

Quantification and discrimination of Soils Developed from Basalt as Evaluated by Terrestrial, Airborne and Orbital Sensors

MARCOS RAFAEL NANNI ¹
JOSÉ ALEXANDRE M. DEMATTÊ ²

¹Universidade Estadual de Maringá - UEM
Departamento de Agronomia, Maringá - PR, Brasil, mnranni@uem.br

²Escola Superior de Agricultura Luiz de Queiroz - ESALQ
Departamento de Solos e Nutrição de Plantas, Piracicaba – SP, Brasil, jamdemat@ciagri.usp.br

Abstract: The aim of this investigation was to evaluate orbital, airborne (simulation) and terrestrial spectral reflectance data of two soils developed from basic rocks on a toposequence in the state of Paraná, Brazil, focusing especially on soil spectral characterization and attribute content estimation. Rhodic Haplortox (RH) and Typic Argiudol (TA). Soil samples were submitted to a laboratory 400-2500 nm spectroradiometer for reflectance data, which were used to simulate data from TM/Landsat and AVIRIS bands. Real data from TM was also obtained. Although the spectral curves of the soils were similar, TA curve presented higher reflectance intensity than RH curve, between 800 and 2500 nm, and both showed differences in absorption features at 850 nm (iron forms), at 1900 nm (mineralogy) and at 2265 nm (gibbsite), due to granulometry and mineralogy. Spectral data obtained in laboratory were important to validation of orbital data, which also discriminated the soils especially through band 7. We may conclude that reflectance extracted from spectroradiometer and orbital data represent soil spectral information more accurately than digital numbers. It was possible to estimate clay and silt contents and silt/clay relation through the analysis of soil samples reflected energy.

Key words: Remote sensing, soils, mineralogy, weathering, radiometry, quantification.

1 Introduction

The remote sensing systems detect the intensity of the electromagnetic radiation emitted, reflected and dispersed by an object in a certain wavelength. Arising out of the terrain conditions electromagnetic radiation intensity variations occur which are usually manifested through brightness and luminance variation of the objects.

Soil spectral evaluation may be carried out with terrestrial (Stoner & Baumgardner, 1981) and orbital (Crosta, 1992) or airborne (Baptista et al., 1998) sensors, but the fundamental principle is the same: soil reflectance is a cumulative feature derived from the heterogeneous combination of its constituents such as particle size, soil structure, surface rugosity, moisture, organic matter (OM), carbonate mineral rate, presence of quartz and iron oxides (Stoner & Baumgardner, 1981). The correlation between soil constituents and their spectral curves has been demonstrated by other authors (Madeira Netto, 1996).

When we work with orbital data, it is common to discuss about what product should be used for soil evaluation: reflectance or digital numbers (DN). Epiphany & Formaggio (1988) commented that the quantitative analysis of digital images on the target spectral behavior should be made with reflectance data for being the most appropriate characterization device and not with gray level (DN). The results showed the necessity of further comparative evaluations of these data.

As for tropical soils, Valeriano et al. (1995) reported that their characteristics have very rarely been investigated through remote sensing (RS), although reflectance patterns are extremely important for many different applications. They also commented that survey studies on reflectance, characterization and experimentation of the principal Brazilian soils may be very helpful to RS activities. Spectral evaluations through laboratory sensing are also relevant because their data are necessary for understanding orbital behavior (Huete, 1996). Demattê et al. (2000), by applying observing spectral data obtained by orbital and laboratory sensors to soil discrimination, reached optimal results, but pointed out the necessity of further experimental confirmation for its use in soil survey, mainly on the tropics, where soil maps are needed.

Therefore the aim of the present investigation is to evaluate terrestrial (IRIS), orbital (TM) and simulated airborne (AVIRIS) sensors spectral data of two soils developed from basic rocks in the State of Paraná, Brazil, focusing especially on: a) soil characterization and discrimination; b) correlation between spectral data and soil weathering; c) evaluation of reflectance and DN; c) estimation of soil element contents. The hypothesis is that although the soils are developed from the same parent material, and, are both clayey, similar color and total iron contents, other particular characteristics related to weathering will provide discriminance and allowed their quantification.

2 Material and Methods

The soil sample-collecting site is located in the northwestern of the State of Paraná, Brazil. Geologically it is located on Serra Geral formation and belongs to São Bento group, which outcrops in approximately 53% of the State. Two soils developed from basic rocks and of great agricultural importance for the region, Rhodic Haphortox (RH) and Typic Argiudol (TA) were investigated (EUA, 1990). Using GPS device to locate the site of occurrence of these soils, eight samples from a 0-20 cm layer were collected. Granulometric and chemical and mineralogical analysis were performed (Raij and Quaggio, 1983; Camargo et al., 1986).

Soil samples were dry in a stove (24 hours, 45°C) ground and sieved (2 mm mesh, these placed on 9 cm diameters petri dish) before spectral data evaluation. The spectral data were obtained through IRIS, Infrared Intelligent Spectroradiometer (400 to 2500 nm) with geometry according to Demattê et al. (2000). There sensor readings for each sample were carried out. The bidirectional spectral reflectance factor was determined. These data were used to generate other results by simulating TM/Landsat and AVIRIS bands.

The orbital images of the region were registered through SPRING software. The site was evaluated through colored compositions 5/4/3 and 3/2/1 in R/G/B. The soil sample sites were localized through field coordinates. Where was verified that the sites presented characteristics of barren soil, the central DN, proportional to radiance values that reach the detecting elements of the satellite sensor which are directly proportional to target reflectance, were extracted from the image through “pixel reading” algorithm (Epiphânio and Formaggio, 1988). The DN of each band was converted to reflectance values.

The description of the spectral curves was performed according to Stoner and Baumgardner (1981) The types of curves established was also compared with the ones obtained by Valeriano et al. (1995) and Formaggio et al. (1996). Absorption features and reflectance factor intensity were also evaluated. Statistical Analysis System program was used for data treatment and the comparisons between the sensing systems were performed through test with $p < 0.05$ (SAS, 1992).

3 Results and discussion

Soil characterization

It was verified that both soils presented high base values, but TA values were higher than RH values (**Tab. 1**). TA occurs in a rolling landscape and RH on plane topography. Base saturation for both soils was higher than 50% and so they were classified as eutrophic at their surface horizon. Through the clay values the soils were classified as highly clayish textural which is common for soils of that area (Nanni and Rocha, 1997), but RH clay content was 770 g kg⁻¹ and TA clay content was 638.8 g kg⁻¹. There was no difference as for organic matter and total iron contents, in agreement with the observations made by Demattê and Garcia (1999) who

evaluated the same kinds of soils, localized in the western area of the State of Paraná. TA Ki value (2.6) was higher than RH Ki value (1.7), characterizing a lower formation stage due to lower weathering. TA silt content was higher (266.2 gkg⁻¹) than RH silt content (172.5 gkg⁻¹), confirming TA lowers weathering degree. Sand content was also higher in TA than in RH, but without any significant difference at 5%. TA displayed a 2:1 mineral constitution while RH displayed a 1:1 mineral constitution, such as kaolinite with gibbsite contribution.

Table 1 – Mean⁽¹⁾ of 0 – 20 depth soil samples and physical properties and statistical evaluation.

Soil ⁽²⁾	Color ⁽³⁾	O.M. ⁽⁴⁾	SB ⁽⁵⁾	CEC ⁽⁶⁾	V ⁽⁵⁾	M ⁽⁷⁾	sand	silt	Clay	Fe ₂ O ₃ Total ⁽⁸⁾	Ki ⁽⁹⁾
RH	2.5YR3/4	gkg ⁻¹ 32,25a ⁽¹⁰⁾	mmol c dcm ³ 103a	153,75a	67,38a	0,25a	5,75a	17,25a	77a	30,6a	1,7a
TA	5 YR 3/4	31a	177,89b	240,39b	74b	0b	9,5a	26,62a	63,88b	29,6a	2,6b

⁽¹⁾ Mean of 8 repetitions; ⁽²⁾ Rhodic Haplortox, RH; Typic Argiudol, TA; ⁽³⁾ Main humid color by Munsel Color Charts, Baltimore, Maryland, U.S.A., 1954; ⁽⁴⁾ Organic Matter ⁽⁵⁾ Sum of Bases; ⁽⁶⁾ Capacity of Exchange Cations; ⁽⁷⁾ Bases Saturation; ⁽⁸⁾ Aluminum Saturation; ⁽⁹⁾ Extracted by sulphuric acid digestion; ⁽¹⁰⁾ Molecular ratio SiO₂/Al₂O₃; ⁽¹⁰⁾ Student *t* test. Same letter on the column indicates no statistical difference at 5 % significance level.

Soil spectral behavior on the earth surface level

In descriptive terms and according by criteria established by Stoner and Baumgardner (1981) both RH and TA curves (**Fig. 1a**) are classified as type 5, in concave form of 850 nm and lower reflectance along the whole electromagnetic spectrum. The curve of these soils is similar to those determined by Epiphanyo et al. (1992) and Demattê and Garcia (1999). On the other hand, Demattê et al. (2000) verified that there may occur variations in the curves of the same soil. In the case, they verified that TA displayed not only a type 5 curve but also a mixture of types 3 and 4, thus demonstrating, the necessity to determine standards for different regions. Even comparing these curves with Formaggio et al. (1996) these was no difference.

When curves are evaluated (**Fig. 1a**), it is verified that they are very similar in accordance with the reports by Valeriano et al. (1995) and Formaggio et al. (1996). The position of the curve between 350 and 700 nm showed identical form and intensity for both soils. The absorption band in the visible portion in the spectrum, strongly influenced by iron and OM contents. Much a behavior is expectable since the contents of these two constituents are similar (**Tab. 1**).

For being developed through basic rock weathering the soils display high contents of hematite, which provide them colors more reddish as 2.5 YR. As a consequence, according to Formaggio et al. (1996), the curves display a reduced albedo with 4 % to 17 % reflectance value in the visible band and 17 % to 21 % in the infrared band within 700 to 2500 nm (**Fig. 1a**). On the other band, despite the similarity of the iron contents there is a slight variation in the concavity centered in 850 nm. Particularly the iron oxides and their absorption bands were studied by Scherman and Waite (1985). Taking into consideration that the OM contents are identical (**Tab. 1**), their effect should be the same. Demattê and Garcia (1999) verified that hematite and goethite crystalline iron forms, are the principals responsible for the concavity formation in 850 nm band. On the other band, amorphous iron form alters the intensity of the curve but not the concavity. In fact RH as being more weathered than TA display higher contents of crystalline iron and a more emphatic concavity.

Beyond 800 nm, the TA spectral curve (**Fig. 1a**) begins to display higher albedo than RH curve, according to Formaggio et al. (1996). Beyond 800 nm the reflectance mean for RH was 17,6 % while for RB it was 19,6 %. In the 300 – 800 nm band no statistically significant difference was observed (**Tab. 2**). For the band beyond 800 nm and for the curve (300 - 2500 nm) the reflectance values are different. This is probably due to higher silt contents in TA, where occurred weathered minerals (**Tab. 1**).

It's remarkable that both soils display the same textural class but different granulometric values (**Tab. 1**). Besides with higher silt content, TA display higher sand contents and lower clay. Al-Ablas et al. (1972) remark that clayey soils display lower reflectance values when compared with sandy soils. That is certainly one more reason why the granulometric components influenced the higher reflectance of TA when compared to RH (**Fig. 1a**). The same soil type, observed with different clay texture were discriminated as presented by Demattê et al. (2000). Hunt et al. (1971) also remarked that heavy minerals as magnetite have very low reflectance influence, which is an important component of these soils (Nanni, 1995).

Table 2. Comparison between the reflectance obtained by IRIS and TM sensor.

Parameter	Wavelength bands (nm)					
	450-520	520-599	630-689	761-901	1549-1750	2082-2352
Typic Argiudol, TA						
Reflectance obtained by IRIS						
Average	3,87 ^{a(1)}	6,72a	14,01a	17,57a	20,29a	20,59a
Standard pattern	0,38	0,34	0,44	0,95	2,30	2,15
CV (%)	9,97	5,10	3,19	5,42	11,32	10,43
Reflectance obtained by TM sensor						
Average	12,98b	11,69b	14,73a	19,91a	18,46a	13,76b
Standard pattern	0,54	0,71	1,37	4,62	3,52	2,46
CV (%)	4,22	6,08	9,35	23,22	19,05	17,92
Rhodic Haplortox						
Reflectance obtained by IRIS						
Average	3,68a	6,54a	14,60a	17,47a	18,77a	19,47a
Standard pattern	0,24	0,41	0,84	1,02	1,68	1,74
CV (%)	6,49	6,26	5,76	5,88	8,98	8,92
Reflectance obtained by TM sensor						
Average	12,98b	11,94b	17,15b	22,23b	18,51a	17,11a
Standard pattern	0,47	0,87	0,86	5,15	5,27	1,91
CV (%)	3,65	7,33	5,01	23,16	28,50	11,21

⁽¹⁾ Same letter on the column indicates no statistical difference at 5 % significance level.

The absorption band centered in 1400 nm is caused by the molecular vibrations of water and OH⁻ groups and the 1900 nm band is caused by the presence of water (Mathews et al., 1973), (**Fig. 1a**). Though the curves are fairly similar, differences of absorption intensities occur in 1900 nm band, due to 2:1 minerals, as verified by the X-ray analysis

The feature centered in 2200 nm band also reveals the presence of clay fraction minerals, due to OH⁻ and Al - OH⁻ groups vibrations. When this feature displays a characteristic shape (**Fig. 1a**), it indicates the presence of kaolinite (Baptista et al. 1998). These features are observed in both soils (**Fig. 1a**), in accordance with mineralogical data. On the other hand, it should be empathized that the presence of 2:1 minerals also generate a feature in this band but without the characteristic degree of kaolinite. Despite the fact that the minerals act simultaneously in both soils their presence may be verified through the evaluation of absorption asymmetry.

The band centered at 2265 nm was characterized through the presence aluminum oxides such as gibbsite (Madeira Netto, 1996). This absorption band, though slender, was verified in RH spectral curves but not in TA curves (**Fig. 1a**), ratified by the diffractogram.

Relation between the reflectance and the weathering stage of the soils

Among basaltic soils TA is less weathered than RH because it displays high saturation of cations, CEC, high Ki, silt, 2:1 mineral dominance and presence of weathering minerals. These characteristics determine the weathering stage of the soils. For displaying very different values RH is characterized as highly weathered. In the sequence from highly weathered RH to lowly, weathered TA there occurred an increase in reflectance intensity between 800 and 2500 nm and alterations in absorption bands between 850 and 1900 nm (**Fig. 1**) because of the respective presence of iron oxides and mineralogy. Besides the 2265 nm showed the presence of gibbsite.

Soil spectral behavior on orbital level

It should be observed that DN bands variation might not correspond to their reflectance variation. The interpretation of soil spectral behavior based only on these values (Ephiphanio and Formaggio, 1988), may mislead to different interpretations. It was verified that both TA and RH laboratory curves are very similar to the respective reflectance curves extracted from TM/Landsat image but very different from DN (**Fig. 2b**). It demonstrates the importance of the laboratory experiments, without influence of atmospheric factors, providing results closer to reality (Huete, 1996), and help full in orbital level evaluation. On the other hand, RH and TA discrimination was feasible through band 3 and 7.

The statistical comparison between: DN and TM bands; reflectance factor and correspondent spectral bands; and the reflectance values obtained through DN transformation (image reflectance); - revealed that CV were relatively low in all bands analyzed for both RH and TA soil (**Tab. 2**). The same is true for DN and reflectance values for both orbital and terrestrial levels. It is basically due to the surface homogenization resulting from the intensive use of both kinds of soils, which gives similar spectral characteristics to their surfaces. Despite their apparent similarity, the component data of the spectral curves was submitted to a statistical analysis. In all spectral intervals significant differences were found.

There was no difference between laboratory and orbital, reflectance in bands 3, 4 and 5 for TA. As for RH reflectances in band 5 and 7 were similar. The behavior of orbital reflectance curves was similar to those obtained through IRIS. On the other band, same intensity variations occurred specially in band 1 and 2.

Soil line (SL) evaluation

SL obtained at laboratory data expresses reality more accurately because their determined directly from a soil sample (**Fig 2**). This confirms the accuracy of the soil reflectance data through samples as they displayed highly consistent r^2 . RH r^2 of the present experiment are higher than the 0.55 found by Galvão and Vitorello (1998). Their inclination values, 0.60, are different from the 1.6 of the present experiment but they are similar to those found by Huete et al. (1984) and Huete (1989). The differences are probably due to the different areas of occurrence (sampling sites): state of São Paulo for the mentioned authors and state of Paraná for this experiment. Moreover the RH analyzed by those authors displayed a lower content of clay (540 g kg^{-1}) and Fe_2O_3 (213 g kg^{-1}) and a higher content of sand (290 g kg^{-1}), very different from the contents of the present experiment, which influenced SL data. It confirms that DN (**Fig 1 b**) do not express soil spectral reality. On the other hand, orbital reflectance data also showed to be more aspersive than the terrestrial data thus indicating that image data are influenced by surface rugosity and humidity factors, which were not homogenized as the laboratory samples. Moreover the presence of crop residues also affected SL data, even so the curves showed to be similar as before mentioned. The evolution of data distribution along for SL showed no difference. It is well known that SL reflectance is particularly influenced by OM, iron and humidity. Humidity was homogenized for all samples and organic matter and iron contents were the same, this explaining their similarity.

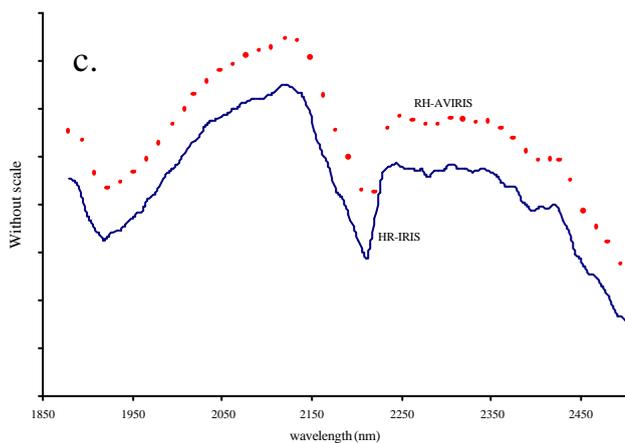
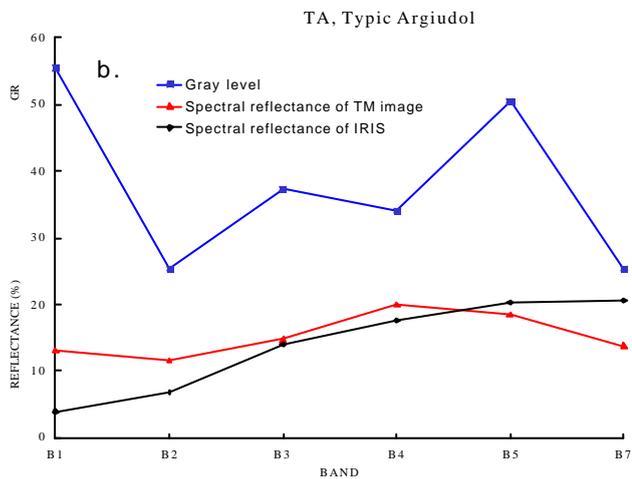
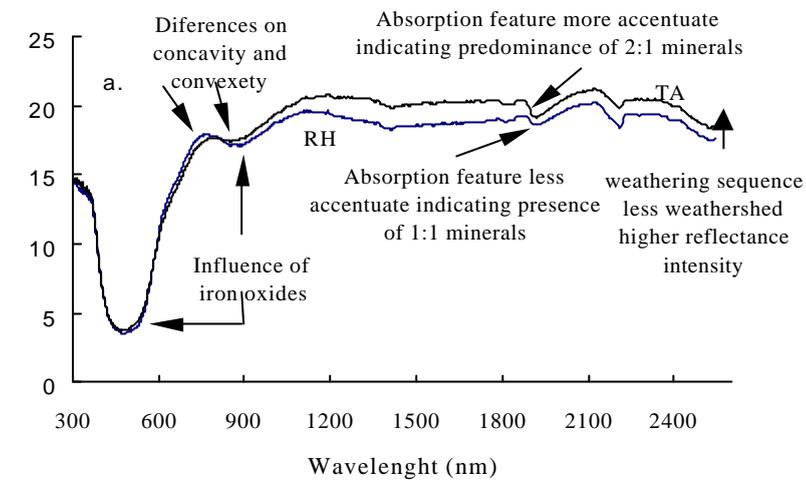


Fig. 1. a. Spectral curves of the Rhodic Haplortox (RH) and Typic Argiudol (TA); b. Average gray levels and spectral reflectance extracted from TM-LANDSAT 5 images and reflectance from IRIS sensor (TA); c. Comparison between spectral curve obtained by IRIS sensor and AVIRIS sensor for RH soil.

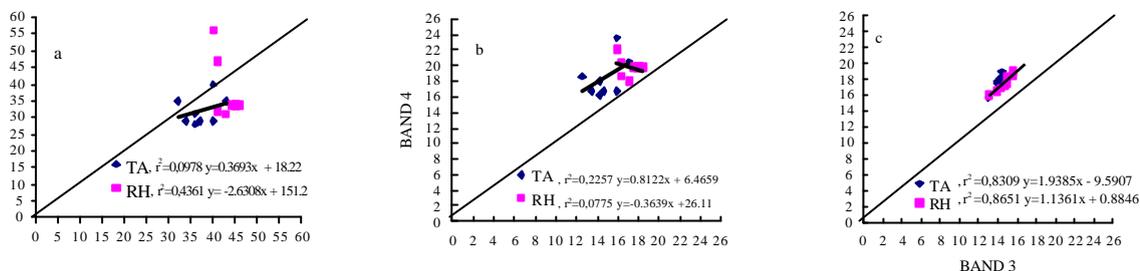


Fig. 2. Spectral data disposed on the soil line (Band 3, X; Band 4, Y): a. Digital numbers; b. Spectral reflectance from TM image; c. Spectral reflectance from IRIS sensor.

Simulation of AVIRIS Spectral data

The spectral curve observed in laboratory is the most detailed, allowing to observe the mineralogy, as described preliminary (**Fig. 1c**). The simulation of AVIRIS sensor presented a more smoothly spectral curve, but the shape was the same and allowed to observe differences. The mineralogy as kaolinite and gibbsite could be observed, as was with Baptista et al. (1998). These authors detected when these minerals are in basaltic soils it should be more difficult mainly on gibbsite bands happens because the iron oxides and magnetite, forces the spectral absorption on not to appear very well. Although, AVIRIS data detected the most important bands and was quite better than TM.

Soil attributes estimate through spectral data

The determination of soil attributes quantification methods through remote sensing was carried out by different authors. Demattê and Garcia (1999) verified that the spectral curve evaluated between 400 and 2500 nm may provide crucial information on the contents of some soil elements. These authors determined a whole series of multivariate equations looking forward on the estimative of some soil attributes. These equations were formed by statistically grouping. Following the methodology of these authors, the present work tested their equations with the present spectral data. Using the general equation for basaltic soils, the analyses of TA, OM, clay, silt, silt/clay rate, calcium, magnesium, base amount and Ki showed no statistical difference between laboratory chemical and granulometric analyses (**Tab. 3**). The same occurred with clay content and silt/clay rate differently from Fe_2O_3 when the individual equation was used. As for RH the general equation provided a satisfactory estimation for 5 attributes against 3 discrepant values.

The quantification of some soil parameters only through reflected energy showed to be feasible for a few elements in the present experiment, but it should be noted that further research and tests are necessary to determine reliable methodologies and that the best results were obtained in estimating structural attributes such as sand, silt and clay. The possibility of quantification through these methodologies opens an avenue for such different applications as provide a assist instrument to the conventional techniques of soil survey and mapping. These techniques may lower the costs and save time in data evaluations, but it should be emphasized that these are assist techniques. Until now, laboratory analysis cannot be substituted, mostly because the patterns for spectral data calibration has to be made in laboratory. Besides, laboratory analysis have a very large background on this type of evaluation.

Table 3. Comparison between soil content of some attributes obtained in conventional laboratory and estimation obtained by spectral reflectance (laboratory condition).

	O.M. ⁽¹⁾	Clay	Silt	silt/clay	Ca ⁺⁺	Mg ⁺⁺	SB ⁽²⁾	CEC	V ⁽³⁾	Ki ⁽⁴⁾	Fe ₂ O ₃ Total ⁽⁵⁾	
	-----g kg ⁻¹ -----				-----mmolc dcm ³ -----				%			
	Typic Argiudol, TA (geral equation)⁽⁹⁾											
VD ⁽⁶⁾	31,0a ⁽⁸⁾	638,7a	266,2a	0,41a	136,2a	35,6a	177,8a	240,4 ^a	-	2,56a	-	
VE ⁽⁷⁾	24,9a	677,9a	265,3a	0,39a	111,5a	35,9a	142,5a	144,7b	-	2,26a	-	
	Rhodic Haplortox, RH (geral equation)⁽⁹⁾											
VD	32,2a	770,0a	172,5 a	0,22a	70,1a	29,8a	103,0a	153,7a	-	1,74a	-	
VE	20,6b	786,3a	165,1 a	0,21a	51,6a	20,3b	67,5b	104,0b	-	1,74a	-	
	Typic Argiudol, TA (individual equation)⁽⁹⁾											
VD	-	638,7a	-	0,41a	-	-	-	-	-	-	30,60a	
VE	-	786,8a	-	0,64a	-	-	-	-	-	-	21,25b	
	Rhodic Haplortox, RH (individual equation)⁽⁹⁾											
VD	32,2a	-	-	-	-	-	-	153,7a	67,3a	-	-	
VE	42,2b	-	-	-	-	-	-	133,4b	88,4b	-	-	

⁽¹⁾ Organic matter; ⁽²⁾ Sum of bases; ⁽³⁾ Base saturation = SB*100/CEC; ⁽⁴⁾ Ratio molecular SiO₂/Al₂O₃; ⁽⁵⁾ Extracted by sulphuric acid digestion; ⁽⁶⁾ Average of the conventional laboratory soil analysis; ⁽⁷⁾ Estimation of soil contents by spectral sensor at laboratory; ⁽⁸⁾ Same letter on the column indicates no statistical difference at 5 % significance; ⁽⁹⁾ The equations used on this test were determined by Demattê & Garcia (1999) and are presented in table 1; "-" Not determined due to inexistent data.

4 Conclusions

The spectral behavior of the soils studied was influenced by iron forms, granulometry and mineralogy.

Soil characterization and discrimination was made feasible through spectral data extracted from orbital images. Laboratory spectral data and soil line analysis were helpful to validate the orbital data. Reflectance represents the soils more accurately than digital numbers. Band 7 showed to be the best to discriminate the soils in this experiment.

Basaltic soil weathering degree is related to reflectance intensity between 800 and 2500 nm. The lower weathered Typic Argiudol displayed higher reflectance intensity. Furthermore absorption features at 850 nm (iron oxides), 1900 nm (matter present in minerals) and 2265 nm (gibbsite) revealed the weathering degree.

Especially clay and silt contents and silt/clay rate were possible to be estimated through their reflected energy. Although, further studies are still necessary on this subject.

Acknowledgments

We would like to thank Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP) for providing IRIS spectroradiometer (Process n° 95/6259-6) which made this experiment possible.

References

AL-ABBAS, A. H.; SWAIN, P. H.; BAUMGARDNER, M. F. Relating organic matter and clay content to multispectral radiance of soils. *Soil Science*, v.114, n.6, p.477-485, 1972.

- BAPTISTA, G. M. M.; MARTINS, E. S.; MADEIRA NETTO, J. S.; CARVALHO Jr.; O. A.; MENESES, P. R. Use of AVIRIS data for mineralogical mapping in tropical soils, In: Seventh Annual JPL Airborne Earth Science Workshop. Jet Propulsion Laboratory (JPL) NASA. Pasadena, CA, 12-14 January. JPL Publication, 1998, v.1, pp. 33-42.
- 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: IAC, 1986. p. (IAC. Boletim Técnico, 106). 94p.
- CRÓSTA, A. P. Processamento digital de imagens de sensoriamento remoto. Campinas, IG/UNICAMP, 1992, 170p.
- DEMATTÊ, J. A. M. HUETE, A. R. FERREIRA Jr., L. G.; ALVES, M. C.; NANNI, M. R.; CERRI, C. E. Evaluation of tropical soils through ground and orbital sensors. In: INTERNATIONAL CONFERENCE ON GEOSPATIAL INFORMATION IN AGRICULTURE AND FORESTRY, 2., Florida, 10-12 January, 2000. Proceedings, ERIM, p.34-41, v.2, 2000.
- 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, v.63, v2, p.327-342, 1999.
- EMBRAPA. SNLCS. Levantamento de reconhecimento dos solos do Estado do Paraná. Curitiba-P.R. EMBRAPA/SNLCS/SUDESUL/IAPAR, 1984 791p. (EMBRAPA/SNLCS. Boletim Técnico, 57).
- EPIPHANIO, J.C.N. & FORMAGGIO, A.R. Abordagens de uso de número digital e de reflectância em sensoriamento remoto com dados de satélites. In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 5., Natal, 1988. Anais. São José do Campos, INPE, 1988. p.400-405.
- EPIPHANIO, J.C.N.; FORMAGGIO, A.R.; VALERIANO, M.; OLIVEIRA, J. B. Comportamento espectral de solos do Estado de São Paulo. São José dos Campos: INPE, 1992.131p.
- UNITED STATE OF AMERICA. Department of Agriculture. Soil Survey Division. Soil Conservation Service. Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil survey. Washington, 1990. (USDA, Soil Conservation Service, 18).
- FORMAGGIO, A.R.; EPIPHANIO, J.C.N.; VALERIANO, M.M.; OLIVEIRA, J.B. Comportamento espectral (450-2.450 nm) de solos tropicais de São Paulo. Revista Brasileira de Ciência do Solo, Campinas, v.20, p.467-474, 1996.
- HUETE, A. R. Extension of soil spectra to the satellite: atmosphere, geometric, and sensor considerations. Photo Interpretation, v.34, p.101-114, 1996.
- HUNT, G. R.; SALISBURY, J. W. Visible and infrared spectra of minerals and rocks. II Carbonate. Modern Geology, v. 2, p.23-30, 1970.
- MADEIRA NETTO, J. S. Spectral reflectance properties of soils. Photo Interpretation, Paris, v.34, p.59-70, 1996.
- MATHEWS, H. L.; CUNNINGHAM, R. L.; PETERSEN, G. W. Spectral reflectance of selected Pennsylvania soils. Soil Science Society of America Proceedings, v.37, p.421-424, 1973.
- NANNI, M. R. Delimitação de unidades fisiográficas para estudo de solos utilizando análise multivariada e técnicas de sensoriamento remoto. Curitiba, 1995. 196p. Dissertação (Mestrado) - Universidade Federal do Paraná.
- NANNI, M. R.; ROCHA, H. O. da. Integration of GIS technology, remote sensing and multivariate analysis in the delimitation of physiographic units for pedological mapping. Boletim IG-Universidade de São Paulo – Série Científica, v.28, p.129-143, 1997.
- RAIJ, B. van; QUAGGIO, J. A. Métodos de análise de solo para fins de fertilidade. Campinas: IAC, 1983. 40 p. (Boletim técnico, nº 8).
- SCHERMAN, D.M.; WAITE, T.D. Electronic spectra of Fe³⁺ oxides and oxide hydroxides in the near IR to near U.V. American Mineralogist, v.70, p.1262-1269, 1985.
- STATISTICAL ANALYSIS SYSTEM INSTITUTE. SAS, software: user's guide, version 6.0, Cary, 1992. 291p.
- STONER, E. R. & BAUMGARDNER, M. F.; Characteristic variations in reflectance of surface soils. Soil Science Society of American Journal, Madison, 45:1161-1165, 1981.
- VALERIANO, M. M.; EPIPHANIO, J. C. N.; FORMAGGIO, A. R.; OLIVEIRA, J. B. Bi-directional reflectance factor of 14 soil classes from Brazil. Int. Journal of Remote Sensing, 16(1):113-128, 1995.