Characterization and discrimination of soils by their reflected electromagnetic energy[1]

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Abstract – The objective of this work was to verify if reflected energy of soils can characterize and discriminate them. A spectroradiometer (Spectral reflectance between: 400-2,500 nm) was utilized in laboratory. The soils evaluated are located in Bauru region, SP, Brazil, and are classified as Typic Argiudoll (TR), Typic Eutrorthox (LR), Typic Argiudoll (PE), Typic Haplortox (LE), Typic Paleudalf (PV) and Typic Quartzipsamment (AQ). They were characterized by their spectral reflectance as for descriptive conventional methods (Brazilian and International) according to the types of spectral curves. A method for the spectral descriptive evaluation of soils was established. It was possible to characterize and discriminate the soils by their spectral reflectance, with exception for LR and TR. The spectral differences were better identified by the general shape of spectral curves, by the intensity of band absorption and angle tendencies. These characteristics were mainly influenced by organic matter, iron, granulometry and mineralogy constituents. A reduction of iron and clay contents, which influenced higher reflectance intensity and shape variations, occurred on the soils LR/TR, PE, LE, PV and AQ, on that sequence. Soils of the same group with different clay textures could be discriminated. The conventional descriptive evaluation of spectral curves was less efficient on discriminating soils. Simulated orbital data discriminated soils mainly by bands 5 and 7.

Index terms: remote sensing, infrared spectrophotometry, reflectance, absorbance.

Caracterização e discriminação de solos pela sua energia eletromagnética refletida

Resumo – O presente trabalho teve por objetivo verificar se a análise da energia eletromagnética refletida por solos permite sua caracterização e discriminação. Foi utilizado espectroradiômetro em laboratório (Faixa espectral: 400-2.500 nm). Os solos avaliados, ocorrentes na região de Bauru, SP, foram: Latossolo Roxo (LR), Terra Roxa Estruturada (TR), Podzólico Vermelho-Escuro (PE), Latossolo Vermelho-Escuro (LE), Podzólico Vermelho-Amarelo (PV) e Areia Quartzosa (AQ). Os solos foram caracterizados espectralmente pelos métodos convencionais (nacional e internacional). Foi idealizado um método para avaliação espectral descritiva. Foi possível caracterizar e discriminar solos pela refletância, e as diferenças espectrais foram identificadas pela forma geral das curvas, intensidade das bandas de absorção e pela tendência de angulação. Essas características foram influenciadas principalmente pela matéria orgânica, ferro, granulometria e constituintes mineralógicos. Nos solos LR/TR, PE, LE, PV e AQ, nesta seqüência, ocorreu diminuição nos teores de ferro e argila, que influenciaram no aumento da intensidade de refletância e variações na forma. Solos de uma mesma classe, com texturas diferentes, puderam ser discriminados. A avaliação descritiva convencional mostrou-se pouco eficaz na discriminação dos solos. Os dados orbitais simulados permitiram discriminar os solos, principalmente nas bandas 5 e 7.

Termos para indexação: sensoriamento remoto, espectrofotometria de infravermelho, refletância, absortividade.

Introduction

Remote sensing (RS) is a technique that allows for the evaluation of different targets at the surface of earth, such as soils, water, plants or atmosphere. When radiant energy strikes any type of surface,

it is distributed through three distinct processes, i.e., reflection, absorption and transmission. Therefore, reflection + absorption + transmittance = 1, with this unit being equivalent to the energy of the incident rays. Transmittance of opaque minerals that occur in soils is zero. High amount of reflectance leads to a relative proportional decrease in absorption in equivalent proportion. The possibility of moist in the thermal region (~1.900 nm) have to be considered. Certain soil characteristics that influence soil processes, such as moisture, must be taken into consideration when determining energy absorption (Stoner & Baumgardner, 1981). The energy of incident rays can be evaluated by a sensor, which can be used in a variety of platforms, such as satellites, aircrafts, in the field or laboratory. However, each type of sensor, has different characteristics, depending on the level of data acquisition. The device used in laboratory and fieldwork covers different ranges of the electromagnetic spectrum and is known as a spectroradiometer. Soil studies normally involve evaluations in the range of 400 to 2,500 nm (Epiphanio et al., 1992).

Reflected electromagnetic energy can be represented as the ratio between the spectral radiation reflected by the soil surface and the spectral radiation reflected by the reference material. This ratio is used to generate the "bidirectional spectral reflectance factor". When this type of study is performed, spectral curves are evaluated, where the *x* axis presents wavelengths and the *y* axis the reflectance factor which can be represented as a percentage or as a fraction. Thus, each soil sample can have a spectral "signature" or "spectral curve", which is a cumulative property derived from its intrinsic heterogeneous characteristics, such as mineralogy, organic materials, particle distribution and chemistry which constitute the soil.

Condit (1970) evaluated American soils by descriptive spectral analysis, and determined three typical patterns. As a complement to the observations of this author, Stoner & Baumgardner (1981) determined other two types. In 1980, these authors published the first atlas about soil characteristics and spectral data, showing the importance of determination of patterns and its practical application. Since then, many works have been produced to determine the relationship between soil attributes and reflected

energy, such as those of Coleman & Montgomery (1990) and Henderson et al. (1992).

Despite the importance of the subject, few studies have been carried out in Brazil, and Formaggio (1983) can be mentioned. Afterwords, Epiphanio et al. (1992) drew up an atlas of the spectral patterns of the main soils found in the State of São Paulo, Brazil. Later, Formaggio et al. (1996) determined the existence of four types of curves depicting four soil patterns. Madeira Netto (1996) evaluated the mineralogy of tropical soils, determining the gibbsite band.

The appearance of new sensors such as AVIRIS (Aircraft) and TM and ETM+ (Landsat) and more sophisticated spectroradiometers, motivated studies. However, Brazil, a country with continental dimensions, has a lack of pedologists (Dalmolin, 1999) to carry out the task of mapping.

The spectral reflectance of tropical soils has been neglected, which has implication for mapping, as performed by Dematté et al. (1999). The lack of descriptive data on soil reflectance limits progress in this subject. The key question was: Would it be possible to characterize and verify differences among soils simply by reflected electromagnetic energy? It was expected that different soil constituents would lead to differences in their spectral curves, permitting discrimination and characterization.

The purpose of this study was to determine whether analysis of reflected electromagnetic energy from soils allowed for their characterization and discrimination.

Material and Methods

The studied area was located in São Paulo State, (latitude 22°45'-22°70' and longitude 48°60'-49°0'), which included the counties of Lençóis Paulista, Macatuba and Bauru. In geological terms, the region is characterized by rocky outcrops of the Serra Geral Formation (Basalts). The outcrops are of the basic eruptive type, occupying river valleys, such as the Lençóis river. Over this formation are extensive depositions of variably textured material, principally intermediate to sandy texture that belongs to the sandstones of Botucatu Formation. Material of the sandstone from Bauru Group is also found in this region (Instituto de Pesquisas Tecnológicas, 1981). The area has a Cwa (Köppen) type climate, characterized by dry, cold winters and hot, humid summers. Mean annual temperature is 21.6°C and precipitation is 1,238 mm (Prado, 1997).

Soils were selected based on their geographical relevance and wide occurrence in the State of São Paulo and classified according to Camargo et al. (1987). As in that work authors compare soil classification of diverse papers, the same nomenclature was maintained in the present work to facilitate discussion. However, looking forward the new Brazilian Classification and international community, the following soil classifications have been correlated: United States (1990), Embrapa (1999) and Camargo et al. (1987) (abreviations), respectively: Typic Eutrorthox, Latossolo Vermelho, LR; Typic Argiudoll, Nitossolo, TR; Typic Argiudoll, Argissolo, PE; Typic Quartzipsamment, Neossolo, AQ; Typic Paleudalf, Argissolo Vermelho-Amarelo, PV; and a Typic Haplortox, Latossolo Vermelho, LE. Typic Haplortox was divided in three categories according to the clay content in B horizon, i.e., above 350 g kg^{-1} for the first one (LE1), 220 to 350 g kg^{-1} for the second category (LE2) and 150 to 220 g kg^{-1} for the third soil type (LE3). Soil profiles were evaluated (Lemos & Santos, 1996), and samples collected at the surface and subsurface horizons of each soil profile (C horizon for AQ).

Through chemical analysis, the pH (H_2O and $CaCl_2$), organic material (OM), P, K^+, Ca^{2+}, Mg^{2+}, Al^{3+} and H^+ (Raij et al., 1987) were determined. Granulometric analysis measured sand, silt and clay. Sulphuric acid digestion was carried for Fe_2O_3 determination (Camargo et al., 1986). Sand, silt and clay fractions were analyzed by X-ray diffraction (XRD), using Ni-filtered CuKa radiation (Jackson, 1969). Kaolinite and gibbsite were determined semi-quantitatively by thermo-differential analysis based on standard mixtures of kaolinite and gibbsite (Dixon, 1966). Iron oxides were identified by XRD on samples treated with 5M NaOH (Norrish & Taylor, 1961; Kampf & Schwertmann, 1982). The 2:1 minerals, particularly the micas and chloritized-vermiculite, were identified by the peaks at 0.10 and 0.14 nm peaks. The iron oxides in the clay fraction (iron not in the crystalline structural of the minerals and amorphous iron) were measured by the CBD - citrate-bicarbonate-dithionite method (Fe_d) (Mehra & Jackson, 1960). Amorphous material of Si and Al was quantified by the difference: 1000 - (kaolinite + gibbsite + 2:1 minerals + free iron).

The Infra-Red Intelligent Spectroradiometer (IRIS), Mark V (manufacturer), sensing system, with a resolution of 2 nm in the range of (450-1,000 nm) and 4 nm (1,000-2,500 nm), was used to obtain spectral curves. Samples were oven-dried at 45°C for 24 hours (Stove), after which they were ground and sieved (2 mm mesh). The sensor was positioned vertically at a distance of 27 cm over the soil sample. The samples were placed in a 9 cm-diameter Petri dish, forming a 1,5 cm layer of soil. The light source,

a 650 W halogen lamp with non-collimated rays for the sample plane, was positioned 61 cm from the sample container at a 15° zenithal angle. A grey plate with 50% reflectance was used as a primary standard, and corrected for 100% afterwards (Epiphanio et al., 1992). Three reflectance readings were taken for each sample.

Spectral curves were described according to the following points: (Figure 1), (I) Soil types (Stoner & Baumgardner, 1981): 1-with predominance of organic matter, 2-minimally altered by oxides, 3-affected by iron oxides, 4-affected by organic matter, and 5-with predominance of iron oxides; (II) Soil types (Formaggio et al., 1996): a-spectral curves typically from A1 horizon of LR, b-spectral curve from "Ap" horizon of PV, c-spectral curve of A11 horizon of a Pachic Umbriorthox and d-spectral curve of the B2t horizon of a Podzolic Dark Red soil; (III) Angles: for bands centered at 400, 500, 600 and 1,600 nm, the angle formed with a vertical axis perpendicular to the x axis (wavelength, nm) and the inclination of the curve was measured with a one-degree precision protractor; bands were chosen based on specific positions of the spectral curve; (IV) Shape: different degrees of curve concavity and convexity were qualitatively characterized between 400 and 600 nm, and between 780 and 1,000 nm (occurrence of iron oxides); (V) Bands: parameters were established for the bands appearing at 1,400, 1,900, 2,200 and 2,265 nm so as to compare them within the same curve.

At a later stage, the same data obtained by the IRIS sensor were used to simulate superficial layer bands according to the Thematic Mapper (TM) sensor of Landsat-5. A calculation was made of the mean spectral responses obtained by IRIS sensor in the wavelengths corresponding to TM bands. These responses (nm) were: 450-520, 520-600, 630-690, 760-900, 1,550-1,750, and 2,080-2,350, which correspond, to bands 1, 2, 3, 4, 5 and 7, respectively.

Results and Discussion

LR was characterized as very clayish soil (Table 1). Mineralogically, these soils are predominantly kaolinitic, although occurring gibbsite and, to a lesser extent, mica, with a 0.10 nm reflection, as well as 0.14 nm chloritized-vermiculite minerals (Figure 2). The average of kaolinite content in these soils was 323 g kg^{-1} while for gibbsite was 98 g kg^{-1}. Total iron was 207 g kg^{-1}. Similarly to TR, the silt and sand fractions in LR showed a predominance of quartz, and with magnetic minerals, such as magnetite and ilmenite.
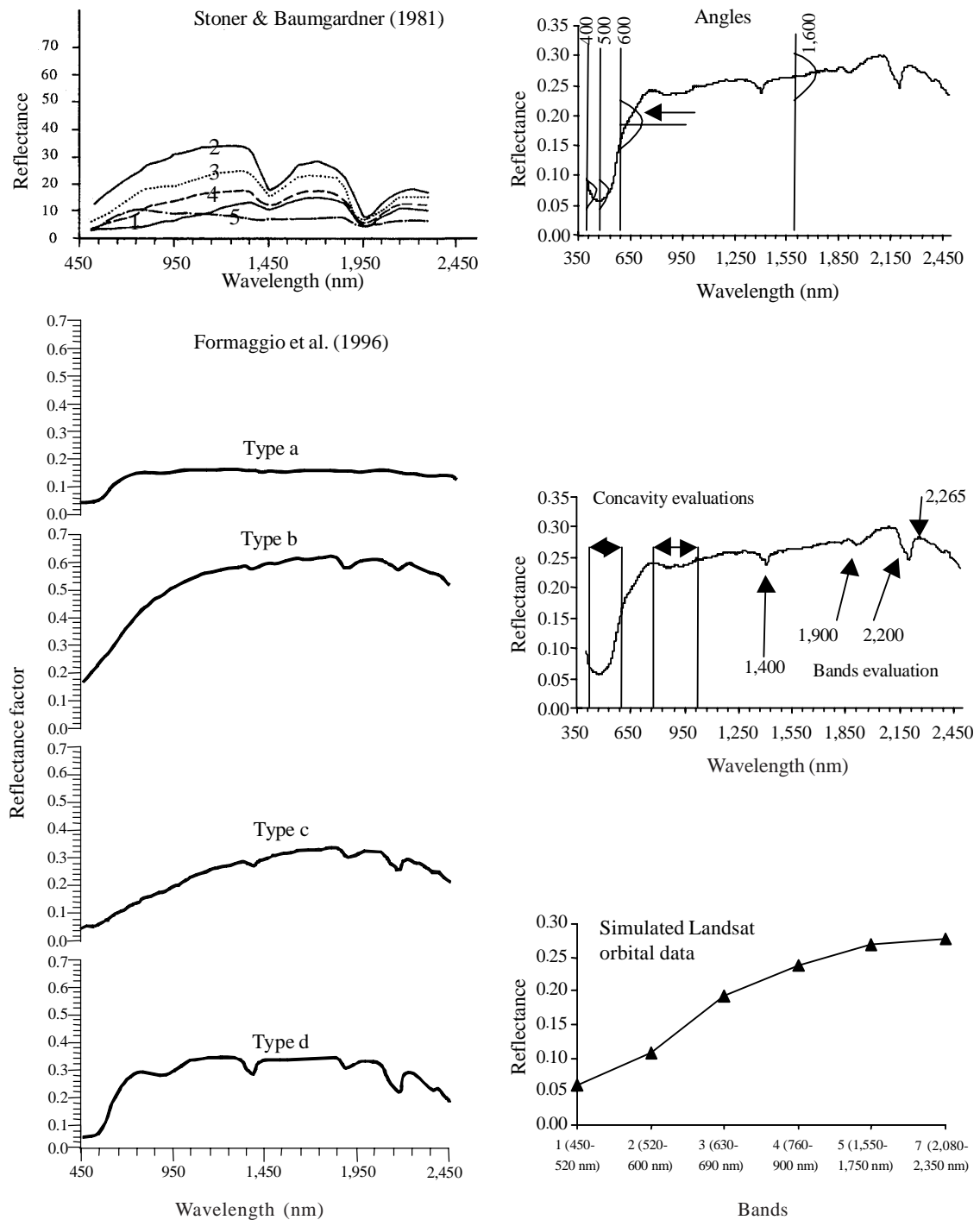
Figure 1. Angles determination, concavity and band evaluations and simulated data of spectral curves of studied soils, compared with the spectral curves of soil types according to Stoner & Baumdardner (1981) and to Formaggio et al. (1996).

The TR soil was characterized as clayish to highly clayish (Table 1). Saturation by bases, varied from 43 to 72% in the superficial horizon and from 53 to 63% in the B horizon. Cation exchange capacity (CEC) was high in comparison with the other soils studied, but was still lower than 240 $mmol_c$ dm^{-3} clay (low-activity clay). Organic matter (OM) content in the A horizon was 27 g kg^{-1}, decreasing to 18 g kg^{-1} in the B horizon. These soils presented kaolinite as the dominant mineral, with reflections at 0.72 and 0.35;

Table 1. Chemical, physical and mineralogical results of the soil attributes and the respective statistical analysis[1].

Soil[2]	Horizon[3]	Chemical analysis[4]				Granulometry		
		OM	SC	CEC	V	Sand	Silt	Clay
		(g kg^{-1})	-- ($mmol_c$ dm^{-3}) --		(%)	---------------- (g kg^{-1}) ----------------		
LR	A	22.3b	50.3	77.6	62.0	263.0de	113.0ab	623.3ab
	B	17.0	19.0	61.3	29.3	230.0	123.0	646.0
TR	A	27.0a	61.5	107.0	55.3	206.0e	180.0a	641.6a
	B	18.0	53.0	88.6	59.0	121.6	148.3	730.0
PE	A	16.8c	52.0	76.0	67.2	634.0c	100.0bc	266.0c
	B	13.0	29.8	105.2	40.6	554.0	86.0	360.0
PV	A	12.1c	21.8	43.1	61.5	793.0ab	60.0de	147.0d
	B	9.6	10.3	37.0	40.5	738.0	65.0	197.0
LE1	A	21.3b	41.3	91.0	45.6	396.0d	116.0ab	486.0b
	B	17.6	14.6	77.0	23.3	326.0	116.0	556.0
LE2	A	16.5c	73.3	98.8	52.0	703.3c	61.7cde	235.0c
	B	12.6	15.8	53.5	30.2	643.3	68.3	288.3
LE3	A	16.4c	23.8	52.0	47.2	780.0b	52.0e	168.0d
	B	12.0	9.0	42.6	25.0	768.0	52.0	180.0
AQ	A	11.0d	21.2	38.2	55.7	846.7a	53.0de	99.0e
	C	9.8	8.0	32.5	27.2	838.0	62.0	100.0

		Fe_2O_3	Clay fraction mineralogy				Amorphous Si+Al	Moist color[5]
			Kaolinite	Gibbsite	Vermiculite chloritized+micas	Free iron		
		------------------------------------ (g kg^{-1}) ------------------------------------						
LR	A	207.1a	323a	98	42	143a	15	2.5YR 3/4
	B	212.6	363	97	38	142	6	2.5YR 3/4
TR	A	215.0a	296a	94	47	151a	43	2.5YR 2/4
	B	212.1	359	118	57	152	44	2.5YR 3/4
PE	A	86.2c	133c	40	14	75c	13	2.5YR 3/4
	B	94.0	203	39	30	80	32	2.5YR 3/6
PV	A	32.0e	81d	18	10	25cd	13	5YR 3/4
	B	34.0	105	31	14	34	12	5YR 4/4
LE1	A	127.0b	260b	78	21	102b	25	2.5YR 2/4
	B	144.0	312	75	28	130	18	2.5YR 2/6
LE2	A	58.0d	120c	19	15	46cd	33	2.5YR 3/4
	B	62.0	160	29	19	53	27	2.5YR 3/6
LE3	A	38.0e	85d	34	15	32d	10	2.5YR 2/4
	B	34.0	94	24	14	29	14	2.5YR 3/4
AQ	A	11.0f	54e	18	6	10e	11	5YR 3/4
	C	10.0	56	18	5	9	12	5YR 4/6

[1]For organic matter, sand, silt, clay, Fe_2O_3, kaolinite and free iron, averages followed by a same letter on the column, do not differ at 5% significance (t test). [2]LR: Typic Eutrorthox, Latossolo Vermelho; TR: Typic Argiudoll, Nitossolo; PE: Typic Argiudoll, Argissolo; AQ: Typic Quartzipsamment, Neossolo; PV: Typic Paleudalf, Argissolo Vermelho-Amarelo; LE: Typic Haplortox, Latossolo Vermelho, divided in three categories, according to clay texture in B horizon, i.e., above 350 g kg^{-1} (LE1), between 220 and 350 g kg^{-1} (LE2), and between 150 and 220 g kg^{-1} (LE3). [3]Main horizons, of surface (A) and subsurface (B or C). [4]OM: organic matter, respectively 3, 6, 5, 5, 3, 6, 5, 6 repetitions for each soil; SC: sum of cations; CEC: cation exchange capacity. [5]Extracted from Munsell color charts.
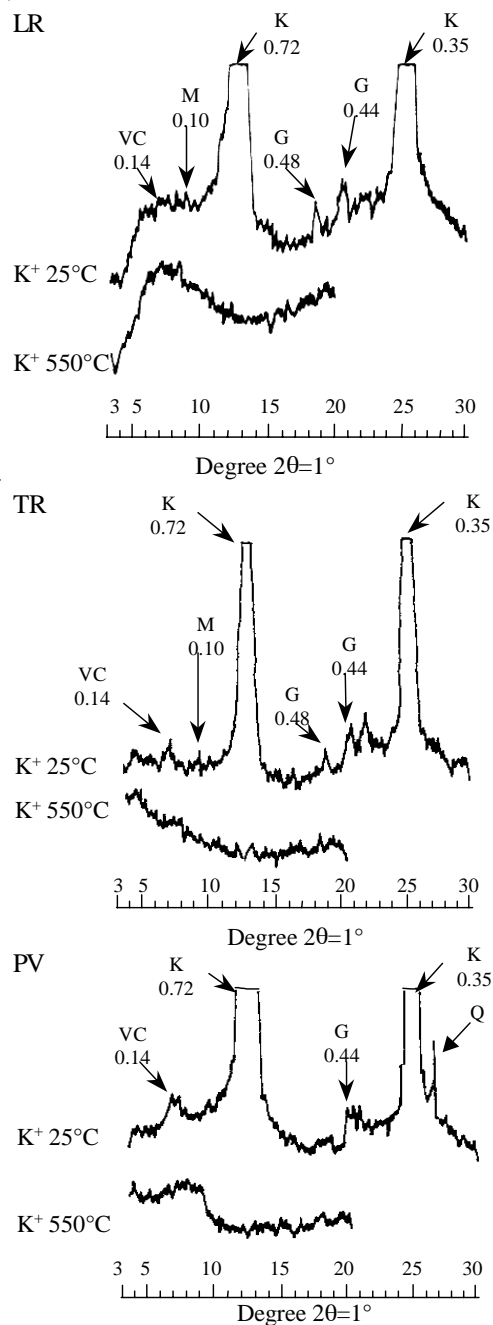
Figure 2. X-ray diffractograms of clay fraction with iron removed and K$^+$ satured in superficial and subsuperficial horizons of Typic Eutrorthox (LR), Typic Argiudoll (TR) and Typic Paleudalf (PV) soils showing the Kaolinite (K), gibbsite (G), micas (M), vermiculite chloritized (VC) and quartz (Q) peaks.

gibbsite with reflections at 0.48 and 0.44, and chloritized-vermiculite reflections at 0.14 nm (Figure 2). High magnetic attraction indicated the occurrence of magnetite and ilmenite in the coarsest fraction. X-ray diffractograms (XRD) patterns of silt showed a predominance of quartz, with some heavy metals, such as magnetite.

PE soil presented medium texture with intermediate clay contents (Table 1). Silt content was low, with average values of 100 g kg^{-1} (A horizon) and 86 g kg^{-1} (B horizon). Cation exchange capacity (CEC) was less than 240 mmol$_c$ dm^{-3}. Mineralogically, these soils contained kaolinite with gibbsite and 2:1 minerals in smaller proportions. Gibbsite was identified by the endothermic peak of 300 to 350ºC. Total iron content was 86 g kg^{-1}, with considerable variation. Silt fraction XRD patterns for silt fraction indicated a predominance of quartz. On the diffractograms of clay fraction treated with NaOH 5 M, for the soils LR, TR and PE, was found a series of spacements (in nm), typical of hematite, as follows: 0.269, 0.184 and 0.163. Although the spacement at 0.269 can be common for both hematite and goethite, there was no diagnostic spacement at 0.240 and 0.418 of goethite.

The PV are usually present in association with sandier-textured LE or LV that occupy a mid-slope position. This favors a slight textural gradient that causes it to be present in a transitional position in terms of morphology. Thus, physical, chemical and morphological characteristics of PV were very similar to those of the LE3 and AQ (Table 1). The mineralogy of PV soil includes kaolinite as indicated by a strong X-ray reflections at 0.72 and 0.35 nm and some vermiculite-chloritized manifested by a broad X-ray reflection near 0.14 (Figure 2).

The differences between the LE studied here was on the clay content, total iron and organic matter (Table 1). These are deep, well-drained, dark red, 2.5YR for LE1 and LE2 and, in some cases, 5YR for LE3. Organic matter and total iron content in the A horizon decreased from LE1 to LE3. The Al$_2$O$_3$/Fe$_2$O$_3$ relationship in the soils with intermediate clay (LE2) and intermediate sandy texture (LE3) was lower than 3.14, which differentiates these soils from LV. Clay fraction mineralogy in these soils was represented mainly by kaolinite, followed by gibbsite and 2:1-type minerals in smaller quantities. Silt and sand

fractions were predominantly well-crystallized quartz. The peaks of gibbsite, as observed on the thermographics of LE2 and LE3 soils were far more evident than the same peaks in LE1, indicating that the gibbsite in LE2 and LE3 soils was better crystallized than that in LE1 soil, despite of the higher contents of gibbsite occurring in LE1 (Table 1).

The AQ was the sandiest soil studied here, with clay contents less than 150 g kg^{-1} on both horizons (Table 1). These are deep, well-drained soils with 5YR hues slightly darkened by organic matter. Silt content was extremely low as occurred with cation exchange capacity, sum of cations and organic matter (Table 1). Mineralogically, the clay fraction was dominated by kaolinite, with presence of gibbsite and small amounts of 2:1-type minerals. Total iron content was around 11 g kg^{-1} (Table 1), while sand and silt fractions showed a predominance of quartz.

Variations of shape configurations and reflectance intensity in both A and B horizons for all the soils studied were observed on the spectral curve (Figures 3 and 4). Stoner & Baumgardner's (1981) Type 1 curve is characterized by a slight concavity in the region until 1,000 nm and contained a constant inclination from 1,000 to 1,300 nm (Figure 1). Type 2 curve presented a clearly convex feature from visible wavelengths up to 1,300 nm, with an inclination between 600 and 700 nm. This is normally attributed to soils with low contents of organic matter. Type 3 curve has a strong ascending inclination and then a slightly descending curve up to 600 nm, followed by an almost zero inclination from 620 to 740 nm, or even a negative slope from 760 to 880 nm. Beyond 880 nm, the inclination increased as the wavelength increased. This was due to soils with a moderately high iron content. The Type 4 curve showed a descending inclination from 880 to 1,000 nm, leveled to zero and even became negative from 1,000 to 1,300 nm. Curve Type 5 was identified as characteristic of a Latosol "Typic Haplortox" and was similar, in some aspects, to the Type 3 curve, although with an inclination dropping to zero and becoming negative from 750 to 1,300 nm (Figure 1).

The comparisons of curve Types are better visualized by mean reflectance of each studied soil (Figures 3 and 4) and defined at Table 2. Soil curves originated from basic rock demonstrated a slight concavity in the range of 400 to 500 nm, with a strongly ascending inclination up to 750 nm, followed by a moderate concavity from 750 to 1,100 nm. Afterwards, curves increase with a slight inclination up to 1,300 nm, followed by a slight slope up to 2,000 nm, where a negative inclination begins.

These characteristics allowed LR and TR soils to be related with Stoner & Baumgardner's (1981) curve Type 5. These soil curves were also observed by Epiphanio et al. (1992), since they have high magnetite and ilmenite contents and a low reflectance. These compounds generated a curve with practically no bands at 1,400 and 1,900 nm (Table 2) which are characteristics of water as also observed by Epiphanio et al. (1992). Moreover, the high Fe content favors electromagnetic energy absorption and generates low reflectance intensity. The Fe oxides, mainly hematite and goethite, are responsible for the concavities at 450 and 850 nm (Figure 3) confirming the 850 nm observed by Vitorello & Galvão (1996).

PE curves were characterized as Type 5 for both horizons (Table 2). The concavities between 400 and 600 nm and 850 and 1,000 nm were considered weak in both layers, though lower than those of the LR and TR (Figure 3). The angulations in the bands at 400, 500, 600 and 1,600 were 128, 78, 42 and 86 degrees, respectively, in the first horizon and 128, 77, 35 and 88 degrees in the second horizon (Table 2). These angles show that the intensity and shape of the spectral curves of this soil began to present an ascendance from 850 to 2,000 nm (Figure 3). This behavior may be associated with soil constituents. It starts to present lower contents of Fe and clay. Quartz presented a high intensity reflectance (White et al., 1997) and its presence in coarser fractions was a contributing factor, which was not mentioned in Stoner & Baumgardner (1981).

Mean spectral curves of LE1 showed Type 5 characteristics (Figure 3) and were similar to the other soils with high clay, i.e., LR and TR (Table 2). Concavities from 400 to 600 nm and from 850 to 1,000 nm were similarly weak in both horizons of LE1. They were presented as weak and medium, and again similar to the correspondent curves of clayey soils. The angles were 124, 75, 45 and 86 degrees for A horizon, and 130, 77, 35 and 85 degrees for B horizon (Table 2), thus revealing sample homogeneity in the two horizons (Figure 3).
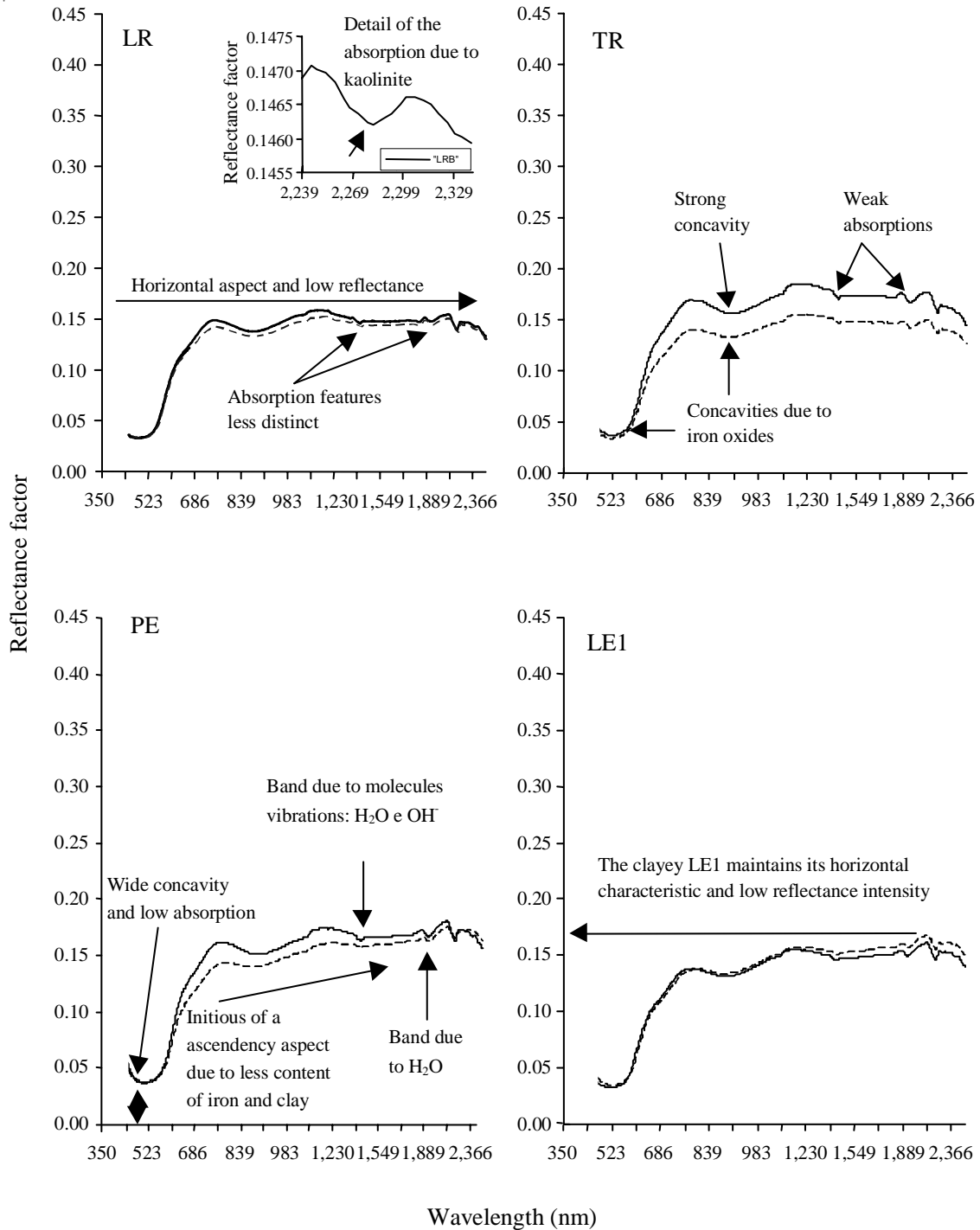
Figure 3. Mean spectral curve of Typic Eutrorthox (LR), Typic Argiudall (TR), Typic Argiudall (PE) and Typic Haplortox with clay texture above 350 g kg^{-1} (LE1) soils from surface (-----) and subsurface (——) horizons.
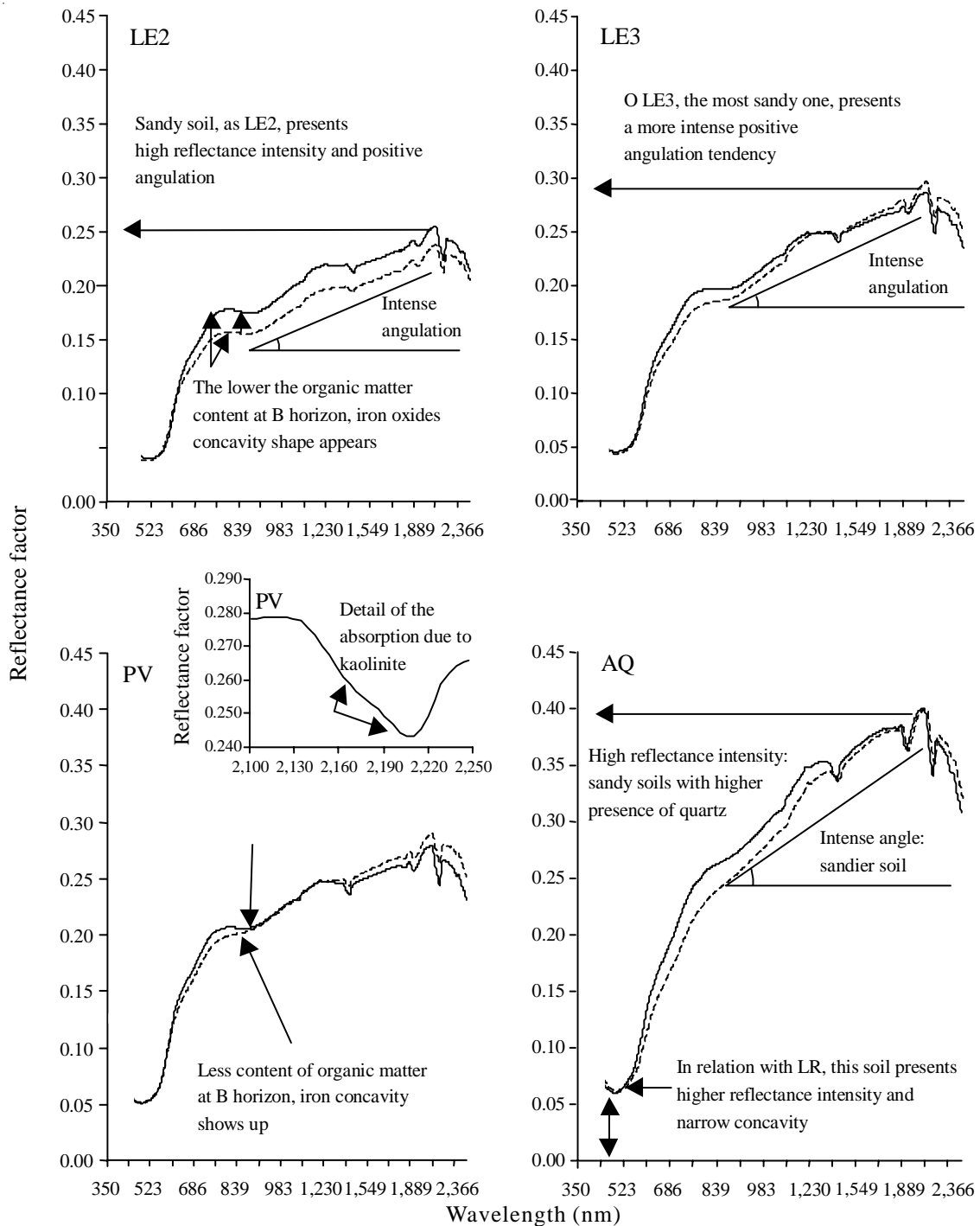
Figure 4. Mean spectral curve of Typic Haplortox with clay texture between 220 and 350 g kg^{-1} (LE2) and between 150 and 220 g kg^{-1} (LE3), Typic Paleudalf (PV) and Typic Quartzipsamment (AQ) soils from surface (-------) and subsurface (———) horizons.

Table 2. Descriptive characterization and statistical analysis of the spectral curves of superficial and subsuperficial horizons of the soils studied and selected bands for evaluation[1].

Soil[2]	Type[3]	Type[4]	Inclination (degrees)[5]				Band shape[6] (nm)		Absorption band intensity[7] (nm)				
			400	500	600	1,600	400-600	780-1,000	1,400	1,900	2,200	2,265	2,365
Surface horizon													
LR	5	a	132.6bc	71.3ab	42.0ab	87.3a	cc weak	cc medium	W	W	MW	VW	VW
TR	5	a	134.3ab	73.5ab	40.3ab	90.6a	cc weak	cc medium	W	W	MW	VW	VW
PE	5	a	127.6cd	78.0a	42.0ab	86.2ab	cc weak	cc weak	VW	W	MW	VW	VW
PV	3	a	136.8ab	70.0b	39.6ab	79.6c	cc medium	cc weak	W	MW	MI	VW	W
LE1	5	a	124.3d	75.3ab	45.0a	86.6a	cc weak	cc medium	W	W	MW	VW	VW
LE2	5	a	135.5ab	74.3ab	40.1ab	81.3bc	cc weak	cc weak	W	W	M	VW	W
LE3	3	a	137.3ab	71.8ab	38.3bc	77.6cd	cc medium	cc null	W	W	MI	VW	W
AQ	2	b	139.3a	50.6c	33.1c	74.0d	cc intense	cc null	MW	MI	I	VW	VW
Subsurface horizon													
LR	5	a	128.0c	75.3a	36.0a	88.6a	cc weak	cc medium	W	W	MW	VW	VW
TR	5	a	130.6bc	75.1a	35.1a	91.1a	cc medium	cc medium	W	W	M	VW	VW
PE	5	a	128.2c	77.2a	35.2a	88.2a	cc weak	cc weak	W	W	MW	VW	VW
PV	3	a	131.8abc	67.2a	35.8a	81.2bc	cc medium	cc weak	MW	MW	MI	VW	W
LE1	5	a	130.3bc	77.0a	35.3a	85.6ab	cc weak	cc medium	W	W	MW	VW	VW
LE2	5	a	132.6abc	75.0a	35.5a	80.8bc	cc weak	cc medium	W	W	M	VW	W
LE3	3	a	137.0a	71.6a	33.6a	78.3cd	cc medium	cc weak	MW	W	MI	VW	VW
AQ	3	b	134.8ab	56.0b	37.5a	73.1d	cc intense	cc null	M	MI	I	VW	VW

[1]Averages followed by the same letter on the column for inclination indicate no significant difference at 5% (t test). [2]LR: Typic Eutrorthox, Latossolo Vermelho; TR: Typic Argiudoll, Nitossolo; PE: Typic Argiudoll, Argissolo; AQ: Typic Quartzipsamment, Neossolo; PV: Typic Paleudalf, Argissolo Vermelho-Amarelo; LE: Typic Haplortox, Latossolo Vermelho, divided in three categories according to clay texture in B horizon, i.e., above 350 g kg⁻¹ (LE1), between 220 and 350 g kg⁻¹ (LE2), and between 150 and 220 g kg⁻¹ (LE3). [3]Soil types (Stoner & Baumgardner, 1981): 2: minimally altered by oxides; 3: affected by iron oxides; 5: with predominance of iron oxides. [4]Soil types (Formaggio et al., 1996): a: spectral curves typically from A1 horizon of LR; b: spectral curve from "Ap" horizon of PV. [5]Values higher and lower than 90 degrees indicate positive and negative, respectively, spectral curve tendency. [6]cc: concavity. [7]VW: very weak; W: weak; MW: moderate-weak; M: moderate; MI: moderate intense; I: intense.

The spectral curves of LE3 and PV soils fit Type 3 for both horizons, while AQ fit curve Type 2 (Figure 4), differentiating from those originated from diabase. This occurred due to the slight alteration on spectral curve shape at 850 nm, being more concave on the B horizon, as a result of the lower organic matter content, allowing the Fe effect to appear. Indeed, B horizon samples usually presented higher intensity reflectance in comparison to surface samples (Figure 4), in agreement with Galvão et al. (1997).

When moving from clayish soils LR and TR with high Fe contents, to intermediary PE, LE1 and LE2 soils and then to sandier soils LE3, PV and AQ, with lower Fe contents, differences on the angles of spectral curves shape also changes. It passes from horizontal to a positive ascendancy tendency (Figures 3 and 4).

Stoner & Baumgardner's (1981) curve Types were obtained based on a descriptive analysis of moist soil samples, while here and in Epiphanio et al. (1992) dry samples in stove were used. Moisture affects spectral curve and absorption band intensity (Formaggio et al., 1996). Moreover, most soils used by Stoner and Baumgardner were from the United States, except for Type 5 soil.

Characterization of Brazilian soil spectral patterns (Epiphanio et al., 1992) was very important. Later, with regard to curve interpretation, Formaggio et al. (1996) used dry soil samples, which permitted additional comparisons to those of Stoner & Baumgardner (1981).

Formaggio et al. (1996) classified soil curves in São Paulo State into four Types (Figure 1). These soils – LR, TR, PE and LE1 – were classified as Type *a*, while AQ fit class Type *b*. The LE2 and mainly LE3 and PV, presented intermediate behavior between Types *a* and *b*, since the curve from 1,000 nm onwards showed a different shape as compared with the previous classes (Figures 1 and 4). The slope was clearly positive, while curves of Type *a* were almost horizontal. Furthermore, the 850 nm concavity was still perceptible in these soils, which is not the case in Type *b* curves. Thus, this fact suggests the possibility of a fifth curve Type which is intermediary to Types *a* and *b*.

There was no difference among the soils, except for AQ. Even so, some aspects do not fit into the Types formulated by Formaggio et al. (1996). The PV soils of the Bauru region, for instance, had a reflectance of 0,2 and 0,3 and a slight concavity centered at 850 nm, while the PV soils had a reflectance intensity of 0,5 with no concavity. These differences may be explained by the differences on genetic and soils evolution, although they have the same classification.

Descriptive analyses of type curves, as proposed by Stoner & Baumgardner (1981) and Formaggio et al. (1996) did not allow for an adequate discrimination of studied soils. Out of eight units, only two Types fit. On the other hand, they help the interpreter in a preliminary reconnaissance of soils and inferences about their physical and chemical characteristics, for which reason this type of approach should continue to be employed.

Other approaches for soil discrimination, would be through mineralogy and the study of soil and reflectance relations. Therefore, it was possible to identify gibbsite, with absorption close to 2,265 and 2,280 nm (Madeira Netto, 1996), ratified by X-ray analysis and observed in the LR soils (Figures 2, 3), in agreement with observations of the LR soils of Paraná (Demattê & Garcia, 1999). The same holds true for the kaolinite in the PVs (Figure 4) detected at 2,200 nm, which, however, presented a characteristic step (Hauff et al., 1990).

Soils can also be differentiated according to their reflectance intensities, mainly in the range of 800 nm up to 2,360 nm, as well as the different angulations in specific bands. In the case of more clayish red soils, this differentiation was less evident, particularly between the LR and the TR, although it was possible to differentiate them from the LE1, also clayish (Table 2). The soil curve variations can be observed at 1,600 nm. Therefore, the angulation of the LR is 87,3° against 74° of the AQ. In other words, the AQ curve presents a stronger positive tendency. The same thing can be seen among the soils with different textures. From the LE1 to the LE2 and from there to the LE3, the angulations decrease, with values 86°, 81° and 77°, respectively, indicating the variation with a positive tendency for the sandier soil.

The descriptive evaluation based on the absorption bands is also useful in the discrimination of the soils (Table 2). The concavity between 780 and

1,000 nm, caused by iron oxides, goes from medium in the LR to null in the AQ. This is mainly due to free iron oxides, which influence the concavity on this spectral band, in agreement with Demattê & Garcia (1999). The same thing is found in the absorption band intensities. At 1,400 and 1,900 nm, these reflectance intensities shift from weak to moderate in the same soils. In the kaolinite band at 2,200 nm, they are weak-moderate in the LR, shifting to intense in the AQ. Although both soils contain kaolinite in their composition, other factors, such as the presence of opaque minerals (i.e., magnetite and ilmenite), contributed to help them stand out more clearly in the AQ. All the soils showed gibbsite in their compositions; however, the descriptive evaluation was difficultated, since they all presented very weak absorption intensities. In this case, the quantification would have shown better results with quantitative analyses of the spectral data such as those performed by Madeira Netto (1996).

Spectral curves obtained with a laboratory sensor presented greater details for shape, allowing for better discrimination of soils (Figures 3 and 4), because of the greater number of bands (675) evaluated. When the data were simulated for a Thematic Mapper (TM) sensor, the number of bands was considerably reduced to 6. For this reason, TM spectral curves were much less detailed (Figure 5). However, a series of differences, in terms of curve shape or band intensity, allowed for discrimination between soils.

The LR and TR soils presented the same spectral curves (Figure 5), while PE indicated similarities observed in the land data, with a positive inclination starting at band 4, to the highest intensity found in band 7. On the other hand, Demattê et al. (2000) discriminated LR from TR by discriminant analysis, thus demonstrating the limitation of descriptive evaluation. The PV and AQ soils, with higher contents of sand, were significantly discriminated by these same bands.

As the soils present lower contents of opaque minerals (such as magnetite=$Fe^{2+}Fe^{3+}O_4$); getting higher the contents of sand and presence of quartz; the intensity of reflectance increased on the sequence LR, TR, LE1, PE, LE2, LE3, PV, and AQ, owing to these soil properties. Moreover, the shape of the

spectral curves changed, with the sandier soils presenting a positive tendency from bands 1 to 5, proceeding to almost null and being negative in bands 3 to 7 for LR and TR soils. In this case, band 5 discriminated AQ soils from the PE of TR. On the other hand, on the visible interval, it was not possible to discriminate them. Soils such as PV, LR and LE were discriminated in all bands. These spectral curves are in agreement with Demattê et al. (2000). These authors obtained data of similar soils from Piracicaba region extracted from Landsat images.

Soils from the same group but with different textural classes can be discriminated. Clay and iron content decreased from the LE1 soil to the LE2 and to the LE3. Reflectance intensity increased in this same sequence. In fact, in band 4 (760-900 nm), which is related to iron oxides, different intensities were found and are related to the iron content. Indeed, Frasier (1991) describes the discrimination and identification of iron oxides by Landsat images.

The descriptive analysis based on curve Types has its merits since it can discriminate between soils,
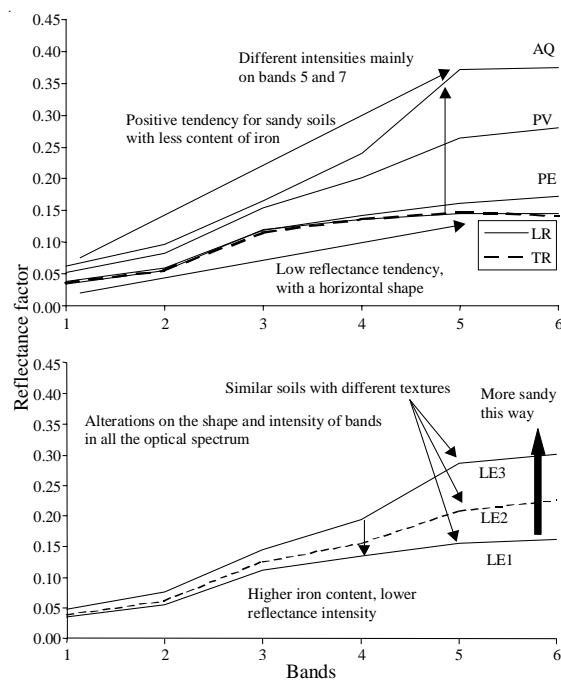
Figure 5. Radiometric simulated Landsat 5-TM orbital data of spectral curves of soils evaluated for wavelinghts (nm) at 450-520 (1), 520-600 (2), 630-690 (3), 760-900 (4), 1,550-1,750 (5) and 2,080-2,350 (7) bands.

but it cannot determine beforehand their final discrimination, because soils are variable and the same unit may possess different characteristics. Textural classification (Embrapa, 1999) defines intermediary-textured soils with clay contents of 150 to 350 g kg⁻¹. In this study two soils fitted in the same textural classification (LE2 and LE3), and were spectrally discriminated. Moreover, this work indicated that the best evaluation of these curves was not achieved with only dry or only moist soils, but with both (Demattê et al., 1998).

This technique allowed to discriminate and identify descriptive information about soil sample constituents, with no special soil treatment, as presents to be fast and simple. Innumerable data can be extracted from this technique, ranging from the discrimination of soil elements to the classification of soils, as realized by Stoner et al. (1980), Stoner & Baumgardner (1981) and Epiphanio et al. (1992).

Finally, it is necessary to continue obtaining and analyzing spectral curve patterns, to assist in soil survey and management. This technology is still an integral and auxiliary part of the conventional methods; it can not supplant fieldwork.

Conclusions

1. The soils LR, PE, PV, LE and AQ can be discriminated by their electromagnetic reflected energy.

2. Spectral differences are better identified by the general shape of the spectral curves, absorption bands, reflectance intensity, and by the angles of the direction of their tendency.

3. Descriptive evaluation of spectral curves is not so efficient on the discrimination of soils, althouhg it can provide assistence on their previous characterization.

4. Soils from the same group, such as LE, but with different textural classes, can be discriminated; sandy soils present a positive ascendancy shape curve when compared with clayey soils.

5. Simulated orbital data, although less detailed, enable to discriminate the soils under study, mainly in 1,550-1,750 nm and 2,080-2,350 nm wavelengths.

Acknowledgements

References

CAMARGO, A. O. de; MONIZ, A. C.; JORGE, J. A.; VALADARES, J. M. **Métodos de análise química, mineralógica e física de solos do IAC**. Campinas: Instituto Agronômico, 1986. 94 p. (Boletim Técnico, 106).

CAMARGO, M. N.; KLANT, E.; KAUFFMAN, J. H. Classificação de solos usada em levantamentos pedológicos no Brasil. **Boletim Informativo da Sociedade Brasileira de Ciência do Solo**, Campinas, v. 12. n. 1, p. 11-13, jan./abr. 1987.

COLEMAN, T. L.; MONTGOMERY, O. L. Assessment of spectral characteristics for differentiating among soil categories in the Southeastern United States. **Photogrammetric Engineering and Remote Sensing**, Bethesda, v. 52, p. 1659-1663, 1990.

CONDIT, H. R. The spectral reflectance of American soils. **Photogrammetric Engineering**, Bethesda, v. 36, p. 955-966, 1970.

DALMOLIN, R. S. D. Faltam pedólogos no Brasil. **Boletim Informativo da Sociedade Brasileira de Ciência do Solo**, Viçosa, MG, v. 24, n. 4, p. 13-15, out./dez. 1999.

DEMATTÊ, J. A. M.; CAMPOS, R. C.; ALVES, M. C. Evaluation of soil survey by spectral reflectance. In: INTERNATIONAL CONFERENCE ON APPLIED GEOLOGIC REMOTE SENSING, 13., 1999, Vancouver. **Proceedings**… Ann Arbor: Erim, 1999. v. 2, p. 126-133.

DEMATTÊ, J. A. M.; GARCIA, G. J. Alteration of soil properties through a weathering sequence as evaluated by spectral reflectance. **Soil Science Society of America Journal**, Madison, v. 63, n. 2, p. 327-342, 1999.

DEMATTÊ, J. A. M.; HUETE, A. R.; FERREIRA JUNIOR, L. G.; ALVES, M. C.; NANNI, M. R.; CERRI, C. E. Evaluation of tropical soils through ground and orbital sensors. In: INTERNATIONAL CONFERENCE GEOSPATIAL INFORMATION IN AGRICULTURE AND FORESTRY, 2., 2000, Lake Buena Vista. **Proceedings**... Ann Arbor: Erim, 2000. v. 2, p. 35-42.

DEMATTÊ, J. A. M.; SOUSA, A. A.; NANNI, M. R. Avaliação espectral de amostras de solo e argilo-minerais em função de diferentes níveis de hidratação. In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 9., 1998, Santos. **Anais**... Santos: Instituto Nacional de Pesquisas Espaciais/Sociedade Latino-Americana de Sensoriamento Remoto e Sistemas de Informações Espaciais, 1998. [5 p.]. CD-ROM. Seção pôster.

DIXON, J. B. Quantitative analysis of kaolinite and gibbsite in soils by differential thermal and selective dissolution methods. **Clays and Clay Minerals**, Boulder, v. 14, p. 83-90, 1966.

EMBRAPA. Centro Nacional de Pesquisa de Solos (Rio de Janeiro, RJ). **Sistema brasileiro de classificação de solos**. Brasília: Embrapa-SPI/Embrapa-CNPS, 1999. 412 p.

EPIPHANIO, J. C. N.; FORMAGGIO, A. R.; VALERIANO, M. de M.; OLIVEIRA, J. B. **Comportamento espectral de solos do Estado de São Paulo**. São José dos Campos: Instituto Nacional de Pesquisas Espaciais, 1992. 131 p.

FORMAGGIO, A. R. Comportamento espectral de quatro solos do Estado de São Paulo nos níveis orbital, de campo e de laboratório. 1983. 90 f. Dissertação (Mestrado em Sensoriamento Remoto) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 1983.

FORMAGGIO, A. R.; EPIPHANIO, J. C. N.; VALERIANO, M. de M.; OLIVEIRA, J. B. Comportamento espectral (450-2450 nm) de solos tropicais de São Paulo. **Revista Brasileira de Ciência do Solo**, Campinas, v. 20, p. 467-474, 1996.

FRASIER, S. J. Discrimination and identification of iron oxides using satellite thematic mapper data: a Newman case study. **International Journal of Remote Sensing**, London, v. 12, p. 635-641, 1991.

GALVÃO, L. S.; VITORELLO, I.; FORMAGGIO, A. R. Relationships of spectral reflectance and color among surface and subsurface horizons of tropical soil profiles. **Remote Sensing Environment**, New York, v. 61, p. 24-33, 1997.

HAUFF, P. L.; KRAUSE, F. A.; THIRY, M. Spectral identification and characterization of kaolinite/smectite clays in weathering environments. In: AUSTRALIAN REMOTE SENSING CONFERENCE, 5., 1990, Perth. **Proceedings**... Perth: Environmental Research Institute of Michigan, 1990. p. 898-905.

HENDERSON, T. L.; BAUNGARDNER, M. F.; FRANSMEIER, D. High dimensional reflectance analysis of soils organic matter. **Soil Science Society of America Journal**, Madison, v. 56, p. 865-872, 1992.

INSTITUTO DE PESQUISAS TECNOLÓGICAS. Divisão de Minas e Geologia Aplicada. **Mapa geológico do Estado de São Paulo**. São Paulo, 1981. Escala 1:1000.000.

JACKSON, M. L. **Soil chemical analysis**: advanced source. Madison: Wisconsin University, 1969. 895 p.

KAMPF, N.; SCHWERTMANN, U. The 5 M NaOH concentration method for iron oxides in soils. **Clays and Clay Minerals**, Boulder, v. 30, p. 401-408, 1982.

LEMOS, R. C. de; SANTOS, R. D. dos. **Manual de descrição e coleta de solo no campo**. 3. ed. Campinas: Sociedade Brasileira de Ciência do Solo, 1996. 84 p.

MADEIRA NETTO, J. S. Spectral reflectance properties of soils. **Photo Interpretation**, Paris, v. 34, p. 59-70, 1996.

MEHRA, O. P.; JACKSON, M. L. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. **Clays and Clay Minerals**, Boulder, v. 7, p. 317-327, 1960.

NORRISH, K.; TAYLOR, R. N. The isomorphous replacement of iron by aluminum in soil goethites. **Journal of Soil Science**, London, v. 12, p. 294-306, 1961.

PRADO, H. do. **Os solos do Estado de São Paulo**: mapas pedológicos. Piracicaba: H. do Prado, 1997. 205 p.

RAIJ, B. van; QUAGGIO, J. A.; CANTARELLA, H.; FERREIRA, M. E.; LOPES, A. S.; BATAGLIA, C. O. **Análise química do solo para fins de fertilidade**. Campinas: Fundação Cargill, 1987. 170 p.

STONER, E. R.; BAUMGARDNER, M. F. Characteristics variations in reflectance of surface soils. **Soil Science Society of America Journal**, Madison, v. 45, n. 6, p. 1161-1165, 1981.

STONER, E. R.; BAUMGARDNER, M. F.; BIEHL, L. L.; ROBINSON, B. F. **Atlas of soil reflectance properties**. West Lafayette: Purdue University, 1980. 75 p.

UNITED STATES. Department of Agriculture. Soil Conservation Service. Soil Survey Staff. **Keys to soil taxonomy**. 4. ed. Blacksburg: Virginia Polytechnic Institute and State University/Agency for International Development, 1990. 422 p. (Soil Management Support Services Technical Monograph, 6).

VITORELLO, I.; GALVÃO, L. S. Spectral properties of geologic materials in the 400 to 2500 nm range: review for applications to mineral exploration and lithologic mapping. **Photo Interpretation**, Paris, v. 34, p. 77-99, 1996.

WHITE, K.; WALDEN, J.; DRAKE, N.; ECKARDT, F.; SETTLE, J. Mapping the iron oxide content of dune sands, Namib Sand Sea, Namibia, using Landsat Thematic Mapper Data. **Remote Sensing Environment**, New York, v. 62, p. 30-39, 1997.