

Bi-directional reflectance factor of 14 soil classes from Brazil

M. M. VALERIANO

Agronomy Institute of Campinas (IAC) Cx.P. 28, 13101-902, Campinas, SP, Brazil

J. C. N. EPIPHANIO, A. R. FORMAGGIO

National Institute for Space Research (INPE), Cx. P.515 12201-970
São José dos Campos, SP, Brazil

and J. B. OLIVEIRA

University of Campinas (UNICAMP), Cx.P. 6011, 13081, Campinas, SP, Brazil

(Received 15 August 1993; in final form 18 May 1994)

Abstract. The spectral reflectance of soils is required for effective use of remote sensing products. The absence of studies concerned with spectral reflectance of the soils from the tropical region in the 400 to 2500 nm spectral range is the main motivation of this research. The objective of this study was to present spectral reflectance data from different tropical soil types. This spectral characterization was done through measurements of the bi-directional reflectance factor of 111 selected soil samples, grouped in 14 tropical soil classes, taken from 53 sites (São Paulo State, Brazil). The measurements were made with a spectroradiometer operating in the 400 to 2500 nm region of the electromagnetic spectrum. Each soil sample is associated to a set of physical and chemical analyses data, with part of these published in descriptive reports of soil surveys.

1. Introduction

The reflectance patterns of the different soil types are of fundamental importance for many applications respective of remote sensing techniques. Indeed, the spectral reflectance of vegetated areas is affected by the underlying soil reflectance. This enforced spectral vegetative indices to be developed taking into account this effect. The data requirements for the optimal remote sensing applications are improving, together with the advance of sensor technology. Thus, the reflectance characterization of terrestrial objects must be performed through high spectral resolution data in order to match the requirements of studies concerning both existing and future sensors.

Tropical soils have rarely been studied from the point of view of remote sensing, and the number of spectral curves including the 400-2500 nm region are negligible compared to the temperate soils. Such studies about Brazilian soils are limited to a few authors who worked with broad band visible near-infrared radiometry (e.g., Formaggio 1983, Epiphanio *et al.* 1987, Formaggio and Epiphanio 1988, Stoner *et al.* 1991). Taken from Brazilian soils, there are only around ten spectral curves comprising the 400 to 2500 nm range published in literature (Stoner and Baumgardner 1980, Madeira Netto 1991). The spectral reflectance survey, characterization

and experimentation of the main Brazilian soils therefore, can bring necessary inputs to present day and future activities in remote sensing.

The objectives of this paper are therefore to present the results of laboratory measurements of bi-directional reflectance factor of important tropical soil types from Sao Paulo State in the visible, and near- and middle-infrared spectral regions of the spectrum (400–2400 nm). The average spectra of the studied soil classes are presented and classified into groups of curve types. Each curve type is defined according to four key attributes: albedo; presence and localization of spectral absorption features; overall curve shape; and curve details in the visible, near-infrared range.

2. Material and methods

2.1. Soils

The available soil surveys for Sao Paulo, as for Brazil, were made under low and medium detailing levels, like the Recognition Soil Survey of Sao Paulo State, made by the Comissao de Solos (1960), under a 1:500 000 scale. At the present moment, as part of the semi-detailed pedological mapping of São Paulo State programme, there are some areas which have semi-detailed (1:100 000) mapping.

According to such surveys, the main soil classes (taken from the Brazilian classification system which is summarized in Oliveira *et al.* 1992) of Sao Paulo State are: *Latossolo Roxo*, *Latossolo Vermelho-Escuro*, *Latossolo Vermelho-Amarelo*, *Latossolo Amarelo*, *Latossolo Variação Una*, *Podzólico Vermelho-Amarelo*, *Podzólico Vermelho-Escuro*, *Podzol*, *Terra Roxa Estruturada*, *Areias Quartzosas Profundas*, *Solos Litólicos*, *Solos Hidromórficos/Gleizados*, *Cambissolos*, *Brunizém Avermelhado*, *Petroplintossolo*, *Planossolo*, *Solos Orgânicos*, *Solos Aluviais* and *Solos Indiscriminados de Mangue*. Although we do not have a *Brazilian Taxonomy System*, the category of these classes can be said mostly to be bearing the subgroup level and, for some cases, the family level. Thus, in this study the term *class*, simply will be employed.

It is reasonable to say that, once these surveys comprise a meaningful fraction of the State territory, they practically account for all major soil types. Additionally, these soil classes represent much of the Brazilian soils.

In this study, the following soil classes were used: *Latossolo Roxo* (LR), *Latossolo Vermelho-Escuro* (LE), *Latossolo Vermelho-Amarelo* (LA), *Latossolo Variação Una* (LU), *Latossolo Húmico* (LH), *Podzólico Vermelho-Amarelo* (PV), *Podzólico Vermelho-Escuro* (PE), *Terra Roxa Estruturada Podzólica* (PR), *Podzol* (Pz), *Terra Roxa Estruturada* (TE), *Brunizém Avermelhado* (BV), *Areia Quartzosa* (AQ), *Cambissolos* (Cb) and *Solos Hidromórficos* (Hi). These 14 classes were represented by 111 soil samples, taken from different layers of 53 sites, and are of great pedological and agricultural importance. Figure 1 shows the spatial distribution of the quads where the soil samples were taken from, for the survey reports (IAC—Agronomy Institute of Campinas) of Sao Carlos (Oliveira and Prado 1984), Araras (Oliveira *et al.* 1982), Piracicaba (Oliveira and Prado 1989), Campinas (Oliveira *et al.* 1979), Guaira (Oliveira and Prado 1991) and Ribeirao Preto (Oliveira and Prado 1987). The samples used here are the same used in those surveys, and therefore physical chemical and morphological reliable descriptions are available. The selected samples for the measurements correspond to superficial and sub-superficial layers (A and B horizons) of each site.

The classification of the samples by the Soil Taxonomy System were available, for the samples reported in the survey bulletins. Although our records are not

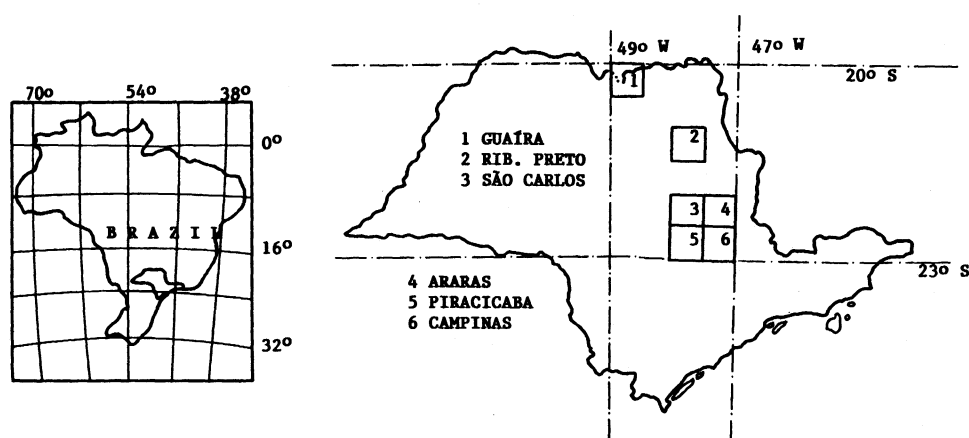


Figure 1. Spatial distribution of the quads containing the sampled sites.

complete, the following soil type association were found, according to the 1975 Soil Taxonomy Key, for each collection of Brazilian soil class studied as shown below. The names inside parentheses are the possible soil classification (at the subgroup level) of the remaining samples of the class collection, based on the soil analyses and the information in the surveys:

Class	Subgroup possible association
LR	Typic Haplorthox (Rhodic Haplustox)
LE	Typic Haplorthox (Rhodic Haplustox)
LA	Typic Umbriorthox, Quartzipsammentic Haplorthox, Typic Haplorthox and Haplic Acrorthox
LU	(several Acrustox subgroups)
LH	Pachic Umbriorthox
PV	Typic Paleudalfs and Abruptic Paleudult
PE	Rhodic Paleudalfs
PR	(Paleudalfs?)
Pz	(Humod?)
TE	(Rhodic Plaeudult)
Bv	Typic Arguidoll
AQ	Typic Quartzipsammentic
Cb	Fluentic Oxic Dystrochrept and Typic Dystrochrept
Hi	Typic Tropaquept

The samples were studied in air-dried conditions, after sieving to smaller than 2 mm particles. For general characterization of the whole sample set moisture, ten representative samples had their moisture determined by gravimetric means. The samples were oven-dried under 110° C for 48 h, according to Kiehl (1979), for air-dried soil sample (hygroscopic) moisture.

For the spectral measurements, the soil samples were carefully placed inside plastic sample holders (12.8 × 12.8 × 1.0 cm) with inside surface painted in black matt

paint in order to avoid undesirable reflection. The sample holders were designed to allow adequate placement of the field of view of the radiometer (5×2 cm) safely inside the sample surface area, for the used configuration (figure 2).

2.2. The acquisition system

A dual field of view Mark IV Infra-Red Intelligent Spectroradiometer (IRIS) was used in a laboratory configuration to make the reflectance factor measurements. This spectroradiometer is a semi-portable microcomputer-controlled compact system. It takes simultaneous radiance measurements from two fields of view (one for a target and the other for a reference), calculating and logging automatically the ratio between them for further processing. This avoids measurement errors due to radiation source fluctuation. The nominal spectral resolution ranges from 2 nm (300–1000 nm) to 4 nm (1000–3000 nm).

IRIS sensing head was positioned vertically around 61 cm above the sample, defining a rectangular sampled area of approximately 5×2 cm. The illumination source, a 600 watt halogen tungsten iodine filament lamp, which supplies a non-collimated beam to the sample/reference viewing plane, was mounted 90 cm above this plane, and tilted 15° off from vertical (figure 2).

A grey spectralon plate (reflectance around 50 per cent) was used as reference panel. The spectral absolute reflectance of this panel, determined by the manufacturer (Labsphere, s.d.), was used to determine the absolute reflectance factors of the soil samples.

2.3. Acquisition methods

An intercalibration factor between the two singular systems (i.e., the system respective to the targets and that respective to the reference) was determined in order to: (a) uniform possible sensitivity differences between the two systems; and (b) control environmental effects (the laboratory scenery) that could be causing differences in the illumination conditions for the target and for the reference.

If the illumination and detection systems work identically for both target and reference systems, a ratio between measurements taken from the same target should

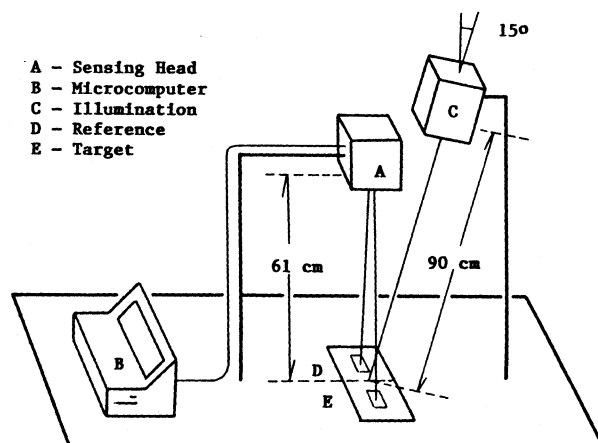


Figure 2. Geometrical configuration for the spectral measurements.

equalize 1 for all the spectrum. Since this perfect similarity between systems is unusual (though it is ideally so), the intercalibration factor is designed to neutralize the differences. Usually, it is a multiplying factor consisting of a ratio of the reference system reading by the target system reading (or a dividing factor for the inverse fraction), with the two readings taken from the same reference panel.

For reason (b), this intercalibration factor was calculated for every measurement session (around six soil samples per session), as the objects in the laboratory (as the operator clothes, for example) could be moved between one session and another. For reason (a), the intercalibration factor was determined four times and averaged, since little noise-originated fluctuations can bring considerable false variations after rationing. The repetitions are also necessary to reduce possible effects of irregularities on the uniform target used, as the mean will have a much smaller effect. Between each of the four pairs of readings taken for intercalibration, the reference panel used (a white spectralon plate, in this case) was rotated 90° to allow sampling in different places of the panel. Because of the simultaneity of the readings made by the target/reference systems, the white spectralon plate (reflectance near 100 per cent and size 25.4 × 25.4 cm) was used. The reason is that the grey plate (size 12.7 × 12.7 cm) was too little to comprise the two fields of view simultaneously, for the current configuration.

After the intercalibration readings, each soil sample had its spectrum read four times. Each one of these readings corresponds to a different sampled surface area, as the sample holder was also rotated 90° between the readings and the field of view was not centred in the sample holder. The repetition and averaging procedures reduce random detector noise, as well as improve the observed area of the samples.

2.4. Data processing

To summarize the following readings were addressed for each session:

- (a) Four repetitions were taken, with two fields of view on the white spectralon panel, in order to obtain the intercalibration factor (ICF) for each soil sample of the session.
- (b) Four repetitions for the target-reference set were taken over the soil sample and the grey reference panel in order to obtain a relative reflectance factor (RRF).

As the relative reflectance factor is referenced to a 50 per cent reflectance panel, an additional reading (the one made by the manufacturer) should be employed. The actual reflectance of the panel is the absolute calibration factor (ACF) necessary to correct the actual RRF ratio to a ratio obtained with a perfect (100 per cent reflectance) reference. The following equation describes the calculation of the bi-directional reflectance factor (BDRF) of a soil sample *i*.

$$BDRF_i = [(\text{mean } RRF_i) / (\text{mean } ICF)] \times (ACF) \quad (1)$$

The data processing brought 111 BDRF files which each consisted of 875 reflectance and wavelength value pairs, corresponding to the radiometer channels.

3. Results and discussion

The soil classes which had three or more samples per layer had their average and 95 per cent confidence interval curves determined. These classes were: LR, LE, LA, LU, PE, PV, TE and Cb. The remaining classes (LH, PR, Pz, BV, AQ and Hi) have

their average reflectance curve shown only when their description cannot be based on curve types already. From the spectral reflectance point of view, some soil classes have quite similar behaviour. Therefore, the discussion will be made by groups of spectrally homogeneous soil classes. The soil class heading each block of comments is followed, inside parentheses, by the other spectrally similar soil classes. At the last part of each block, remarkable distinctions between the classes of the group may be presented.

The key description of the spectral curve groups was made according to four attributes, which are described through the following systematics:

- (a) Albedo, which can be understood as the overall reflectance (height, in the graphics) of the curve, neglecting minor details, such as absorption features and the visible range.
- (b) Absorption features, which can be understood as the depressions along the curves; they are characterized by the position and width (narrow, when having a sharp minimum, or broad, when the bottom is round). These absorption features can further be strong, when well pronounced, or light, otherwise.
- (c) Shape, which can be defined by the overall appearance of the curves, as it would be seen through coarse spectral resolution. This attribute also includes the main slope of the reflectance curve, regardless of the visible range details and any absorption feature.
- (d) Details of the visible near-infrared region, particularly the shape, slope, and the presence of inflexion points. The importance of this part of the spectrum is that it is related to the soil colour. The presence (and intensity) of inflexion points indicates dominance of certain hue in the composition of the colour, which is known to bring important information on soil mineralogy. Most of the previous studies of soil reflectance had dealt with this portion of the spectrum.

Once these criteria were established, four groups of soil class could be identified. Table 1 summarises the key differences between these groups, referred to as groups (a), (b), (c) and (d) in this paper. Further comments in each group are made separately.

Table 1. Spectral characteristics of the soil groups.

Group	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
Albedo	low around 15%	variable between 20% and 70%	medium between 30% and 45%	medium between 30% and 40%
Shape	horizontally flat	bow shaped	bow shaped	flat and sloped
Absorption features	broad at 900 and 450 nm light narrow at 1400, 1900 and 2200 nm	broad at 900, 450 and 650 nm strong narrow at 1400, 1900 and 2200 nm	broad absent narrow at 1400, 1900 and 2200 nm	light broad at 900 nm light narrow at 1400, 1900 and 2200 nm
Visible/ near-infrared	inflexion at 650 nm red colour	no inflexion but sloped yellow colour	flat grey colour	inflexion at 650 nm red colour

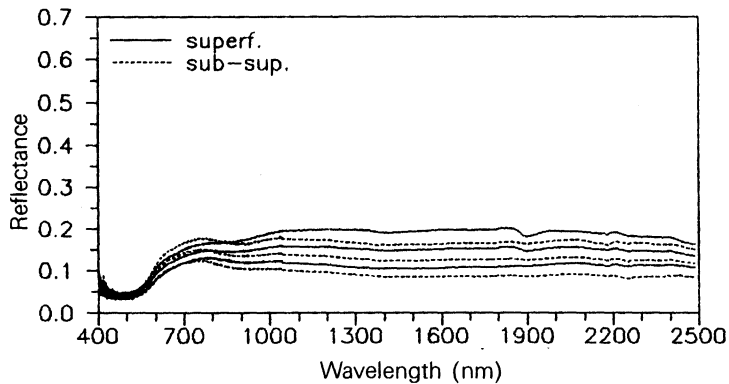


Figure 3. *Latossolo Roxo* reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

The groups of spectrally similar soil classes are:

(a) *Latossolo Roxo* (*Terra Roxa Estruturada*, *Latossolo Una*, *Terra Roxa Estruturada Podzólica* and *Brunizem Avermelhado*): The soils of these classes resulted in an homogeneous set of spectral curves (see figure 3). The constancy in shape and in magnitude of the reflectance spectra within the soils of this group is remarkable, as indicated by the narrow confidence interval of this graphic. It was observed that slight narrow absorption features, mainly at around 1900 nm, occur in curves with the higher albedos (20 per cent for this group). This particular behaviour is quite well represented by the curves in figure 3, which correspond to LR average and 95 per cent confidence interval reflectance spectra for superficial and sub-superficial samples.

Superficial samples taken from naturally vegetated areas have their spectra even more flattened through the 450–1100 nm wavelength range. Besides, such soil samples are those of highest albedos and have curve maximum situated somewhere between 1100 and 1300 nm, while it usually occurs in this group normally at around 750 nm. This indicates the organic matter influence. For these particular cases, the 900 nm broad absorption band does not match an absolute depression, but just a slight decrease in the slope. It must be remarked that LR and TE showed extremely similar spectral reflectance curves.

LU curves (figure 4) were also sloped slightly in the infrared range. This class is distinguished in group (a) by the 600–800 nm region, where the reflectance curve is straightened, while for the whole group it is curvilinear. Such detail is presumably the effect of the goethitic iron content of the LU (Sherman and Waite 1985) by contrast with the hematite influence of the samples of the other classes in this group. LU is actually regarded to be an essentially goethitic soil class (Oliveira *et al.* 1992). Samples taken from areas containing plinthic and petroplinthic minerals had visible reflectance sloped increasingly from the blue/green region (from around 500 nm), resulting in a yellowish hue. By contrast (as shown in figure 4), the lower limit curve of the confidence interval exhibits the flat region until it reaches 550 nm (in the same way as for *Latossolo Roxo*), thus resulting in red hue.

All the soil classes of this group, as stated by Oliveira *et al.* 1992), comprise basic rock derived soils (LR and TE) or soils with high Fe_2O_3 content (LR, LU and TE).

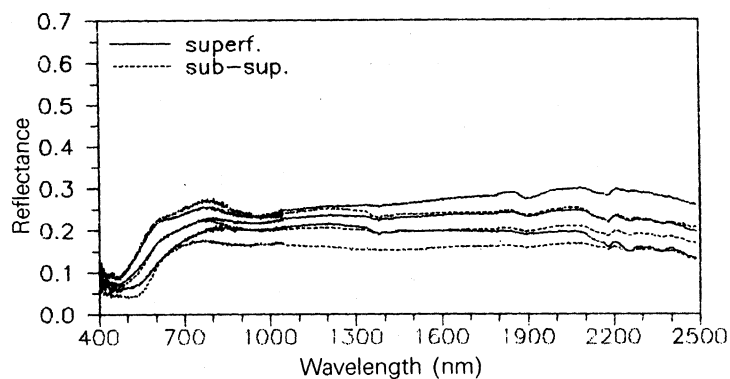


Figure 4. *Latossolo Una* (LU) reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

The soil chemical data (tables 2 and 3) showed the samples of the remaining classes of this group to have high Fe_2O_3 contents, around 18 per cent (PR) and 22 per cent (BV). Additionally, the sampled BV soil unity was derived from basic rocks. Summarizing, it is reasonable to say that the spectral curves similar to those of this group may correspond to basic rock originated soils (or soils having considerable contributions of basic rocks) and with a naturally high Fe_2O_3 content. The soil samples from other group soil classes (occasionally LE, LA and PV which have this reflectance pattern partially confirm such characteristics.

(b) *Podzólíco Vermelho-Escuro* (*Podzólíco Vermelho-Amarelo*, *Latossolo Vermelho-Escuro*, *Latossolo Vermelho-Amarelo*, and *Cambissolo*): This group presents the highest variability of spectra, with remarkable differences between classes and between layers (see figures 5 to 8). These classes also comprise soil samples with typical-*a* spectral reflectance, in addition to the typical-*b* samples. Large visible near-infrared reflectance differences between the sub-superficial and the superficial samples due to higher organic matter content are present (see figure 7). The absorption features occurring for the sub-superficial samples (at around 900 and 650 nm) are totally or partially absent for the superficial ones.

Recently defined as a class out of PV soils (Oliveira *et al.* 1992), PE soils form a unique homogeneous set of curves in this group (figure 5). The variation within PE curves occurs only for the albedo, remaining the shape constant for any horizon of the sample sets (which consists in a superficial and a sub-superficial sample from a site). Therefore, figure 5 is a good representation of the curves obtained for this class, as a consequence of the physical-chemical uniformity within these soils. The confidence interval of this class is the smallest in the group.

LE and LA classes are included in this group for the minority of their samples, which would pertain mostly to group (a). Of the soil classes included in LA class, Typic Haplorthox and Haplic Acrorthox accounted for the *a*-type curves. For the PV class, there was only one sampled site not classified in the typical-*b* reflectance pattern, corresponding to an Abruptic Paleudult. There was no exception for PE, for this is the soil class name heading the *b* group block.

All samples of the classes of this group, (even the spectrally exceptional), often showed goethitic spectral feature in reflectance, characterized by the flattening due

Table 2. Average and variation coefficient (%) of physical-chemical data for superficial samples of the soil class subsets

	LR (n=18) ^a	LE (n=6)	LA (n=5)	LU (n=4)	LH (n=2)	PV (n=6)	PE (n=3)	PR (n=1)	Pz (n=1)	TE (n=5)	BV (n=1)	AQ (n=2)	Cb (n=3)	Hi (n=2)
Sand ^b	8(36) ^d	23(46)	31(49)	25(41)	16(-)	19(59)	8(12)	6(-)	22(-)	6(64)	6(-)	47(-)	10(127)	40(-)
Fine sand ^b	13(38)	53(63)	33(50)	25(38)	35(-)	56(32)	39(33)	52(-)	66(-)	16(51)	14(-)	44(-)	40(36)	20(-)
Silt ^b	22(28)	8(105)	2(107)	10(44)	10(-)	13(91)	18(48)	14(-)	2(-)	33(32)	45(-)	1(-)	17(34)	12(-)
Clay ^b	56(9)	37(38)	32(63)	41(36)	39(-)	13(49)	34(6)	28(-)	10(-)	45(8)	35(-)	8(-)	31(42)	27(-)
pH (H ₂ O)	5.9(11)	5.3(7)	5.0(10)	5.5(6)	4.7(-)	5.2(4)	6.0(7)	5.6(-)	4.9(-)	6.4(5)	5.9(-)	6.0(-)	5.0(11)	4.3(-)
Ca ^{++c}	6.8(82)	1.6(63)	0.6(90)	1.4(70)	0.6(-)	1.4(77)	6.0(66)	5.0(-)	5.6(-)	11.2(39)	13.9(-)	1.5(-)	1.6(70)	0.2(-)
Mg ^{++c}	2.2(70)	0.7(99)	0.2(101)	1.0(86)	0.2(-)	0.5(48)	1.3(36)	1.3(-)	1.1(-)	2.9(67)	3.5(-)	0.6(-)	0.7(83)	0.1(-)
K ^{++c}	0.40(75)	0.12(95)	0.07(87)	0.20(62)	0.17(-)	0.24(90)	0.59(40)	0.20(-)	0.09(-)	0.81(53)	0.80(-)	0.01(-)	0.17(47)	0.09(-)
Al ^{+++c}	0.16(123)	0.48(70)	1.10(64)	0.40(50)	2.30(-)	0.45(115)	0.36(87)	0.00(-)	0.80(-)	0.06(82)	0.10(-)	0.15(-)	1.60(66)	3.8(-)
H ^{++c}	4.3(43)	3.7(34)	4.1(74)	4.5(33)	9.0(-)	2.5(36)	2.9(41)	4.2(-)	2.5(-)	2.9(26)	1.6(-)	1.5(-)	2.1(63)	14.1(-)
S ^c	9.4(73)	2.4(74)	0.9(87)	2.7(73)	1.0(-)	2.2(57)	7.9(56)	6.5(-)	6.8(-)	14.9(40)	18.2(-)	2.1(-)	2.4(71)	0.5(-)
T ^c	13.9(47)	6.6(42)	6.2(64)	7.6(37)	12.3(-)	5.1(42)	11.0(32)	10.8(-)	10.1(-)	18.3(32)	19.9(-)	3.7(-)	6.1(34)	17.9(-)
V ^b	61(43)	34(32)	13.8(83)	32(52)	9(-)	41(30)	68(27)	61(-)	68(-)	79(9)	91(-)	52(-)	37(76)	4(-)
C ^b	6.3(132)	1.4(43)	1.7(101)	2.3(42)	2.9(-)	1.0(62)	2.1(27)	1.3(-)	1.2(-)	2.6(42)	2.8(-)	0.4(-)	1.5(6)	5.6(-)
N ^b	10.3(-) ^e	50.1(27)	0.1(80)	30.2(44)	0.2(-)	40.1(39)	0.2(22)	0.1(-)	0.1(-)	10.2(-)	0.2(-)	10.1(-)	20.1(-)	0.3(-)
Fe ₂ O ₃ ^c	121.3(-)	7.5(39)	4.3(55)	11.0(52)	4.5(-)	2.0(68)	6.0(30)	17.4(-)	0.5(-)	221.7(-)	23.6(-)	1.1(-)	23.3(-)	0.9(-)
Al ₂ O ₃ ^c	110.5(-)	11.8(43)	12.1(63)	12.6(37)	12.3(-)	4.3(33)	10.7(22)	7.5(-)	2.8(-)	211.4(-)	7.7(-)	1.6(-)	214.3(-)	12.7(-)
SiO ₂ ^c	111.5(-)	10.46(64)	13.3(88)	12.7(57)	13.3(-)	4.7(56)	13.6(13)	7.9(-)	4.2(-)	214.0(-)	18.5(-)	0.7(-)	217.0(-)	12.2(-)
TiO ₂ ^c	17.4(-)	2.5(45)	1.2(58)	4.7(47)	1.1(-)	0.6(84)	1.4(25)	11.3(-)	0.2(-)	27.1(-)	6.6(-)	0.2(-)	20.6(-)	1(-)

^a n is the number of samples; ^b %, ^c e. mg/100 g of sieved air-dry soil; ^d the percentual variation coefficient follows the average, inside parentheses; ^e the superscript numbers are referred to the number of sample data employed on the average determination, when different from n; * two groups may be distinguished within LR superficial samples: sites under natural vegetation (mean C% = 8.4; CV = 114% and n = 12) and cultivated sites (mean C% = 1.7; CV = 16% and n = 6).

Table 3. Average and variation coefficient (%) of physical-chemical data for sub-superficial samples of the soil class subsets

	LR (n=12) ^a	LE (n=6)	LA (n=5)	LU (n=4)	LH (n=2)	PV (n=6)	PE (n=3)	PR (n=1)	Pz (n=1)	TE (n=4)	BV (n=1)	AQ (n=2)	Cb (n=3)	Hi (n=2)
Sand ^b	6(43) ^d	23(46)	31(57)	18(55)	11(-)	11(60)	5(43)	4(-)	66(-)	7(25)	3(-)	48(-)	14(136)	30(-)
Fine sand ^b	11(50)	53(44)	30(63)	21(60)	37(-)	34(51)	20(33)	33(-)	1(-)	15(46)	7(-)	42(-)	47(25)	23(-)
Silt ^b	18(17)	6(80)	3(57)	11(50)	6(-)	10(97)	11(48)	8(-)	12(-)	13(61)	34(-)	1(-)	13(52)	10(-)
Clay ^b	64(7)	45(37)	37(62)	49(31)	45(-)	37(38)	64(2)	55(-)	7(-)	68(6)	56(-)	8(-)	26(13)	37(-)
pH (H ₂ O)	5-6(10)	5-1(8)	4-9(9)	5-4(7)	4-6(-)	4-8(7)	6-1(18)	6-3(-)	5-4(-)	6-1(9)	6-3(-)	5-4(-)	4-9(10)	4-5(-)
Ca ^{+++c}	1-6(74)	0-4(100)	0-1(61)	0-1(111)	0-1(-)	1-4(62)	6-4(87)	5-9(-)	8-6(-)	4-9(33)	17-8(-)	0-6(-)	0-8(115)	0-22(-)
Mg ^{+++c}	0-5(102)	0-2(138)	0-0(99)	0-1(111)	0-0(-)	0-5(33)	0-9(66)	1-1(-)	0-4(-)	1-8(46)	5-8(-)	0-2(-)	0-7(82)	0-0(-)
K ^{++c}	0-05(68)	0-01(51)	0-03(63)	0-02(73)	0-01(-)	0-11(41)	0-17(54)	0-09(-)	0-08(-)	0-26(67)	0-45(-)	0-05(-)	0-06(49)	0-02(-)
Al ^{++++c}	0-08(145)	0-65(80)	0-52(54)	0-02(173)	2-20(-)	1-77(70)	0-27(94)	0-1(-)	0-1(-)	0-1(66)	0-0(-)	0-2(-)	1-2(54)	3-0(-)
H ^{++c}	2-4(53)	2-4(52)	2-1(47)	1-6(54)	6-3(-)	1-9(42)	1-7(50)	1-9(-)	2-9(-)	2-1(24)	2-1(-)	1-4(-)	1-5(22)	5-7(-)
S ^c	2-1(74)	0-6(105)	0-2(65)	0-2(106)	0-2(-)	2-0(51)	7-5(83)	7-1(-)	9-1(-)	6-9(35)	24-1(-)	0-9(-)	1-5(96)	0-3(-)
T ^c	4-5(47)	3-5(41)	2-9(36)	1-8(45)	8-6(-)	5-7(30)	9-4(55)	9-2(-)	12-1(-)	9-2(23)	26-2(-)	2-5(-)	4-2(14)	9-5(-)
V ^b	43(56)	20(105)	7(55)	13(71)	1(-)	34(41)	67(35)	78(-)	75(-)	73(17)	92(-)	33(-)	33(87)	2(-)
C ^b	0-9(44)	0-6(46)	0-5(33)	0-5(48)	1-4(-)	0-5(25)	0-7(17)	0-7(-)	1-6(-)	0-5(58)	0-8(-)	0-3(-)	0-4(27)	1-1(-)
N ^b	10-1(-) ^e	40-1(25)	40-1(26)	20-1(-)	0-1(-)	20-1(-)	0-1(24)	0-1(-)	0-2(-)	10-1(-)	0-1(-)	10-1(-)	10-1(-)	0-1(-)
Fe ₂ O ₃ ^c	123-5(-)	58-6(40)	4-7(56)	315-4(29)	5-0(-)	4-1(65)	8-9(26)	19-2(-)	0-7(-)	123-4(-)	22-3(-)	1-0(-)	12-1(-)	0-9(-)
Al ₂ O ₃ ^c	111-4(-)	514-1(39)	11-5(71)	318-1(24)	12-6(-)	10-1(32)	19-0(10)	11-5(-)	2-8(-)	112-5(-)	12-9(-)	2-3(-)	19-1(-)	11-8(-)
SiO ₂ ^c	111-3(-)	511-0(64)	10-0(95)	313-1(20)	14-6(-)	513-6(45)	23-8(10)	19-3(-)	4-9(-)	115-3(-)	22-1(-)	2-0(-)	19-5(-)	14-0(-)
TiO ₂	18-5(-)	52-5(51)	1-2(57)	38-3(36)	1-4(-)	1-0(79)	1-8(46)	7-4(-)	0-3(-)	14-7(-)	6-9(-)	0-3(-)	10-3(-)	1-1(-)

^a n is the number of samples; ^b %; ^c e. mg/100 g of sieved air-dry soil; ^d the percentual variation coefficient follows the average, inside parentheses; ^e superscript numbers are referred to the number of sample data employed on the average determination, when different from n.

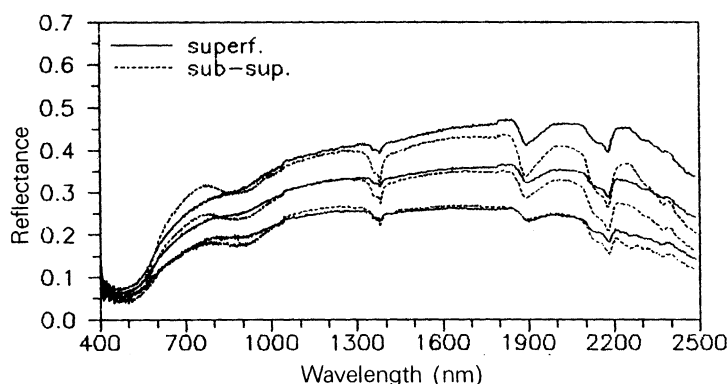


Figure 5. *Podzólico Vermelho-Escuro* reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

to the broad absorption band on the slope centred at around 650 nm (Sherman and Waite 1985) and the yellow hue. LE and PE samples present as a rule red colour.

Layer spectral differences could be seen within this group mainly in the visible-near-infrared curve shape (according to group description block) and in the narrow band absorption features depths. For the visible-near-infrared range, only the Cb samples were spectrally similar for both layers, as this class comprises soils with poor layer differentiation (Oliveira *et al.* 1992). Generally, the spectral absorption features are better seen in sub-superficial samples for any portion of the spectrum. Superficial samples also showed bow-shaped curves, sloped until 1800 nm, approximately, while sub-superficial ones presented a flat-shaped in the 1100–1800 nm range. For LA samples, the layers were generally quite different in albedo, and in shape. Such samples showed smaller albedo and less variability among superficial samples than for sub-superficial ones.

For each layer separately, it seems that there is a direct relation between the depth of the absorption features and the albedo of the soil samples pertaining to LE and LA classes. This could not be confirmed for PV, PE and Cb soil classes.

Oliveira *et al.* (1992) describe such classes as having an upper limit for the Fe_2O_3 content, which excludes obligatorily soils with high iron contents. The maximum Fe_2O_3 content of the typical-*b* soil samples were around 10 per cent, starting to become similar to a typical-*a* curve to the extent that the iron content was above this threshold.

Continuing the description, Oliveira *et al.* (1992) report that the soil classes of this group occasionally comprise clay soils (LE and LA), but more commonly comprise soils of sandy to medium texture. Within *b* group samples, soils derived from sandstone or from sandy sediments prevail. Taking the LE samples, that showed the two described reflectance patterns, those derived from (or simply containing) basic rocks are typically *a* type. When the LE parent material is a basic rock, this group can be distinguished from the LR only by laboratory Fe_2O_3 analysis. Hence, the two classes are separated by a discrete analytical threshold. Formaggio and Epiphanyo (1988), studying reflectance of soils taken from two different sites, and observing LE samples with spectra similar to LR, (typically *a*-curve), in one site and similar to LA ones, in the other. This is evidence of the effect

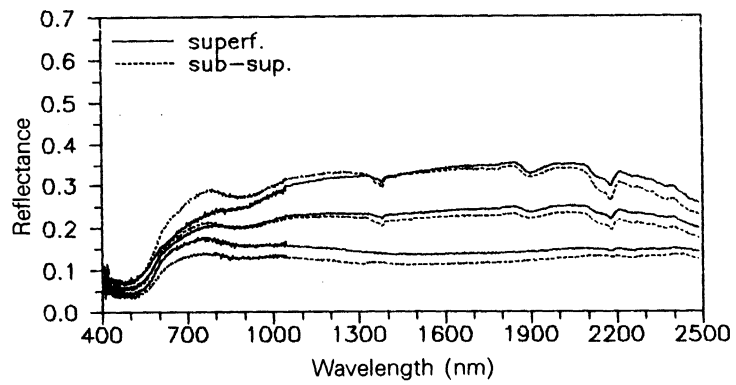


Figure 6. *Latossolo Vermelho-Escuro* reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

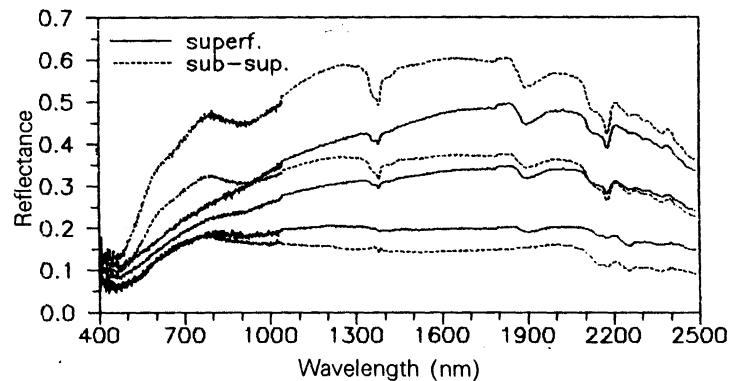


Figure 7. *Latossolo Vermelho-Amarelo* reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

of the parent material. Figure 6 curves illustrate well the possible reflectance patterns observed for the LE samples.

As a rule with LA spectra, (see figure 7), the curve appearance on the visible-near-infrared range indicates the presence of goethite, (as previously described). Actually, the basic concept of this class limits the colour hue to less red than 1.5 YR (Munsell notation) to yellow. Fernandez and Schulze (1987) state that inferences about soil iron oxides mineralogy can be better made if the colours are determined through reflectance measurements. The *a*-type LA spectra were very similar to the LU spectra. Oliveira *et al.* (1992) state that LA soils can be similar to LU, from which the former are distinguished by their lower Fe_2O_3 content. Indeed, LU samples were typically yellowish. As a result of the great difference within LA curve types, the lower limits of the confidence intervals do not represent the low-albedo curves, which are typically *a*-type. The Standard Deviations, relatively smaller on the absorption regions, caused the lower limit curves of the confidence intervals to be deformed, with artificial peaks. Thus, only the mean and the upper limit curves of figure 7 illustrate real cases.

The PV class, like LE and LA, largely comprises varying soils. The PV spectra express this variability through a great diversity in appearance spectral features, and in the albedo, despite fitting well predominantly in the *b*-type. By figure 8, one can observe that the mean and the confidence interval limits had their shape not affected by the exceptions, as they all appeared *b*-type. But, with respect to the albedo, the exceptional *a*-type shifted the means and the confidence intervals downwards, since among *b*-type curves of this class, the smallest albedos rounded 45 per cent.

(c) *Hidromórfico (Podzol and Latossolo Húmico)*: The soil classes pertaining to this group are agriculturally meaningless, and comprise a small portion of the land surface. Thus, there were few available samples for such classes, for what they could not here be characterized as were the *a* and *b* groups. However, the reflectance pattern within the soil samples of this group was unique (figure 9), regardless of the observed layer.

For classes of this group, the observations were taken from just a few samples. The unique PZ curve pair showed relatively high albedo (around 45 per cent compared to the other classes, that showed reflectances always below 35 per cent). The absorption feature at around 1900 nm was very strong for PZ and relatively weak for LH. Figure 9 presents the mean spectral reflectances for HI superficial and sub-superficial samples.

From the classes' definitions, (Oliveira *et al.*, 1992), the colour weakness can be regarded as a rule, once they are grey soils usually. Thus, the stated observations about the visible spectrum can be expected to be matched by any soil sample of the classes of this group.

(d) *Areia Quartzosa*: the two sample sets of this class allowed the observation of a fourth behaviour (figure 10), different from the three previously described patterns. There were little differences between the horizons in this class (or group, for this case). Among the two AQ sample sets, a slight difference could be perceived between the Ap_1 and the C_1 layers of one of them, due to the effect of organic matter (lowering and flattening the reflectance curve in the visible near-infrared range). The other sample set did not allow such comparison.

The spectral curves shown by these particular samples, regardless of the layer, were fairly similar to the *b*-curves exhibiting extremely high albedos (up to 65 per

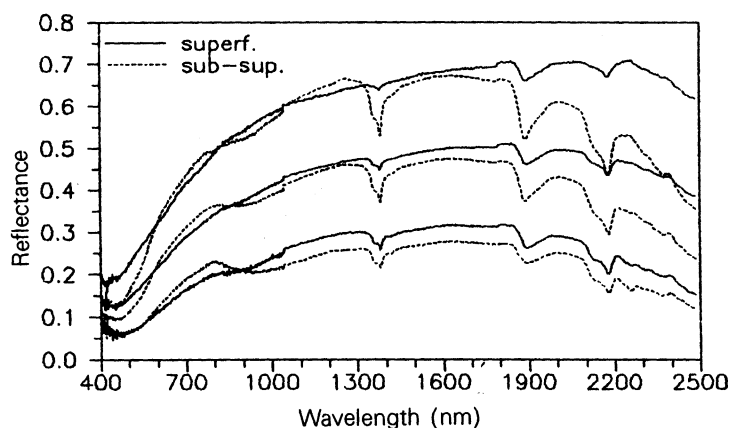


Figure 8. *Podzólíco Vermelho-Amarelo* reflectance spectra average and respective 95 per cent confidence intervals for superficial and sub-superficial samples.

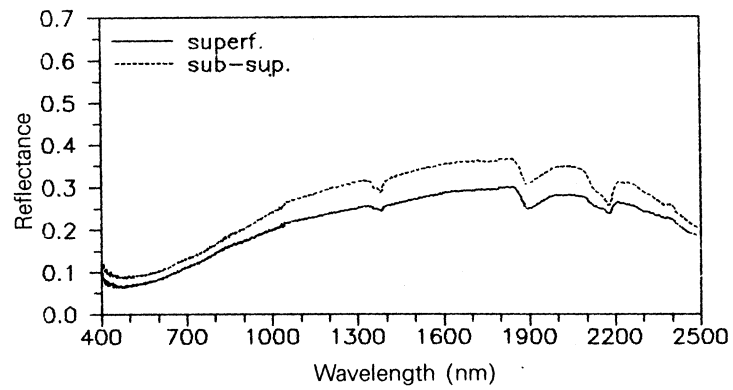


Figure 9. *Hidromórfico* reflectance spectra average for superficial and sub-superficial samples.

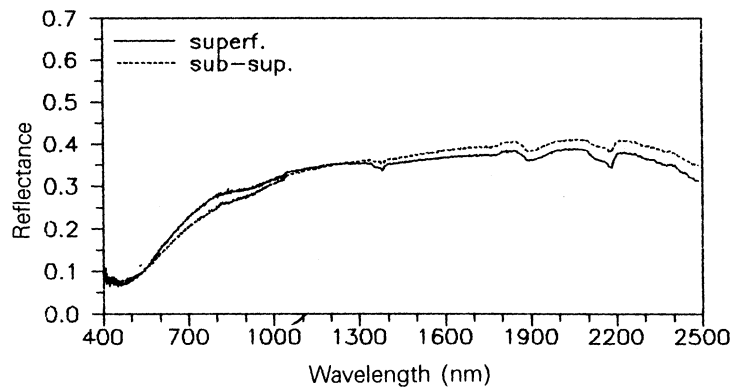


Figure 10. *Areia Quartzosa* reflectance spectra average for superficial and sub-superficial samples.

cent). Though AQ samples showed albedo not more than 40 per cent, the *b*-group curves with medium albedo (not more than 50 per cent) differed from the *d*-group ones in the shape.

Taking the class concept, the curve appearance in the visible range is not expected to remain fixed, once this class comprises yellow, white, red, or even grey soils (Oliveira *et al.* 1992). On the other hand, its sandy nature, plus the absence of easily weathered primary minerals, will lead the other three attributes, (high albedo, the shape and absorption features), to be a rule for the class. It should be stated, however, that the AQ samples herein observed do not comprise AQ from the sea shore, which are usually brighter in colour. Possible spectral differences between these and the samples employed here are expected to exist in colour (visible range) and in albedo.

4. Concluding remarks

After studying the reflectance spectra pertaining to fourteen soil classes, four general reflectance patterns could be distinguished. An intense overlapping of the original classes was observed, therefore the soil types cannot be determined at this level simply by means of observation of the reflectance spectra. Nevertheless, the groups of spectrally similar soils were consistent from the point of view of their physical-chemical characteristics.

The reflectance patterns were closely related to the parent material of the soil sample, regardless of the soil class. For the classes defined by the parent material, the reflectance spectra can perfectly exclude an observed soil from this class, if it does not match the expected pattern.

Organic matter and iron content were the main soil properties affecting the reflectance spectra, (beside parent material), conditioning spectral features especially along the visible-near-infrared range. Further studies are necessary to understand the interactions between these properties as affecting the observed spectra.

Acknowledgments

The research was partially supported by Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP); M. M. Valeriano was initially supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

References

- COMISSÃO DE SOLOS, 1960 (Serviço Nacional de Pesquisas Agronômicas). Levantamento de Reconhecimento de Solos do Estado de São Paulo. Ministério da Agricultura/Centro Nacional de Ensino e Pesquisas Agronômicas. Rio de Janeiro (Boletim no 12).
- EPIPHANIO, J. C. N., LAMPARELLI, R. A. C., BERTOLDO, M. A., and FORMAGGIO, A. R., 1987, Bandas termal e refletidas do TM/Landsat-5 no estudo do comportamento espectral de tres latossolos. *XXI Congresso Brasileiro de Ciencia do Solo, Campinas, 1987*. 33p. (INPE-4341/PRE-1181).
- FERNANDEZ, R. N., and SCHULZE, D. G., 1987, Calculation of soil color from reflectance spectra. *Soil Science Society of America Journal*, **51**, 1277-1282.
- FORMAGGIO, A. R., 1983, Comportamento espectral de quatro solos do Estado de São Paulo nos niveis orbital, de campo e de laboratorio. M.Sc. Dissertation, São José dos Campos, INPE, 1983.
- FORMAGGIO, A. R., and EPIPHANIO, J. C. N., 1988, Reflectance pattern from Brazilian oxisols and their physical and chemical characteristics. *Proceedings of the 16th International Congress of International Society for Photogrammetry and Remote Sensing, Kyoto, Japan, ISPRS, 1-10 July 1988*, volume 27 (B10), pp. 497-505.
- KIEHL, E. J., editor, 1979. *Manual de Edafologia: relações solo-planta* (São Paulo: Agronômica Ceres).
- MADEIRA NETTO, J. S. M., 1991, Etude quantitative des relations constituants mineralogiques—réflectance diffuse des latosols brésiliens/application a l'utilisation pedologique des données satellitaires TM (region de Brasília). Thèse de Doctorat, Université Pierre et Marie Curie, Paris.
- OLIVEIRA, J. B., and PRADO, H., 1984, Levantamento pedológico semidetalhado do Estado de São Paulo: quadrícula de São Carlos. II. Memorial Descritivo (Campinas: Instituto Agronômico (SAAESP)). (Boletim técnico no 98).
- OLIVEIRA, J. B., and PRADO, H., 1987, Levantamento pedológico semidetalhado do Estado de São Paulo: quadrícula de Ribeirão Preto. II. Memorial Descritivo. (Campinas: Instituto Agronômico (SAAESP)). (Boletim técnico no 7).
- OLIVEIRA, J. B., and PRADO, H., 1989, *Carta pedológica semidetalhada do Estado de São Paulo: quadrícula de Piracicaba. Escala de 1:100 000* (Campinas: Instituto Agronômico).
- OLIVEIRA, J. B., and PRADO, H., 1991, *Carta pedológica semidetalhada do Estado de São Paulo: quadrícula de Guairá. Escala de 1:100 000* (Campinas: Instituto Agronômico).

- OLIVEIRA, J. B., MENCK, J. R. F., and ROTTA, C. L., 1979, *Levantamento pedológico semidetalhado do Estado de São Paulo: quadricula de Campinas* (Rio de Janeiro: FIBGE).
- OLIVEIRA, J. B., MENCK, J. R. F., BARBIERI, J. L., ROTTA, C. L., and TREMOCOLDI, W., 1982, *Levantamento pedológico semidetalhado do Estado de São Paulo: quadricula de Araras*. (Campinas: Instituto Agrônomo (SAAESP)) (Boletim técnico no 71).
- OLIVEIRA, J. B., JACOMINE, P. K. T., and CAMARGO, M. N., 1992, *Classes gerais de solos do Brasil: guia auxiliar para seu reconhecimento* (Jaboticabal: FUNEP).
- SHERMAN, D. M., and WAITE, T. D., 1985, Electronic spectra of Fe⁺³ oxides and oxide hydroxides in the near IR to near UV. *American Mineralogist*, **70**, 1262-1269.
- STONER, E. R., and BAUMGARDNER, M. F., 1980, Physicochemical, site, and bidirectional reflectance factor characteristics of uniformly moist soils. West Lafayette, IN, Purdue University, 1980. (LARS Technical Report 111679.)
- STONER, E. R., DERKSEN, I., and MACEDO, J., 1991, Discriminação espectral de latossolos do planalto central Brasileiro. *Pesquisa Agropecuária Brasileira*, **26**, 1509-1606.