-combination of SPOT bands and DEM factors.

A largest proportion of the variability was explained taking into consideration three or four canonical variables (SPOT bands or DEM factors) but the results were not significantly better than those produced with SPOT band 1 and DEM elevation band. This study proved that SPOT and DEM data are useful for soil pattern recognition and soil-unit design addressed to perform detailed soil surveys in grasslands. This analysis is possible by applying a GIS software containing satellite images and DEM data.

Ratio transformations.

The main target of using ratio transformations is to reduce differences in digital numbers caused by slope, shadows, or seasonal changes in sunlight, illuminating angle and intensity. However, this is not the only application for them because they can provide unique information band to discriminate soils and vegetation. Furthermore, LEE *et al.* (1988) reported that principal component transformations were found to be less definitive than ratio transformations in a study of Wisconsin soils.

An example of application of ratio transformations for classification purposes is the work done by FRAZIER and CHENG (1989) in a study of the Eastern Palouse Region, Washington State. In the studied area, the Fe(h)/ C relation (where Fe(h) is content of amorphous iron)was able to define areas where topsoils have been thinned to the extent that paleosoils were exposed. TM ratios 3/4, 5/4 and 5/3 showed to be related with the Fe(h)/C ratio.

Thus, they proved to be a good mean of mapping this relationship which is able to distinguish between eroded soil surfaces (higher values of the ratios) and non eroded soils (lower values of the ratios). When there is an interest in mapping soils based on organic carbon, they advised the use of TM 1/4, 3/4 and 5/4 as an useful choice.

Addition of image texture to spectral features.

Another technique has been described for identification and classification purposes with even highest potential than rationing. The addition of textural information to spectral reflectance information allows the user to measure the similarity between a central picture element in a subset of the image matrix and the block of surrounding elements. Three textural measurements usually used are variance code, contrast code and range code. AGBU and NIZEYIMANA (1991) used a textural image based in the variance code to generate soil spectral units for two sites in Ford Count, Illinois, and they compared the results with a field map using discriminant analysis of significant soil properties. In order to do this, they read SPOT tapes with ERDAS (Earth Resources Data Analysis System Software) and they referenced them to UTM.

After this, they transformed the three visible bands of SPOT into variance codes following the methodology defined by JENSEN (1979) producing the generation of the texture transformed image. From this image, they produced an spectral soil map with an unsupervised maximum likelihood algorithm. - "Unsupervised classifications are those where there are not training data and spectral classes are created based on the similarity values of the pixels; the results of these methodologies should be checked with reference data. In the training methods we define useful information categories and then examine their spectral separability; in the unsupervised approach we determine spectrally separable classes and then we define their informational utility." LILLESAND and KIEFER, 1987.

They also created their own reference data from field work based in a 402 * 402 m grid where they collected soil samples for each cell of the grid and measured different properties (pH, texture, Munsell color for different horizons, depth for the different horizons, percent slope etc.). With these field data, they applied a discriminant function to classify the multiple vector data (each sample had several associated values) in the most suitable class and produce a field map.

Once they had their own field reference map and the spectral map generated from the satellite image, they wanted to test the goodness of the classification performed with the spectral classes.

Their final results showed that the overall difference of the two maps was not very big, but the field map had a slightly better quality and accuracy. However, it is important to notice that the field map they used could not be a good template to test the spectral map goodness because both maps could be emphasizing different soil properties instead of patterns of general soil variability.

Overall, they concluded that the spectral unit defined by their analysis could help to define useful soil units in a detailed survey program.

Image spectrometry applied to pedology

Imaging spectrometry is the remote sensing technique that refers to the collection of images in many, very narrow, contiguous bands through the visible, near-IR and mid-IR portions of the spectrum (LILLESAND and KIEFER, 1987). It is a suitable technique to recognize or identify minerals in rocks and soils because a lot of minerals have specific absorption peaks in the shortwave infrared.

This is a powerful advantage compared with the broad bands of the satellite sensors that can easily identify rock types but not minerals. The recognition of mineral types through remote sensing techniques is an important advance for the geology and pedology fields because sensors such as the Landsat Thematic Mapper are only able to recognize rock types with their broad sensors (MURPHY, 1994).

However, this technique has also problems: the use of narrow IS bands force the detectors to collect low signals from the Earth surface (specially in the IR region because the emitted solar energy is low there) that can be easily affected by noise, atmospheric disturbances and undesired effects of other features than those we were interested in (e.g. vegetation masking effect upon minerals).

Next, two interesting studies dealing with the use imaging spectrometers with mineralogical and pedological purposes are going to be commented.

Data collected with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) from a field site in the foothills of the Sierra Nevada, California were analyzed with the objective of producing a spectral map identifying the principal components of the landscape. (AVIRIS is a imaging spectrometer designed to collect data in 224 bands 10 nm wide, in the 0.4-2.4 micrometer region of the spectrum. It can be flown in a NASA's U-2 aircraft at an altitude of 20 Km, with a swath width of 11 Km and a ground pixel resolution of approximately 20 m. LILLESAND and KIEFER, 1987).

This study was a challenge to the effective analysis of imaging spectrometer data because the terrain was a heterogeneous mixture of soils, rocks and vegetation in a hilly environment that had many slope changes over short spatial distances producing variable illumination conditions. The zone had previously been studied through satellite data and field spectrometers that allowed the scientists to use a good knowledge of the spectral properties of the vegetation and geologic features of the area.

Applying spectral mixture analysis (This means that, based on the "spectral library" they had, they can model the total energy sensed from pixels that can have more than a relevant feature to identify), and classification techniques of the digital data (principal component analysis) they were able to distinguish areas that concentrated short term changes in time from less transient areas.

The transient areas had a very clear signal and were composed by vegetal communities that were affected by intense grazing activities. The less transient areas were composed mainly by arid bare soils. The most interesting point of this research is that, trough a spectral mixture analysis, the results were able to show that the soils of the zone had an important lithological influence. The distinction of the three different soils of the region was subtle but their spatial distribution observed in the images revealed coherent patterns with the lithology.

Therefore, this demonstrates the tremendous value of high spectral and spatial resolution data in discriminating subtle differences in soil composition, despite the complicating effects of highly variable transient surface components (MUSTARD, 1993). An interesting approach is the capacity of relating soil surface spectral properties with subsoil properties. There are not many references dealing with the capacity of relating subsurface soil properties with spectral data. AGBU *et al.* (1991) have shown that a significant correlation exists among some pertinent subsurface soil properties and spectral data, suggesting that subsurface pedogenic processes influence soil properties including organic matter, amount and kind of clay, surface soil texture, etc., which are directly related to spectral reflectance.

Classifying soils by masking out pixels with a high proportion of vegetation using a ratio near-infrared / red ratio is a common technique. However, this technique does not take into account the effects of dead vegetation.

In 1989, a study was done as a part of the European Imaging Spectrometer Airborne Campaign (EISAC) with the purpose of doing research about the effects of life and dead vegetation on the remote identification of soils and the amount of vegetation cover that could be tolerated to accurately classify a soil.

The area studied was Almaden, in central Spain, about 150 Km south of Madrid in an zone where natural rock and soil exposure was low (<10%). The data were collected by the GER-2 imaging spectrometer. This scanner (GERIS) produces a 63-band image with 16-bit dynamic range and the following bandwidth characteristics:

Wavelength(nm)	Bandwidth(nm)	No. of bands
477-761	25.5	24
774-848	120.0	7
1440-2443	16.5	32

The spatial resolution of the data is 10m and there are 512 pixels across the image swath. The signal-to-noise ratio of the GERIS short wavelength IR bands for the Almaden data set was approximately 19:1 (0.6 albedo), for bright targets and 9:1 (0.2 albedo) for darker targets within the image (MURPHY and WADGE, 1994).

Sampling of the vegetation cover, field spectra and soil samples were collected in a period of time close to the day where the data were collected with this airborne sensor. As the previous work, they also modeled the energy associated with a pixel as a possible combination of spectra of different features (soil, rocks, dead and life vegetation). They did this by combining the spectra that they collected in the field with a field instrument called SIRIS (SIRIS is operated by an user-controlled software and it is able to register reflected radiation in 870 bands between 400 nm and 2500 nm). Once they had the curves of reflectance of life and dead vegetation, rocks and soils collected with the field spectrometer, they calculated all the possible values of energy reflected by different combinations of percentages of coverage of dead and life vegetation over the soils and rocks of the zone.

With this reference and applying a principal components technique, they distinguished among these spectral identities: areas of dead vegetation, areas of wheat fields (which also can be taken as dead vegetation), areas of natural vegetation (Cistus ladanifer, Lavandula stoechas, and herbaceous plants) and soils. However, these results did not show any difference among the pixels classified in the group soils for the PC analysis. In order to differentiate different kinds of soils, the pixels with a proportion of vegetation greater than a 30% had to be masked out from the images.

In this way, they were able to distinguish granite soils, quartz-rich/ pegmatite soils , and contact and exocontact soils (slate soils) through the PC analysis. These final six spectral categories were checked in the field showing significant correlation values. Important conclusions pointed for soil mapping purposes is that soils are easily miss identified with field vegetation covers greater than 50-60 percent and that dead vegetation can have more important effects to identify soils than life vegetation.

This is because life vegetation does not remove the shoulders of an absorption mineral peak (muscovite/illite) at 2200 nm useful for pedological purposes even when the depth and width of this peak are decreased. In an opposite way, the dead vegetation has a less overall effect on the spectrum of soils but can remove the shoulders of this band.

Also, it is important to point out that the technique of mixing spectra of dead and live vegetation is useful to select bands that could be the least affected by the vegetation in future applications of imaging spectrometers dealing with mineralogical and pedological purposes.

CONCLUSIONS

Remote sensing techniques are already able to produce accurate family and series soil maps in suitable areas such as grasslands or arid zones. Furthermore, the use of imaging spectrometers even allow to recognize soil types when their capacities are applied to these kind of regions.

When the identification of soil-types cannot be performed from the analysis of the remotely sensed data, the information extracted from the analysis of these data (patterns of organic matter, iron compounds, soil temperatures, soil minerals, soil colors etc.) can make easier the hard task of producing an accurate map soil at the soil-type level for a region.

Much more uncertainty is produced when remotely sensed data are applied to well vegetated regions. In these conditions, the use of remote sensed data applied to map soils would have to be based on observations of vegetation variability and spots of bare soils to produce base maps addressing a much more detailed soil survey.

However, a good knowledge of the spectral properties of the underlying soils would be very useful for a better interpretation of the sensed signals from the vegetation.

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