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LANDSAT SATELLITE DATA FOR SOIL INVESTIGATIONS IN AN APENNINES REGION OF SOUTHERN ITALY

ABSTRACT: LEONE A.P., TEDESCHI P. & WRIGTH G.G., *Landsat satellite data for soil investigation in an Apennines region of Southern Italy.* (IT ISSN 0391-9838, 1996).

Since the launch of first earth observation satellites at the beginning of 1970s, great attention has been paid to the use of satellite remote sensing techniques in soil studies. Some investigations have studied the relationships between soil surface characteristics and soil spectral behaviour, under both laboratory and field conditions. Others have focused their attention on the image processing techniques applied to satellite and airborne scanner spectral data. This paper presents the results of a research, using spectral information from a Landsat satellite source, for soil studies in a southern Italy Apennines region. Specifically, the objectives of the investigation were to determine the degree with which variations in soil parameters could be monitored and quantified on the basis of radiometric data gathered by the Landsat TM-5 satellite sensor. A spectral soil map has been produced over the test site. An accurate comparison between the latter and numerous available thematic maps has led to the formulation of an hypothesis about the actual and potential applications of radiometric data to soil spatial variability.

KEY WORDS: Remote sensing, Landsat TM, Soil, Southern Apennines, Italy.

RIASSUNTO: LEONE A.P., TEDESCHI P. & WRIGTH G.G., *Dati satellitari Landsat per indagini sui suoli in una regione appenninica del sud Italia.* (IT ISSN 0391-9838, 1996).

Fin dal lancio dei primi satelliti per lo studio della Terra agli inizi degli anni '70, una grande attenzione è stata rivolta all'uso delle tecniche di telerilevamento per lo studio dei suoli. Alcune indagini hanno riguardato lo studio delle relazioni tra caratteristiche superficiali e comportamento spettrale dei suoli, sia in condizioni di laboratorio sia di campo. Altre hanno concentrato la loro attenzione sulle tecniche di elaborazione di dati spettrali telerilevati da sistemi satellitari o aereoportati. Il presente lavoro riporta i risultati di una ricerca basata sull'uso di dati telerilevati dal sensore TM del satellite Landsat per lo studio dei suoli in una regione appenninica del sud Italia. In particolare, l'obiettivo dell'indagine è stato quello di determinare il grado in cui variazioni delle caratteristiche superficiali dei suoli possono essere monitorate e quantificate sulla base dei dati radiometrici acquisiti dal sensore. Il confronto tra una mappa spettrale, prodotta attraverso un procedimento di analisi dell'immagine Landsat TM relativa all'area di studio, e la cartografia tematica esistente ha consentito di formulare interessanti ipotesi circa le possibili applicazioni dei dati radiometrici all'analisi della variabilità spaziale dei suoli.

TERMINI CHIAVE: Telerilevamento, Landsat TM, Suolo, Appennino Meriodionale.

INTRODUCTION

Soil can be defined as a discrete body, generated from the interaction between climate, vegetation and geological surface materials (OLSEN, 1981). It represents a major natural resource (FITZPATRICK, 1986). Therefore, a knowledge of soil, of its potential productivity, limitations of use and its spatial or temporal variability, is essential for correct land use planning. Soil studies at a regional scale, follow important field investigation procedures (MANCINI, 1984). However, these also represent the most onerous part of the whole soil survey program. In this respect it is becoming increasingly necessary to implement innovative tools and techniques able to produce a significant reduction in the total cost of an investigation.

Since the launch of the first earth observation satellites, a great deal of attention has been paid to the use of satellite remote sensing techniques for soil studies. In reality, the opinions of soil scientists about the possibilities of using such techniques have always been discordant, moving from overestimated enthusiasm to total scepticism. In fact, the possibilities of success, for aero-spatial remote sensing applied to soil studies, vary considerably in relation to the characteristics of investigated physical environment, the instruments used and, not least, the methods of image processing used. If the soil is not covered by vegetation, it is possible to obtain direct information about the surface pedological cover through the analysis of remotely sensed radiometric data. For this reason, the majority of remote sen-

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sing investigations applied to soil studies have used arid and semi-arid regions.

The presence of large areas of bare soils between late summer and early autumn (soil prepared for cropping), the frequency of clear sky conditions, and the shortage of rainfall between late spring and early autumn, would suggest the use of satellite data in several areas of the Mediterranean basin used for extensive agriculture (JUSTICE & TOWNSEND, 1981), e.g. the Apennines Mountains of Southern Italy.

This paper presents the results of a research, using spectral information from a Landsat satellite source, for soil studies in a southern Apennines region. Specifically, the objectives of the investigation were to determine the degree with which variations in soil parameters could be monitored and quantified on the basis of radiometric data gathered by the Landsat TM-5 satellite sensor. A spectral soil map has been produced over the test site. An accurate comparison between the latter and numerous available thematic maps, has led to the formulation of an hypothesis about the actual and potential applications of radiometric data to soil spatial variability.

1. BACKGROUND

1.1 *Soil spectral response*

A number of soil parameters which represent physiochemical conditions, have been shown to contribute to the spectral response of soils. The main contributors to soil spectral reflectance are regarded as organic matter, calcium carbonate, moisture, iron content and soil texture (BOWERS & HANK, 1965; CONDIT, 1970; MONTGOMERY & BAUMGARDNER, 1974; GIRARD & GIRARD, 1977; DA COSTA, 1979; AMERICAN SOCIETY OF PHOTOGRAMMETRY, 1983; LEE & *alii*, 1988a and 1988b; REES, 1990, CHANZY & *alii*, 1996). Of all these properties, it has been suggested that organic matter is one of the most influences on soil reflectance (STONER & *alii*, 1980). However, it is important to note that many field studies found no general relationships between soil colour and organic matter (MCKEAGUE & *alii*, 1971). Others have established slight relationships but quote a low accuracy of determination for organic matter (BAUMGARDNER & *alii*, 1970; HAVAROTH & *alii*, 1971; PAGE, 1974). The contrasts found in some studies suggest a local influence, possibly due to the combined effect of physiochemical properties on spectral response.

1.2 *Satellite imagery and soil spectral maps*

If relationships between remotely sensed data and permanent soil characteristics can be defined, then there is a potential to extract useful information about soil distribution, on the basis of visual interpretation of satellite imagery and/or spectral map analysis. Many investigations have highlighted the usefulness of a visual analysis of both single wavebands and their combinations (colour composites), as well as processed spectral data in soil survey programs. DI PAOLO (1979), LUND & *alii* (1980) and HARRISON & JOHNSON (1982), studying the possibilities of using Landsat MSS data for soil investigation in Idaho, found that satellite spectral data could be used to accurately stratify large areas into smaller units that could be sampled more efficiently in the field. In MILTON & COX (1985) we read that spectral maps, when used with conventional aerial photographs, form very useful documents for use in the field by soil surveyors to delineate map unit boundaries, allowing large areas to be surveyed rapidly with little reduction in accuracy.

Although much information on soil may by gathered from visual interpretation of remotely sensed data, digital processing of multispectral scanner data can provide significantly greater detail and definition of soil features, as well as allowing routine tasks to be automated, thus increasing the overall efficiency still further. ROUDABUSH & *alii* (1985) concluded that Landsat multispectral scanning data used for soil survey in Arizona rangeland, increased the accuracy of the survey by helping to improve (in about 35 percent of the mapping units) soil mapping unit boundaries and mapping unit composition. As a consequence of this, the total cost of soil survey effort was reduced by about 33 percent compared to the average cost of soil survey in similar areas. A visual analysis of satellite images in southern Sinai (Egypt) permitted ABD EL HADY & *alii* (1991) to trace the principal geomorphologic unit and processed satellite digital data facilitated the phase of soil survey by supplying the surveyor with a remotely sensed map as an efficient guide for pedological prospecting.

The second-generation Landsat and Spot satellites, together with the increasing use of radar, offer additional possibilities (AGBU & FRANK, 1988; AGBU & COLEMAN, 1990; BISWAS & SINGH, 1991; CHANZY & *alii*, 1996). AGBU & NIZEYIMANA (1991) compared spectral mapping units derived from Spot imagery and field soil map units. LEE & *alii* (1988a, 1988b) and SU & *alii* (1989), in studies combining Spot or Landsat TM with Digital Elevation Model (Dem) data to identify soils, their boundaries and variation in soil information, point towards the possibility of using such information for a general classification of soils at the subgroup level. Their results suggested that high resolution satellite data significantly improves the accuracy of second order soil survey where the dominant land use is rangeland. The conclusion reached was that textural transformation of the original image data and its classification, produces discriminate spectral mapping units which may be used as a basis for formulating and defining soil mapping units in a detailed soil survey program.

1.3 *Imaging spectrometry and soil mapping*

A further interest in the use of remotely sensed data for soil mapping and monitoring arose with the advent of imaging spectrometer (or hyperspectral) scanners. These sensors are able to acquire a complete reflectance spectrum for each picture element (pixel) in the image in many narrow, ideally contiguous spectral bands throughout the visible, near-infrared and short-wave infrared, thus allowing the identification of important properties of land surfaces, which cannot be identified with broadband, low-resolution satellite systems (VANE & GOETZ, 1988).

Interesting applications of imaging spectrometry have recently been carried out for soil mapping. For example, a study carried out by PALACIOS-ARUETA & USTIN (1996) in an agricultural area of approximately 2.900 ha along the southern margin of Putah Creek, California, showed the ability of the Aviris (Airborne Visible/Infrared Imaging Spectrometer) data to discriminate among soil phases.

Many researches on the applications of imaging spectrometry data in soil mapping has been based on a *Spectral Mixture Analysis* (Sma) (ADAMS & *alii*, 1989; BATSON & CURTISS, 1995). This approach, which allows the detection of the fractional abundance of ground materials (e.g. calcium carbonate content, clay percentage) at the sub-pixel scale (SABOL & *alii*, 1992), was successfully used by FISHER (1991) for mapping soils of different age in an area of young glacial deposits. More extensively, Sma has been adopted by HILL (1993) and HILL & *alii* (1993, 1994b, 1995) for mapping soil erosion over a Mediterranean test site, in the Ardèche province (Southern France). This method, applied to the Mivis (Multispectral Infrared and Visibel Imaging Spectrometer) data, is also under investigation for soil erosion mapping in the Fortore study area (e.g. SOMMER & *alii*, 1997).

2. STUDY AREA

The study area, corresponding to the administrative region of «Fortore beneventano» Mountain Community (fig. 1), is located across the North-east part of the Campania Apennines (southern Italy), between the Daunia and Sannio Mountains at the external edge of the southern Apennines chain. The climate shows characteristics typical of Mediterranean environments (BUONDONNO & *alii*, 1989d; LEONE & *alii*, 1989). The total annual rainfall has a narrow range, from 700 to 850 millimetres, particularly concentrated between late autumn and early spring. Temperature and potential evapotranspiration follow an inverse trend in respect to rainfall, with the highest values during summer. As consequence of climatic conditions, the «soil moisture regime» (U.S.D.A., 1975) is definitely «xeric», whereas «soil temperature regime» results tend to be «mesic», between 500 and 600 meters above sea-level, and «thermic» to «mesic» above 600 meters (BUONDONNO & *alii*, 1989a). The parent materials of Fortore's soils are formed by claystones, marls, sandstones, limestones and alluvial depositions. Clayey parent materials are spatially dominant, making up nearly 50 percent of the surface of the study area. The morphology of the land is characterized by the dominance of side slopes; less relevant are the stable areas of floodplain and plateau. Intensive anthropogenic activity, climate, landscape forms and geological nature of substrate are the major causes in determining landslides events and soil surface erosion by water.

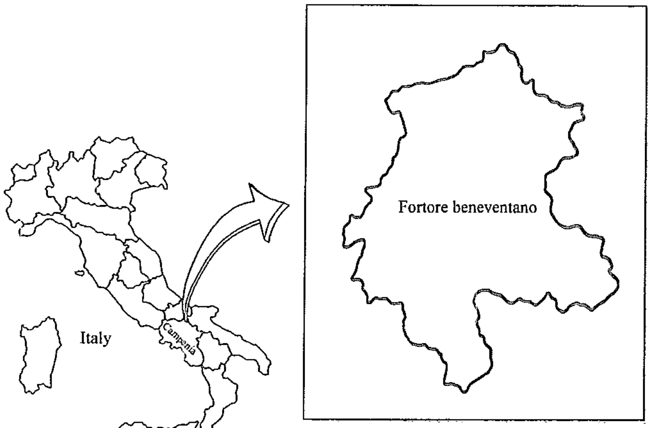


FIG. 1 - Study area: «*Fortore beneventano*» Mountain Community.

A series of studies carried out during the second half of 1980s (BUONDONNO & *alii*, 1989a, b, c, d, e; QUAGLETTA CHIARANDA & *alii*, 1985) allowed the authors to make clear the general relationships between soil types found in the study area and principal factors of soil formation. They highlighted that lithology and morphology were major factors on soil genesis and evolution processes. Over claystones, the dominant soils are Vertisols, (Typic and Chromic Haploxererts) and vertic Inceptisols (Vertic Xerochrepts) (U.S.D.A., 1992). They are well-structured, with a neutral to sub-alkaline reaction and a dominance of clay particles (usually higher than 45 percent). Organic matter content of these soils is rather modest, seldom more than 3 percent.

The main soil types over sandstones are Entisols and Inceptisols. The most wide-spread Entisols of this soil association are Lithic Xerorthents. The Lithic sub-group, with a characteristic A-R profile, predominantly develops on major slopes where soil erosion is common and has a loamy to clay loam texture. The Typic sub-group is represented by relatively deep soils, much better structured and with a loamy to clay loamy texture. Inceptisols (Typic Xerochrepts) of these sandstone formations, occur on the top of convex crests of hills and are characterised by an ochric epipedon.

Over carbonates outcrops, soil are ascribed to the Mollisols (Lithic Haploxerolls) and Inceptisols (Lithic and Ruptic Xerochrepts). Finally, over flood plain alluvial deposits we find soils with typical morphological characteristics of «Alluvial soils» of previous soil classifications. These soils are generally deep with surface stoniness. The dominant types are ascribed to the order of Entisols (Typic and Vertic Xerofluents), Inceptisols and Vertisols.

3. SOIL AND SITE CHARACTERISTICS - SOIL SPECTRAL RESPONSE

3.1 *Soil and site data*

For the purpose of our study, 77 surface soil samples, taken from sites devoid of vegetation at the time of satellite overpass (10 October, 1986) were used. These samples were part of a larger set collected during a previous agro-pedological investigation (QUAGLETTA CHIARANDA & *alii*, 1985). The soils were analysed for the principal chemical and physical properties. For statistical purposes, soil colour, expressed as Munsell notation (MUNSELL, 1975), was converted to the C.I.E. (Commission Internationale d'Eclairage) x, y (chromaticy coordinates) and Y (brightness) (WYSZECHY & STILES, 1982). Site characteristics (elevation, slope and aspect) were derived from 1:25000 IGM (Istituto Geografico Militare) topographic maps. Geological information was obtained from ORTOLANI & PAGLIUCA (1989). Site aspects were coded as transformed variables, defining 8 slope classes, attributing the value 8 to the brightest class and 1 to the darkest one, considering both the direct and diffuse radiation on the Earth's surface (HOLBEN & JUSTICE, 1981). K (soil «erodibility») and R (climatic «erosivity») Usle erosion factor were extracted from an available data base (BUONDONNO & *alii*, 1993).

3.2 *Satellite spectral data*

The pixels associated with the 77 sample points were located on Landsat TM image, acquired on 10 October 1986. To ease the extraction of the most suitable soil radiance values, the image was geometrically corrected and registered with reference to the Universal Transverse Mercator (Utm) world co-ordinate system. Values for all the spectral parameters were read from the imagery using a 3x3 cluster average value to represent the chosen soil site used for chemical and physical analysis. It is believed that variability from the mean is negligible, as it is of a similar magnitude to that which exists within the mapping unit itself, and consequently will not significantly affect the relationships between spectral data and site characteristics (AGBU & *alii*, 1990). The spectral parameters taken into consideration for investigation were five single wavebands (TM bands 2, 3, 4, 5, 7), a Normalized Difference Vegetation Index (Ndvi) (TM band 4-band 3/TM band 4 + band 3), the band ratio Red/Nir (TM band 3/band 4) and a sum of bands (TM band 2+3+4), referred to as the Brightness Index (Bni). Ndvi was considered useful for discriminating vegetated and non-vegetated surface, whereas the band ratio was expected to help reduce the topographic effect with Bni considered useful for visual interpretation of satellite images (AGBU & *alii*, 1990). TM band 1 was excluded because of possible atmospheric affects, and TM band 6 because of the large spatial resolution (120 x 120 m).

3.3 *Statistical analysis discussion*

Site, soil and spectral data were examined to determine the statistical relationships between variables. A collinearity analysis (tab. 1) was performed (JOHNSON, 1980, HORVATH & *alii*, 1984; AGBU & *alii*, 1990; MEAD & CURNOW, 1992) and soil and site parameters which significantly correlated with spectral values (significance level considered <0.05), were inserted (as independent variables) into several multiple regression models, using a stepwise regression procedure (tab. 2). Collinearity and stepwise regression

TABLE 1 - Correlation coefficient (r) between Landsat TM spectral data and soil and site characteristics

Variable	NDVI	TM2	TM3	TM4	TM5	TM7	BNI	RATIO
ELEV	$0.315^{(2)}$	-0.217	-0.143	0.014	0.032	0.010	-0.103	$-0.337^{(2)}$
K-USLE	0.042	0.034	0.096	0.120	0.081	0.164	0.093	-0.108
R-USLE	$0.455^{(3)}$	0-176	$0.259^{(1)}$	$0.406^{(3)}$	$0.261^{(1)}$	$0.261^{(1)}$	$0.305^{(2)}$	$-0.438^{(3)}$
ASPECT	0.100	$0.565^{(3)}$	$0.582^{(3)}$	$0.528^{(3)}$	$0.556^{(3)}$	$0.538^{(3)}$	$0.574^{(3)}$	-0.083
SLOPE	0.060	$0.489^{(3)}$	$0.458^{(3)}$	$0.421^{(3)}$	0.216	0.144	$0.456^{(3)}$	-0.053
SAND	0.111	0.003	0.030	0.104	0.080	0.126	0.054	-0.193
SILT	-0.070	0.114	0.113	0.036	0.088	0.120	0.086	0.114
CLAY	-0.093	-0.042	-0.070	-0.122	-0.115	-0.174	-0.086	0.164
OM	-0.136	$-0.584^{(3)}$	$-0.604^{(3)}$	$-0.586^{(3)}$	$-0.482^{(3)}$	$-0.476^{(3)}$	$-0.610^{(3)}$	0.155
PH	0.012	$0.347^{(2)}$	$0.365^{(2)}$	$0.326^{(2)}$	$0.259^{(1)}$	$0.239^{(1)}$	$0.356^{(2)}$	-0.027
$CaCO_3$	-0.017	$0.572^{(3)}$	$0.564^{(3)}$	$0.457^{(3)}$	$0.453^{(3)}$	$0.536^{(3)}$	-0.044	-0.087
Y – C.I.E.	0.086	$0.458^{(3)}$	$0.421^{(3)}$	$0.364^{(2)}$	$0.281^{(1)}$	$0.260^{(1)}$	$0.420^{(3)}$	-0.027
x – C.I.E.	$0.419^{(3)}$	$0.251^{(1)}$	$0.330^{(2)}$	$0.466^{(3)}$	$0.331^{(2)}$	$0.289^{(1)}$	$0.375^{(3)}$	$-0.461^{(3)}$
y – C.I.E.	0.141	0.220	$0.275^{(1)}$	$0.257^{(1)}$	0.142	0.143	$0.263^{(1)}$	0.121

Significance levels for the correlation coefficient (r): 0.05 (1), 0.01 (2), and 0.001 (3); df = 76, n = 77. - OM = Organic Matter; x – C.I.E., Y – C.I.E. and y – C.I.E. = *chromaticy coordinates* and *brightness coefficient* of the Commission Internationale de l'Eclairage (WYSZECHY & STILES, 1982).

TABLE 2 - Stepwise regression analysis coefficients

Dipendent Variable	Indipendent variable	Coeffic	Standard Error	T-Ratio	Standard Deviation	Cumulat. R-Square
NDVI	Constant	-69.04				
	R – USLE	0.27	0.08064	3.33	11.1	20.7
	x – C.I.E.	1.62	0.05762	2.81	10.7	28.3
TM 2	Constant	24.10				
	O M	-1.24	0.8012	-1.55	2.6	34.1
	SLOPE	0.16	0.03858	4.23	2.3	47.4
	ASPECT	0.48	0.08461	5.71	2.0	62.0
	$CaCO_3$	0.19	0.07154	3.60	1.8	66.7
	Y – C.I.E.	11.30	3.630	3.10	1.7	70.7
TM 3	Constant	19.28				
	O M	-2.20	1.216	-1.84	3.9	36.4
	ASPECT	0.72	0.1287	5.56	3.5	49.9
	SLOPE	0.24	0.05821	4.08	3.1	62.4
	$CaCO_3$	0.29	0.05820	3.78	2.9	66.7
	R-USLE	0.06	0.01952	3.03	2.8	70.1
	Y – C.I.E.	14.00	5.475	2.56	2.7	72.7
TM 4	Constant	-7.26				
	O M	-2.50	1.322	-1.92	4.2	34.3
	R-USLE	0.09	0.02193	3.94	3.8	45.6
	SLOPE	0.24	0.06220	3.87	3.5	55.8
	ASPECT	0.53	0.1391	3.83	3.1	64.5
	x – C.I.E.	54.00	16.46	3.26	3.0	67.8
	$CaCO_3$	0.20	0.08346	2.43	2.9	69.8
	Y – C.I.E.	13.30	5.938	2.23	2.8	71.9
TM 5	Constant	29.26				
	ASPECT	1.37	0.2858	4.79	7.1	30.9
	$CaCO_3$	0.68	0.1596	4.28	6.5	43.1
	R-USLE	0.11	0.04562	2.37	6.3	47.1
TM 7	Constant	14.36				
	ASPECT	0.82	0.1811	4.51	4.4	28.9
	$CaCO_3$	0.40	0.1011	3.95	4.1	39.9
	R-USLE	0.07	0.02890	2.31	4.0	44.0
BNI	Constant	19.55				
(TM2+TM3+TM4)	OM	-5.3	3.092	-1.72	10.3	37.2
	ASPECT	1.66	0.3253	5.11	9.26	49.9
	SLOPE	0.63	0.1455	4.36	8.40	62.7
	R-USLE	0.15	0.05130	2.99	7.60	67.2
	$CaCO_3$	0.70	0.1952	3.60	7.18	71.1
	Y – C.I.E.	41.00	13.89	2.96	6.93	73.5
	x – C.I.E.	89.00	38.51	2.32	6.72	75.4
RATIO	Constant	373.30				
(TM 3/TM 4)	x – C.I.E.	-292.00	86.84	-3.36	16.9	21.3
	R-USLE	-0.37	0.1213	-3.03	16.1	29.9

OM = Organic Matter; x – C.I.E. and Y – C.I.E. = *chromaticy coordinate* and *brightness coefficient* of the Commission Internationale de l'Eclairage (WYSZECHY & STILES, 1982).

analysis were performed using the Minitab statistical package (RYAN & *alii*, 1985).

Tab.1 shows close correlations between the soil characteristics, organic matter and calcium carbonate contents and satellite spectral values. Particularly interesting was the fact that, although the organic matter content of the analysed samples is rather modest (only for a restricted number of samples is it > 2%), its correlation with the visible and near infra-red spectral ranges and *Brightness Index* is very significant ($p < 0.001$). This seems to be in contrast with the results obtained by BAUMGARDNER & *alii* (1970). Nevertheless, it must be considered that, in the case of our study area, the majority of examined soils are clayey soils, and in particular, Vertisols, within which normally a little portion of organic matter has a striking pigment effect. Consequently, the results obtained should be considered as agreeing well with those of previous investigations.

In agreement with the results of other studies (AMERICAN SOCIETY OF PHOTOGRAMMETY, 1983), the statistical analysis highlights a significant influence of colour on soil spectral response. This aspect must be considered particularly useful as it represents an indirect measure of other soil characteristics or qualities (U.S.D.A., 1975). It can therefore be used in soil classifications as a discriminant between different soil types (MAGALDI, 1984). With reference to the study area, the results were particularly affected by parent material chromaticity (BUONDONNO & *alii*, 1989a), as well as organic matter and other soil components (e.g. iron oxides). Contrary to expectations, no significant relationships were found between soil texture and spectral radiance, or with K-Usle coefficient, which is closely related to the textural elements (BUONDONNO & *alii*, 1993).

From the collinearity coefficients matrix, it emerged that there is considerable sensitivity, for single waveband and BNI spectral responses, to slope and aspect. This is either because of the direct effect on slope illumination or its influence on soil evolution, in particular on the soil surface erosion by water (BUONDONNO & *alii*, 1993). Ratio and Ndvi data did not highlight a significant correlation with these environmental parameters, confirming the effect of band rationing in reducing the topographic effect. The effects of the elevation on soil spectral response, only resulted in a limited correlation ($p<0.01$) with bands ratios (TM3/TM4 and Ndvi) or single wavebands and their sum (Bni). Finally, several spectral parameters showed significant coefficients with R-Usle.

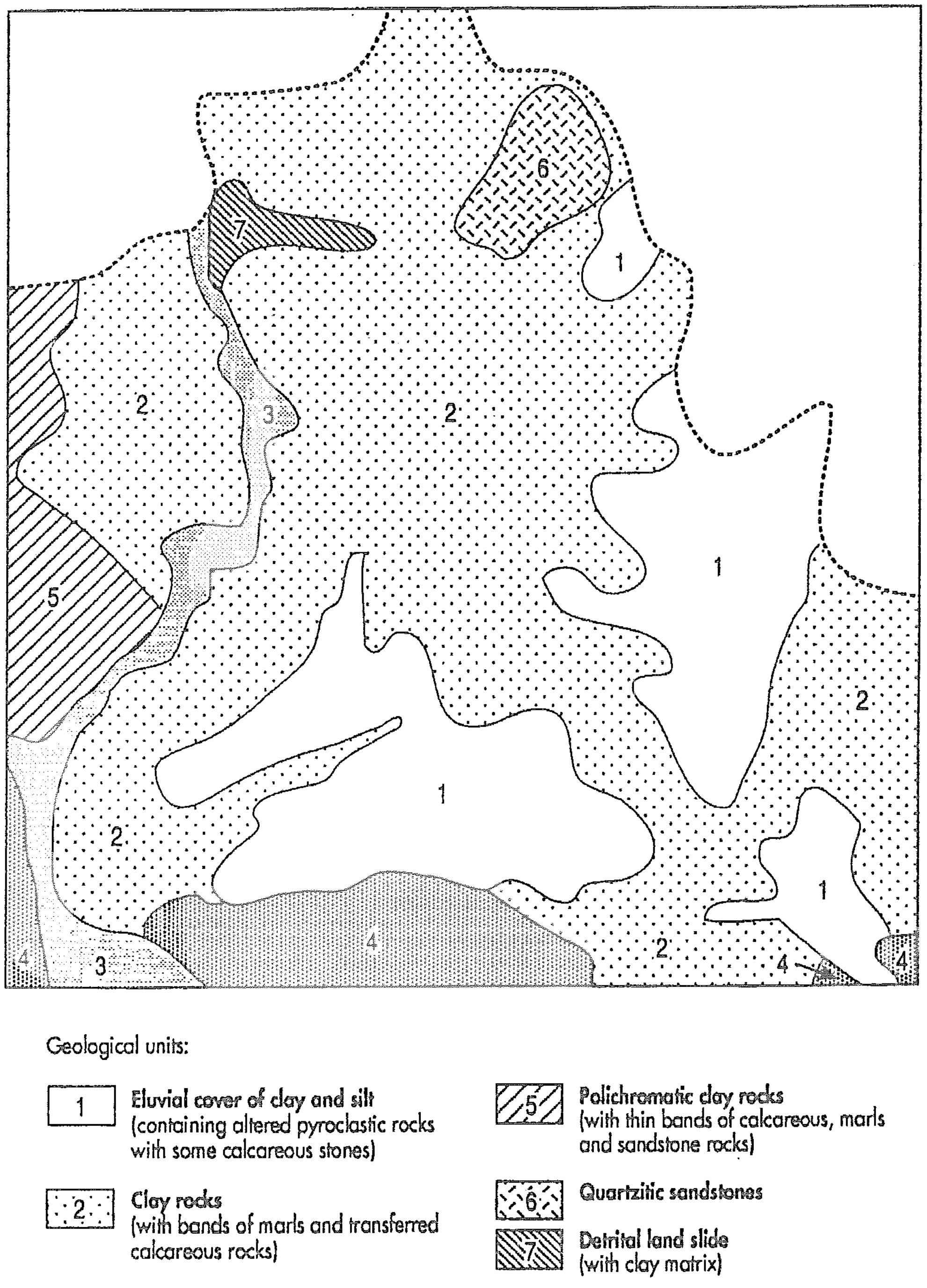
Linear multiple regression analysis between Landsat data and soil and site properties, indicated that visible (TM 2 and TM3), near-infrared (TM4) and their sum (Bni), were the most sensitive spectral parameters related to soil properties and site characteristics. The values of cumulative R^2 indicated that more than 70 percent of total variance of the spectral parameters could be expressed by the dependent variables. The regression model that best described the relationships between soil-site properties and spectral data includes Bni, as a dependent variable and organic matter and calcium carbonate content, aspect, slope, R-Usle, as well as Y, y and x C.I.E. parameters as independent variables. This model accounts for over 75 percent of the total variance. With reference to statistical models in which dependent variables are represented by rationing bands (Ndvi and TM3/TM4), the percentage of total variance expressed by depended variables is not higher than 30 percent, proving the scarce usefulness of such parameters in monitoring spatial variability of soil surfaces.

Finally, no significant prediction was gained from stepwise regression analysis of single soil surface constituents, (e.g. organic matter and calcium carbonate content) on the basis of single band spectral data. Specifically, in multiple correlations often only the first component of the model was significant and further additions to the predictors did not significantly increase the coefficient of determination (R^2). The best single waveband for predicting organic matter content was TM band 3 (tab. 1 and tab. 2). This inverse relationship accounted for some 37 percent of the organic matter variation in the soil sites examined. Multiple regression using other TM bands could only improve this to 40 percent. Landsat TM band 3 also proved to be one of the best predictors for soil spectral behavior as related to calcium carbonate, with a positive predictor regression accounting for 32 percent of the soil values (tab. 1 and tab. 2). It is felt however that more experimentation on the model will be required before any accurate or routine predictions could be made.

4. SPECTRAL MAP PRODUCTION

4.1 *Image analysis*

The previously mentioned Landsat TM sub-scene, geometrically corrected and georeferenced, was classified using Erdas (Earth Resources Data Analysis System), version 7.5 image processing software (Erdas, 1991). A principal component analysis was performed to reduce the number of spectral dimensions to be analysed (MANIERE & *alii*, 1991). The first three principal components, accounted for more than 97 percent of the total variance of the original data set, and as a consequence were used in latter analysis. A 5 x 5 median filter was used to reduce the amount of within soil and land cover variability and to preserve the edges of these units. Because of the difficulties of delineating training samples in the study area, for both bare soils and vegetation cover, an unsupervised spectral clustering classification of both different soils and vegetation types was used. An iterative divergence analysis was then performed, to asses the statistical distances between signatures and, on the basis of the results, pairs of cluster were merged. In the end, 17 clusters were defined from the initial 35 considered. A maximum likelihood classification was then used to assign each pixel to the most probable class. Any expedient (like band rationing, the use of digital elevation data) to reduce the topographic effect were not adopted. Instead, we have used the opportunity to consider as separate classes those areas pertaining to a unique soil unit, but falling in areas with different degrees of illumination (in shadow and in sunshine). The resulting spectral map was then analysed to assess its usefulness to future soil survey programs.



From: ORTOLANI & PAGLIUCA, 1989

FIG. 2 - Solid geology and surface deposits of the *Fortore beneventano* Mountain Community.

4.2 *Spectral map description and analysis*

A preliminary comparison between the spectral map (a condensed version of which is used in fig. 3), a false-colour image (TM band combination: 4, 5, 3) and a set of aerial photography at a scale of 1 : 27 000, allowed us to separate the seventeen spectral classes into eight classes that were dominant by bare soil and nine with vegetation cover. Within the bare soil classes, nearly 400 test points were randomly located, with the number of points for each class, proportional to the extent of the spectral unit. These test points were then positioned on the topographic maps

(1: 25 000) and aerial photography. A few of the initial set of points were rejected because of uncertainty in locating them on the aerial photography.

On the basis of information held on the topographic maps (contour lines), two important factors of soil formation (slope and aspect) influencing spectral response, were determined for each test point. Interpretation of the aerial photography allowed us to describe the colour of soil, in terms of its dominant darkness or brightness. In particular, three broad soil classes of darkness (or brightness) were described, light, medium light and dark on the basis of the pixels appearance. The accuracy of the classifications was then assessed by comparing a significant number of observations on the aerial photographs with field evaluation of soil brightness. The assumption is that soil with a Munsell Value of 3 or less corresponded to dark soils, soils with a Value of 5 or higher were classified as light, whereas soils with a Value ranging from 3 to 5 were considered medium light. Considering the importance of geology and soil erosion processes by water on the soil characteristics of the study area (BUONDONNO & *alii*, 1989a, 1993), each test point was located on the geological and erosion maps and then codified. Finally, on the basis of several satellite colour composite images and field inspections at a similar hour and period of the month corresponding to the satellite overpass, it was possible to separate the test points for each spectral class into two classes of illumination: soils in shadow and soil in sunshine.

This approach has allowed us to evaluate, in first approximation, the «contents» of each spectral unit in terms of soil formation factors and soil colour. A more careful examination, taking into consideration physical and chemical soil surface composition, including soil parameters not routinely determined (e.g.: mineralogy of textural components) may be necessary in the future. The description of each soil spectral class and the associated lithology, is summarised in tab. 3. On this subject, it must be remembered that, within any given spectral class, we considered, as «dominant» a specific soil-site characteristic, when greater than eighty percent of the total number of pixels analysed for each class were represented. When this condition was not satisfied, we have indicated the actual percentage presence of each soil-site characteristic, within the spectral class. Taking into consideration the spectral map «contents» and on the basis of direct experience in the study area, an hypothesis about the typology of soils associated to each spectral class has helped to define the soils at the lower genetic levels of the U.S.D.A. Soil Taxonomy (Great groups and Subgroups). On the basis of the results obtained and to facilitate the discussion of these results, the eight soil classes were grouped into 3 main groups (tab. 3).

TABLE 3 - Soil spectral classes description

Group	Class n.	Soil-site description and dominant soil types	Dominant litology *
A	1	**Dark soils** Chromic Haploxererts, Vertic Xerochrept moderately eroded**, over moderately step slopes. Aspect: 300-350 degrees.	▪ Claystones (Quaternary) ▪ Claystones and marls (U. Cretaceous - L. Miocene)
	2	**Dark soils** Typic Haploxererts, (Typic and Vertic Haploxerolls) weakly eroded, over plateau and gently sloping areas. Aspect: 240-320 degrees.	▪ Claystones (Quaternary) ▪ Limestones (U. Cretaceous - L. Miocene)
B	3	**Medium light soils in shadow** Vertic Xerochrepts, (Typic and Vertic Haploxerolls) moderately to intensively eroded, over moderately steep to steep slopes. Aspect: 300 - 350 degrees	▪ Claystones and marls (U. Cretaceous - L. Miocene) ▪ Limestones (U. Cretaceous - L. Miocene)
	4	**Light soils** Vertic Xerochrepts (Typic and Vertic Haploxerolls) moderately eroded, over moderately steep to steep slopes. Aspect: 20 - 240 degrees	▪ Claystones and marls (U. Cretaceous - L. Miocene) ▪ Limestones (U. Cretaceous - L. Miocene)
	8	**Light soils in shadow** Vertic Xerochrepts, moderately to highly eroded, over steep slopes. Aspect: 200 - 270 degrees	▪ Claystones and marls (U. Cretaceous - L. Miocene)
C	5	**Medium light soils** Typic (Vertic) Xerochrepts, intensively to highly eroded, over steep slopes. Aspect: 40 - 250 degrees	▪ Sandstones and marls (Upper Miocene) ▪ Claystones and marles (U. Cretaceous - L. Miocene)
	6	**Light soils** Typic Xerochrepts and Typic Xerorthent (Typic Xerofluvents) intensively to highly eroded, over steep to moderately steep slopes. Aspect: 50 - 230 degrees	▪ Sandstones and marls (Upper Miocene) ▪ Claystones and marles (U. Cretaceous - L. Miocene) Recent alluvial deposits
	7	**Light soils** Lithic and Typic Xerorthent (Typic Xerofluvents, Badlands, Urban areas), higly eroded, over steep slopes. Aspect: 50 - 200 degrees	▪ Sandstones and marls (Upper Miocene) ▪ Actual alluvial deposits

* Lithology: see ORTOLANI & PAGLIUCA (1989); ** Soil erosion: see BUONDONNO & *alii* (1993).

4.3 *Discussion of map results*

A preliminary image classification over a sub-scene, of the Landsat TM image (LEONE & *alii*, 1995), led to the formulation of an hypothesis about the relationships between soil spectral maps and soil spatial distribution. The results of the present study are based on a more accurate image processing procedure and a more detailed assessment of the «contents» of spectral units (based on field and air-photograph investigations). For ease of presentation and to reduce the complexity of detail which was obtained in the spectral classification, this study will only discuss in detail the dominant clay spectral group and classes of Haploxererts (tab. 3 and fig. 3). Reference is also made to the solid geology and surface deposits of the Fortore beneventano mountain community (fig. 2).

First of all, on the basis of the radiance pattern depicted by the classified image it was possible to separate a dominant Spectral Group A, of dark clayey soils (Typic and Chromic Haploxererts), from the remaining soils. Soils of this Group A have two spectral classes (classes 1 and 2), whose only difference, with concern to the considered soil-site parameters, relates to the degree of erosion risk, one (class 1) associated with moderately eroded soils (Typic Haploxererts) and the second (class 2), associated with weak erosion phenomenon (Chromic Haploxererts and Vertic Haploxererts). Probably, other pedological factors interfere with any further subdivision of these classes, for example, the state of surface roughness.

Another fairly homogeneous spectral group (classes 3, 4 and 8), is dominated by medium-light coloured soils, for which the analysis of their associated pedo-environmental

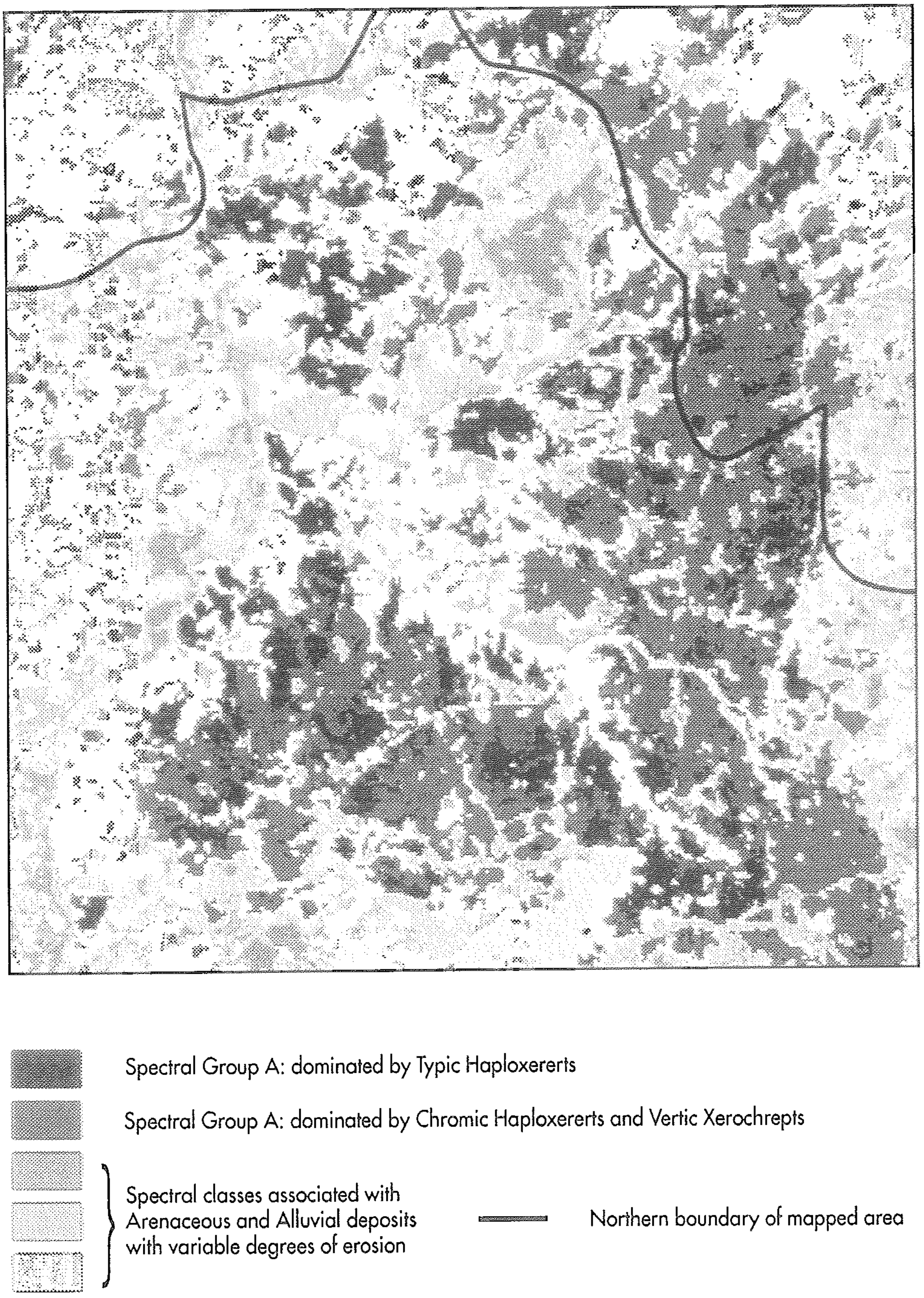


FIG. 3 - Spectral class map derived from an unsupervised classification and visual mapping of spectral classes.

characteristics leads to the suggestion of a taxonomic placement into the Vertic subgroup of the Xerochrepts great group. Classes 3 and 4 are spectrally distinct from class 8, with which it shows substantial environmental analogies, the only exception, is a different predisposition to the soil surface erosion. Evidently, the incidence of erosion events have a considerable affect on soil spectral response. If these results are confirmed by other investigations, then it may be possible to monitor the phenomena of soil evolution in Mediterranean regions similar to the study area, using satellite remote sensing techniques.

It is interesting to point out the usefulness of such a processed image in the delineation of pedogeographical unit boundaries. The above soil boundaries have proved in the past to be very complicated to achieve using air-photographs, during conventional soil survey (BUONDONNO & *alii*, 1989.a). However, fig. 3 shows how close the spectral boundaries are to the known or mapped soil units and also illustrates how the known mapped area can be accurately extended to areas where no field mapping has been undertaken, such as in the north-east corner and the upper central area of the map. Finally, class 8, although spectrally distinct from class 4, showed a nearly complete environmental affinity, with the exception of site aspect, in that it produces a well defined shadow effect. This confirms the hypothesis that it is possible to separate areas pedologically similar, but with strongly differing degrees of illumination, into distinct spectral classes and, thereafter, merge them into a single soil unit.

The other spectral classes show a stronger heterogeneity of content. This taken on its own could lead to the investigation considering remotely sensed spectral maps as not being very useful for pedological applications. But, as mentioned in the introduction of this paper, we want to utilise satellite remotely sensed data as tool for soil spatial variability investigations, by association with other environmental data (geology, geomorphology, climate, etc.). As such spectral data would effectively represent a new and interesting reading key for soil geography comprehension and mapping. Indeed, in support of the spectral classes separations, it was found that the more heterogeneous classes were not so useful for the definition of the soil unit content, but for the delimitation of boundaries. Spectral class 7 provides a good example of this. It's contents are extremely variable, being constituted by alluvial soils, «badlands» and urban areas. Nevertheless, if we associate this information with others, for example, the geology and topographic maps, aerial-photographs, etc., we can easily and proficiently segment the above three land units for soil investigation purposes, an observation confirmed in the field.

5. CONCLUSIONS

The results of the study have allowed the formulation of several interesting conclusions about the use of remotely sensed data for the study of the pedological mantle. In particular, the study suggests that Landsat TM data has provided a valuable addition to conventional soil survey techniques in the study area. Among soil characteristic taken into consideration, organic matter showed a significant influence on soil spectral behaviour, not withstanding the low organic matter contents (maximum around 3 percent, often less than 2 percent) of the investigated soil samples. The explanation of this could reside, as already mentioned, on the textural characteristics of «Fortore» cropped soils, which are dominated by a clayey textural component. In those clayey soils, a small fraction of organic matter has a strong effect on pigmentation. Like organic matter, calcium carbonate was also highly correlated with spectral response in several individual or some of the grouped waveband combinations. What is important to take into consideration is the influence of environmental factors on soil spectral behaviour, especially in consideration of the fact that geomorphological variability and its associated topographic effect, represent the normality for the majority of Apennine areas of Southern Italy.

The procedures used in the image processing emphasised this later aspect. In fact, the «shadow areas» constituted an unique spectral class. The result of such a procedure has in any case pointed out the potential of spectral maps, not just for their ability to locate different pedological types and indicate their spatial variability, but for its usefulness in the identification of land-soil units. This kind of information has led us to hypothesise an advantageous use of aero-spatial remote sensing techniques in soil survey programs, and in particular, during the phases of site field description and pedological unit delimitation.

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