Relationships between Satellite-Based Radiometric Indices Simulated Using Laboratory Reflectance Data and Typic Soil Color of an Arid Environment

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By definition, the color of an object such a soil is highly dependent on its reflectance properties in the visible spectrum. In this study, the relationships between soil color and simulated reflectance values for the Landsat TM and SPOT HRV satellites are examined from a laboratory standpoint. Visible reflectance spectra were acquired for 124 soil samples originated from an arid environment, and selected radiometric indices were worked out for both sensors. All the earlier studies relative to soil color and remote sensing have considered the widely known Munsell method as a reference for soil color quantification. Some characteristics of this system based on a visual comparison of a soil sample with painted color chips may complicate the establishment of simple relationships between reflectance data and soil color. We have applied the CIE 1931 standard method of color measurement which consists in computing color parameters directly from reflectance spectra using colorimetric equations. Color data are expressed according to two polar coordinates called Helmholtz coordinates (dominant wavelength and purity of excitation) and a luminance variable having a similar meaning to the Munsell hue, chroma, and value, respectively. The Munsell system is also employed to estimate soil color. Linear regression analysis between soil color and radiometric indices show a systematic improvement of correlations (r) from about 0.7 to more than 0.9 using Munsell data and Helmoltz data, respectively. Simple radiometric indices (band combinations) calculated from broad blue, green, and red bands are found to be good predictors of each of the soil color components. The increasing availability of spectroradiometers, including in the field, should stimulate the use of Helmholtz coordinates, as a beneficial alternative to the Munsell chart to obtain a precise and reproducible color quantification which may be useful for remote sensing applications. The radiometric indices utilized in this study are potentially helpful to contribute to soil resource and soil degradation cartography using visible satellite data in vast arid regions where soil data are not readily available. ©Elsevier Science Inc., 1998

INTRODUCTION

Soil color is one of the most commonly used parameters in soil study. It represents a direct and easy accessible information in the field. For this reason, color is often used as a basic criteria at different levels in soil classification [see the review of Segalen (1977)]. The presence of some soil constituents, for example, iron oxides, limestone, organic matter, and water content, is revealed by their typical effect on color (Taylor, 1982; Bigham and Ciolkosz, 1993). Further, some authors have established quantitative relationships between color and hematite or organic matter content (Torrent et al., 1983; Fernandez

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et al., 1988). In arid zones, soil color is strongly related to the underlying geological material and/or the nature of the chemical weathering and therefore provides valuable information about lithology (Pouget et al., 1994). Finally space and time variations of soil surface color may also indicate natural processes or anthropic degradations, for example, salinization, erosion, and hydric saturation, which affect the soil (Latz et al., 1984; Mougenot et al., 1993; Thompson and Bell, 1996).

By definition, the color of an opaque object is closely linked to its reflectance properties in the visible range, from 400 nm to 770 nm (Wyszecki and Stiles, 1982). The color sensation that one perceives is determined by the psychosensorial conversion, in the eye–brain system, of the visible light reflected by an object under certain illumination conditions. A recent review shows how spectroradiometric technics are applied to measure soil color for different systems of colorimetric representation (Torrent and Barrón, 1993). From space, visible remote sensing is then a potentially valuable tool to produce an exhaustive spatial information about soil surface color.

Escadafal et al. (1989) found an highly significant relationship between the colorimetric coefficients red, green, and blue calculated from the Munsell color of 84 soil samples, and their reflectance values simulated for the Landsat TM3, TM2, and TM1 bands. This result, due to the low occurrence of metamerism in the case of soils, opens new prospects for using color data available in soil database with the aim of improving satellite images interpretations. Various authors reported some radiometric indices, sensitive to Munsell parameters and easier to associate with soil properties or pedologic processes compared to relative amounts of red, green, and blue color. The Munsell colorimetric system, widely used by soil scientists, is identified by three notions: hue, value, and chroma (Munsell Color Co., 1975). Salmon-Drexler (1977) pointed out that the Landsat MSS4/MSS5 ratio varies according to the hue while the sum of these bands is related to the value. A combination of MSS4 and MSS5 reflectance data was also reported to be significantly correlated with the chroma (Da Costa, 1979). During cartographic works in South Tunisia, Escafadal and Pouget (1987) noticed the usefulness of the Landsat TM1/TM3 ratio for discriminating soils characterized by a different chroma. Recently, new indices have been proposed for Landsat TM such as the Saturation Index (SI) or the Hue Index (HI) (Escadafal et al., 1994). Madeira et al. (1997) defined a TM Redness Index (RI), equivalent to the Munsell Redness Index proposed by Torrent et al. (1983) and adapted to the cartography of Brazilian latosols. This complementary index gives a synthetic expression of soil color.

Two points arise from these works. First, although the results are fairly promising, they are also quite scattered and partial. Consideration of all the colorimetric parameters useful in soil science, that is, value, hue, chroma, and redness index, is rarely done in a single study. Since application scales are heterogeneous (i.e., laboratory, field, and satellite data), comparisons may be delicate and are sometimes contradictory. Some relationships are not well quantified, and new indices, based on the direct application of colorimetric laws to pedologic materials, need to be tested. Therefore, it is important to undertake laboratory studies to determine what can be really expected from satellite data in terms of color remote sensing. Mattikalli (1997) proposed a first method involving an optimal rotational transformation of red, green, and near-infrared Landsat MSS simulated data to maximize the relationships with Munsell color data. Second, all the works involving soil color in remote sensing applications refers to the Munsell color chart as main system of color measurement. However, as suggested by literature (Shields et al., 1966; Fernandez and Schulze, 1987), a more accurate method should be used when high precision color quantification is needed. This is strongly significant in the field where the conditions of an accurate Munsell notation are far from those discussed by Melville and Atkinson (1985).

The main objectives of this study are: i) to examine the relationships between soil color and selected Landsat TM or SPOT HRV radiometric indices simulated from visible reflectance spectra acquired under laboratory conditions and ii) to introduce and apply the Helmholtz coordinates calculated from the CIE 1931 (CIE, 1931) system of color measurement as an alternative to the Munsell color chart method. A special emphasis will be put on soils originating from arid zones which are particularly favorable to soil color remote sensing. While the unlikely cloud presence facilitates optical remote sensing, arid landscapes present a high proportion of bare or sparsely vegetated soils during an extended period of the year.

MATERIALS AND METHODS

In the laboratory, visible reflectance spectra were acquired for 124 soil samples originated from an arid environment, and selected radiometric indices were stimulated for Landsat TM and SPOT HRV. For each sample, color measurements were performed using two methods: a visual comparison with the Munsell soil color chart and the calculation of the Helmholtz parameters from the reflectance spectra. Both sets of color data were then compared to the radiometric indices through linear regression analyses.

Source and Treatment of Soil Samples

The 124 soil samples used in this study correspond to surface and few deeper horizons collected in dry lands of the IVth and Vth region of Chile (30–33°S, 71.5–

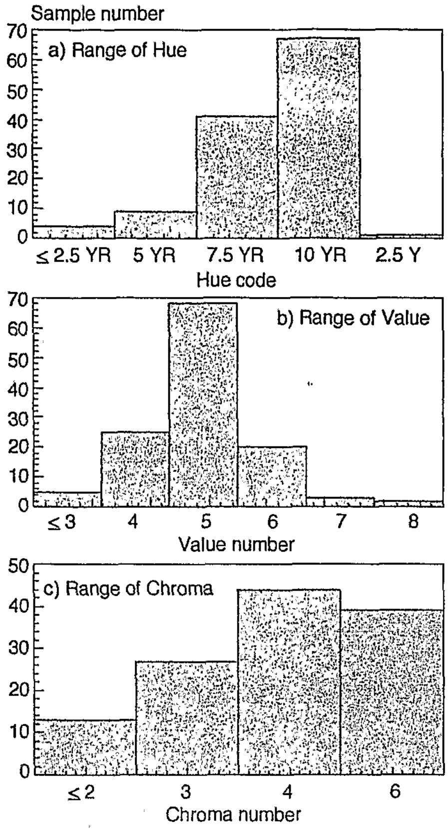


Figure 1. Munsell color of the soil samples investigated.

72°W, average annual rainfall: 100–350 mm/yr). Samples come from two sources. A first group of 86 surface samples (0–10 cm) was taken from representative field sites (1–2 ha each) selected and investigated as part of a regional evaluation of natural resources using remote sensing technologies (Pouget et al., 1996). A second group of 38 samples was collected to examine remote sensing capability to discriminate some levels of erosion degradation exhibiting soil color variations (Mathieu et al., 1997). The latter includes four profiles (0–140 cm) and 18 surface points (0–10 cm) sampled along two toposequences of eroded alfisols. According to the Soil Taxonomy classification system, sampled soils belong to Torripsamments, Torriorthents, Paleargids, Paleorthids, Camborthids, Haploxeralfs, and Haplustalfs Great Groups (Luzio and Alcayaga, 1990). Prior to reflectance and color measurements, samples were air-dried and sieved at 2 mm. The color range of the samples investigated is only representative of those usually found in arid environments and to some extent under temperate climates (Fig. 1). As is common in arid environments, soil color of Chilean dry lands is highly dependent on the lithologic substratum which includes gray-green melagranitic rocks, leucogranitic rocks (granodiorites, monzogranites), and dark gray andesites sometimes purplish to reddish with hematitic alteration (hydrothermal processes) or green with propilitic alteration. One of the main characteristics of arid regions is the water deficiency which is often associated with a low pedogenetic evolution. This has obvious implications on soil color found in Chilean dry lands. Some color categories are not well represented such as strong red colors (i.e., 2.5 YR, 10R) featuring high hematite contents or dark colors due to the low organic matter content inherited from a scarced vegetation cover and widespread erosion processes (Díaz Vial and Wright, 1965).

Reflectance Measurements

Reflectance spectra have been acquired from 340 nm to 1100 nm using a portable spectroradiometer in laboratory conditions (FieldSpec-VNIR of Analitical Device Instrument Inc.). A specific measurement device was designed to control the geometry, the quality, and the intensity of the incident light (Fig. 2). Specular reflectance or glossiness effects are minimized using an angle of 45° between the light beam and the normal axis to the sample surface (Melville and Atkinson, 1985). Interference light multiple reflections were reduced using a dark room and covering the device with black clothes. Black plastic plates of about 30 cm^2 and 1.5 cm of depth were filled with soil samples. Particular attention was given to avoid sorting of remaining microaggregates according to their size, and the sample surface was leveled. A panel coated with polytetrafluoroethylene (Halon) was used as reference for the reflectance calculation. Five spectra per sample were acquired, averaged, and resampled at 5 nm to improve the signal/noise ratio.

Color Determination

A presentation of both systems of color quantification as well as details on the specific measurement procedure will be given further on [see Wyszecki and Stiles (1982) and Mac Adams (1985) for more theorical precision].

Munsell System

Designed to fulfill the specific needs of coloring industries, the Munsell system arranges colors according to equal intervals of visual perception. The color space is represented approximately by a cylinder described by three variables: the hue, the value, and the chroma, which correspond to the dominant color (e.g., red, yellow, blue), the color intensity from black to white, and the amount of color diluted in a neutral gray basis respectively (Fig. 3). Working on soil color standardization, American pedologists have used this system to develop a color chart which gathers painted color samples of the most common soils of the world (Munsell Color Co., 1975). Today, widely used in the soil science community, this chart is made up of eight boards, each of them representing a hue code, that is, red (10R), yellow-red (2.5YR, 5YR, 7.5YR, 10YR), yellow (2.5Y, 5Y), and a specific board for grey colors. On the abscissa axis (left to

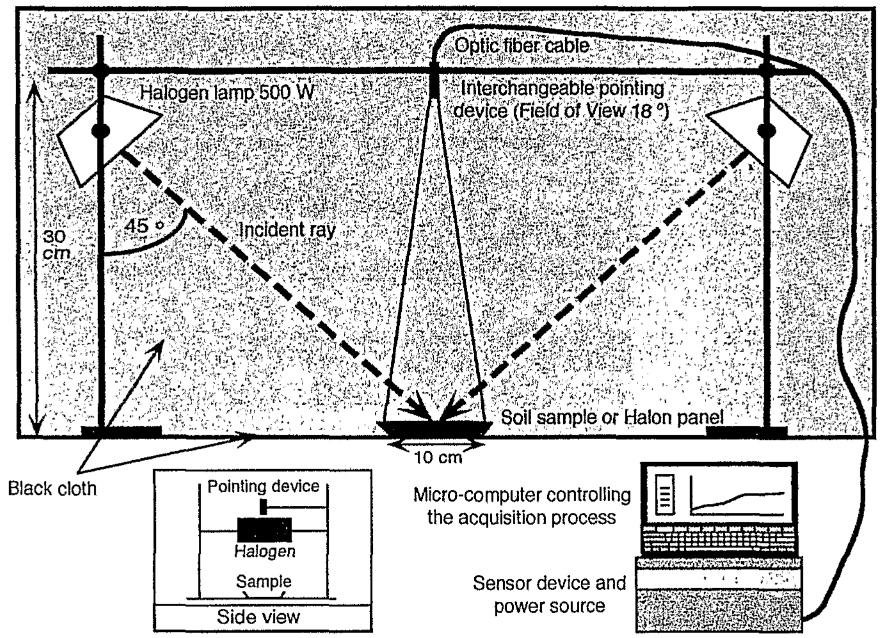
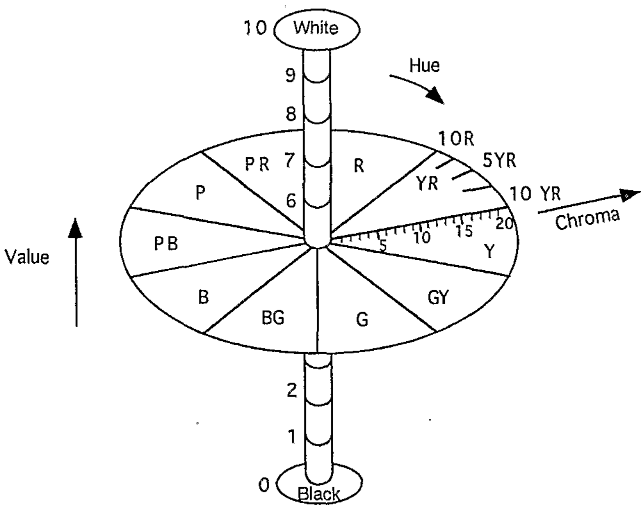


Figure 2. Experimental device used for the reflectance measurements under artificial illumination.

right) and on the ordinate axis (bottom to top) of each board, color chips of increasing chroma and value are disposed. Chroma and value are numbered from 0 up to 8. While using the chart, a soil sample is visually compared with the color chips through small observation holes beside the chips. When an optimal visual color match is found between a chip and a soil sample, the Munsell notation is recorded. A typical Munsell notation 7.5YR 5/4 means that a particular soil sample has a 7.5 yellow-red hue with a value of 5 and a chroma of 4. In this study, Munsell readings, values (V), chroma (C), and hue (H), were performed on each of the 124 soil samples air-dried and sieved at 2 mm. Samples were put in small

Figure 3. Theorical representation of the Munsell color space [adapted from Torrent and Barrón (1993)]. Y=yellow, R=red, P=purple, B=blue, and G=green.



circular sample holders of about 5 cm^2, leveled, and compared with the chart under natural light, outdoors with a cloudless sky from 10 a.m. to 3 p.m., by an experienced observer with a normal color vision. Normal precision was improved considering in-between color chips. This was restricted to one-half the interval between chips as suggested by the Soil Survey Staff (1975). The original Munsell Hue codes were converted into the following numerical system to allow statistical calculations: 10R=15, 2.5YR=12.5, 5YR=10, 7.5YR=7.5, 10YR=5, 2.5Y=2.5. This notation orders Munsell Hue from yellow to red color, what is more coherent with the Helmholtz system presented below. We will refer to this coding as the Munsell hue (H). A color index was also worked out from the Munsell parameter (Torrent et al., 1983).

$$RI(MUN) = \frac{H \times C}{V}.$$

This index gives a synthetic expression of soil color and accounts for the soil redness intensity. Torrent et al. (1983) found a close relationship between this index and the hematite content of European and Brazilian soils.

CIE System and Helmholtz Coordinates

Besides the visual estimation, soil color was calculated according to the CIE 1931 colorimetric system (CIE, 1931). In this system, color is mathematically reproduced with three wavelength-dependent functions: i) the spectral properties of the measured object, ii) the energetic emission of the illumination source under which the target is viewed, and iii) the characteristics of the human eye which acts as a spectral detecting device. A color is defined by two chromaticity coordinates, x and y, and a third parameter accounting for the color intensity called the luminance (Y%). For each soil sample, three stimuli values, X, Y, and Z, are first computed with the following CIE equations (Wyszecki and Stiles, 1982):

$$X=\int_{380\text{ nm}}^{770\text{ nm}} C(\lambda)\cdot R(\lambda)\cdot\bar{x}\,d\lambda,\qquad Y=\int_{380\text{ nm}}^{770\text{ nm}} C(\lambda)\cdot R(\lambda)\cdot\bar{y}\,d\lambda,$$

$$Z=\int_{380\text{ nm}}^{770\text{ nm}} C(\lambda)\cdot R(\lambda)\cdot\bar{z}\,d\lambda,$$

where λ is the wavelength, $R(\lambda)$ is the reflectance spectra of the soil sample, $C(\lambda)$ is the power density of the lighting source, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the three modified color matching functions of the CIE 1931 Standard Observer (CIE, 1931). Three color matching functions, $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$, were originally developed to approximate the sensitivity of a reference human eye to the three primary colors, red, green, and blue, respectively. In order to avoid technical problems in colorimeter design (i.e., negative values were yielded because of the red function), the original functions were modified through a change of basis to give $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ (Mac Adams, 1985). We have used the C CIE Illumination Standard as reference illuminant (CIE, 1931). This signifies that soil color was calculated as if soil samples were viewed under average day light. Steps of 5 nm were used for integral computation. Three chromaticity coordinates, x, y, and z, are then defined in the following manner:

$$x=\frac{X}{X+Y+Z},\qquad y=\frac{Y}{X+Y+Z},\qquad z=\frac{Z}{X+Y+Z}$$

Since $x+y+z=1$, only the chromaticity coordinates x and y are kept. The color intensity Y% is also defined by

$$Y\%=100\cdot\frac{\int_{380\text{ nm}}^{770\text{ nm}}\bar{y}(\lambda)\cdot C(\lambda)\cdot R(\lambda)\,d\lambda}{\int_{380\text{ nm}}^{770\text{ nm}}\bar{y}(\lambda)\cdot R(\lambda)\,d\lambda}.$$

Interpretation of these cartesian coordinates is easier by the use of a chromaticity diagram (Fig. 4). In this reference plane, the representation of monochromatic or pure colors shapes a rounded cone designated as the locus spectra, scaled in wavelength and closed by a purple line which joins blue to red colors. Inside this space, each point, $M(x,y)$, designates a unique color. The C point corresponds to the reference illumination according to which the color is expressed or viewed (here the white light of average day light). The third axis Y% is normal to the x,y plane and defines a pyramidlike volume which corresponds to the volume of color (not shown). The luminance takes the value of 100% within the chromaticity diagram, and the value 0% at the apex of the pyramid, that is, absolute black. Although very accurate to measure subtle color differences, the cartesian chromaticity coordinates are not evocative of the visual sensation caused by a specific color, and the color notation scale is not visually homogeneous. Modifièd polar coordinates called Hemlholoz coordinates, the dominant wavelength

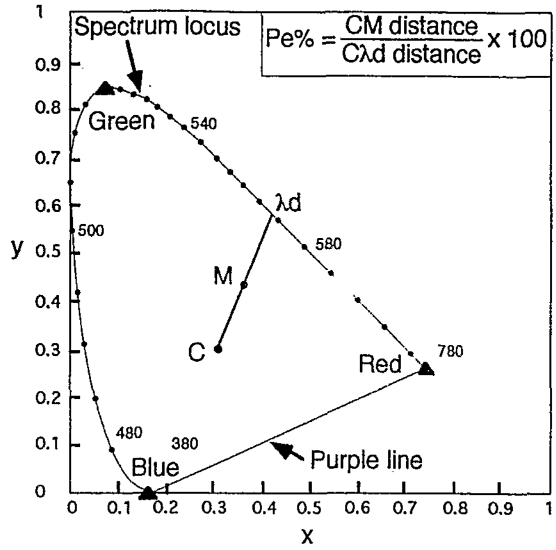


Figure 4. CIE chromaticity diagram and Helmholtz parameters λd and Pe% [adapted from Cervelle et al. (1977)]. Y% passes through C and is normal to the x,y plane.

(λd) and the purity of excitation (Pe%), which are similar to the Munsell hue and chroma, respectively, have then been introduced. λd corresponds to the interception point on the locus spectra of the line passing through C and $M(x,y)$. Pe% corresponds to the distance ratio CM/$C\lambda d$ (Fig. 4). In this new color representation, Y%, which is similar to the Munsell value, keeps its meaning. A specific computer program has been developed to automatically convert x and y into λd and Pe% coordinates (Bédidi, personal communication, 1997). Madeira et al. (1997) defined a synthetic color index similar to RI(MUN) which was calculated as follows:

$$RI(HL)=\frac{(\lambda d-575)\times Pe\%}{Y\%^2}$$

These authors found a high correlation between this index and the hematite content of Brazilian latosols.

Radiometric Indice Calculation

For each sample, reflectance values of Landsat TM1 (blue, 0.45–0.52 μm), TM2 (green, 0.52–0.60 μm), and TM3 (red, 0.63–0.69 μm) as well as of SPOT HRV XS1 (green, 0.5–0.59 μm) and XS2 (red, 0.61–0.68 μm) spectral bands were simulated, integrating the reflectances of the wavelength interval of each band. The calculation was weighted by the detector spectral sensibility curves (Markham and Barker, 1985; Bégni, 1988). According to the colorimetric laws, the spectral domain of color validity is restricted to the visible light, defined as the spectral range of human eye's sensitivity (400–770 nm) (Wyszecki and Stiles, 1982). For this reason, we have only considered visible bands, although previous authors have re-

Table 1. Radiometric Indices Calculated from Landsat TM and SPOT HRV Simulated Bands.[a]

TM Indices	*HRV Indices*	*References*	*Index Properties*
$BI(TM)=\sqrt{\frac{TM1^2+TM2^2+TM3^2}{3}}$	$BI(XS)=\sqrt{\frac{XS1^2+XS2^2}{2}}$	This study	Average reflectance magnitude
$SI(TM)=\frac{TM3-TM1}{TM3+TM1}$	No equivalent	Adapted from Escadafal et al. (1994)	Spectra slope
$HI(TM)=\frac{2\times TM3-TM2-TM1}{TM2-TM1}$	No equivalent	Escadafal et al. (1994)	Primary colors
$CI(TM)=\frac{TM3-TM2}{TM3+TM2}$	$CI(XS)=\frac{XS2-XS1}{XS2+XS1}$	Escadafal and Huete (1991), Madeira et al. (1997)	Soil color Hematite/(hematite+goethite)ratio
$RI(TM)=\frac{TM3^2}{TM1\times TM2^3}$	$RI3(XS)=\frac{XS2^2}{XS1^3}$	Madeira et al. (1997), Pouget et al. (1991)	Hematite content
	$RI4(XS)=\frac{XS2^2}{XS1^4}$	This study	Redness

[a] The spectral bands were simulated from reflectance data acquired in laboratory conditions.

ported comparisons of red, green, and near-infrared multispectral data with Munsell soil color (Mathews et al., 1973; Mattikalli, 1997).

Spectral bands were combined in order to provide selected radiometric indices, which may be useful in terms of soil color remote sensing (Table 1). The brightness index, BI, is calculated as an euclidian distance in a space of n spectral dimensions and hence determines the global reflectance of a target (Richardson and Wiegand, 1977; Robinove et al., 1981). Recently, Escadafal et al. (1994) working on landscape degradation in arid Tunisia proposed two new indices based on colorimetric principles: the hue and saturation indices, HI(TM) and SI(TM). These indices result from a simplification of the general hue and saturation equations defined by Liu and Moore (1990) which is justified by specific soil characteristics; that is, soil reflectance curves are typically monotonous and increasing in the visible range, and a limited range of soil colors exists in nature. In opposition to the BI, which gives a measure of the soil reflectance magnitude, the SI and HI characterize its shape. The SI measures the general slope of a spectra, from red to blue wavelength or, in other words, its deviation relative to a flat spectra characteristic of a neutral color like grey. The HI accounts for the relative proportion of the three primary colors, red, green, and blue. Since a blue band does not exist in the HRV instrument, no similar index were used for simulated SPOT data. The coloration indices, CI(TM) and CI(XS), correspond to the normalized ratio of red and green bands. In this spectral range, soil reflectance curves are mainly affected by the absorption of iron oxides like goethite and hematite (Stoner and Baumgardner, 1981), two of the most important soil coloring constituents. This index was used by Escafadal and Huete (1991) to reduce the influence of soil color on the sensitivity of some vegetation indices and related by Madeira et al. (1997) to the hematite/(hematite+goethite) ratio of Brazilian latosols. Madeira et al. (1997) has also defined a TM-based redness index, RI(TM), which was successfully used to map soil hematite content in the Brasilia region. In the case of SPOT, we have used a redness index RI3(XS) adapted from RI(TM) by Pouget et al. (1991) and we have calculated RI4(SX) in order to have the same denominator weight than RI(TM).

RESULTS

We have first performed linear regression analyses and examined the relationships between soil color and reflectance data for each individual band (Table 2). Low correlation coefficients (r) indicate that no satisfactory relationships exist between multispectral reflectance data and C and H or Pe% and λd. The color intensity of an object is usually proportional to its reflectance level over the whole visible spectral domain. However, moderate relationships are observed between each individual band and V or Y% (i.e., r is more than 0.8). This can be explained by the high correlations observed between re-

Table 2. Linear Correlation Coefficient (r) Matrix between Landsat TM -SPOT HRV Bands and Helmholtz–Munsell Parameters[a]

	TM1	*TM2*	*TM3*	*XS1*	*XS2*
V	0.82°	0.88°	0.81°	0.89°	0.82°
C	−0.28	0.08	0.33	0.02	0.31
H	−0.36°	−0.35°	−0.23	−0.37°	−0.23
RI(MUN)	−0.61°	−0.51°	−0.35°	−0.54°	−0.36°
Y%	0.94°	0.99°	0.93°	0.99°	0.94°
Pe%	−0.54°	−0.2	0.05	−0.26	0.04
λd	−0.47°	−0.44°	−0.28	−0.47°	−0.29
RI(HL)	−0.64°	−0.68°	−0.61°	−0.69°	−0.62°

[a] Sample number=124, ° significant at the 99% level.

Table 3. Linear Corrrelation Coefficient (*r*) Matrix between the Reflectance Data of Landsat TM and SPOT HRV Simulated Bands[a]

	TM1	*TM2*	*TM3*	*XS1*	*XS2*
TM1	1				
TM2	0.92	1			
TM3	0.76	0.95	1		
XS1	0.95	0.98	0.93	1	
XS2	0.77	0.96	0.99	0.94	1

[a] Sample number=124.

flectance data of each simulated band (Table 3). This characteristic is soil-specific and illustrates the typical increasing and relatively monotonous form of soil reflectance spectra in the visible range (Stoner and Baumgardner, 1981).

In a second step, the same analysis have been carried out between soil color and radiometric indices. Table 4 presents the resulting correlation coefficients (*r*). We will examine these results taking into account two index groups: i) the "classical" colorimetric indices, BI(TM), SI(TM), HI(TM), CI(TM), BI(XS), and CI(XS), and ii) the redness indices, RI(TM), RI3(TX), and RI4(XS). For the first group, results show that BI(TM), SI(TM), and HI(TM) are moderately correlated to *V*, *C*, and *H*, respectively (*r* from 0.77 to 0.86). A strong and systematic variation of the radiometric indices is observed for each of the discrete Munsell notation (Fig. 5). Correlations between the same indices and corresponding Helmoltz parameters Y%, Pe%, and λd are systematically and significantly higher with more than 0.9. Each of these indices is strongly related to one and only one color component. Moreover, Figure 6 shows that deviation from the regression lines are relatively low, including for extreme figures, few represented in the sample set investigated (e.g., Y% more than 20%, λd more than 590 nm). The coarse spectral resolution of satellite bands and their specific location could be an explanation of the slight discrepancy observed between both data sets. Helmholtz parameters are computed with a precision of 5 nm while the average width of TM bands is about 70 nm. Also, TM1 is only sensitive from 450 nm and does not take into account the highest frequencies of the visible light. Only moderate relationship are found between CI(TM) and Pe% or λd. Working on soil samples rich in iron oxides from which organic matter was previously removed, Madeira et al. (1997) reported a strong correlation between this index and λd (r=0.98). Sample treatment may be a first explanation of our different result. However, this may also suggest that the most useful band combinations for soil color determination are soil-type-dependent, and hence established relationships should be verified when considering other natural regions. The lack of a blue band limits the number of available indices for SPOT HRV, which are reduced to the BI(XS) and the CI(XS). Results obtained for these two indices are similar to the equivalent TM indices.

Concerning the second group, the three redness indices used, RI(TM), RI3(XS), and RI4(XS), present a close relationship with RI(HL). Developed in a tropical context, RI(TM) confirms its usefulness for measuring soil redness variation in an arid environment. Two redness indices have been tested for SPOT HRV, RI3(XS) and RI4(XS). RI3(XS) increases rapidly, from RI(HL) equal to 0 up to about 3, followed by a variability decrease (Fig. 7a). This result is in agreement with the observations made by Pouget et al. (1991) who used this index to discriminate sandy surfaces from SPOT data in Egypt. Inversely, RI4(SX) increases according to a more linear fashion and gives a better expression of the RI(HL) dynamic (Fig. 7b). RI(TM) exhibits the strongest point scattering compared to RI4(XS) (Figs. 7b and 7c), mainly for the highest values of RI(HL) (typically more than 5). Soil redness is mainly due to the presence of hematite (Schwertmann, 1993), and the RIs give a measurement of the absorption feature intensity characterizing this iron oxide (Madeira et al. 1997). Since both satellite simulations TM and SPOT have been made from the same spectra, a possible explanation for this difference could be the better overlapping of XS1 on the characteristic hematite adsorption feature around 530 nm compared to TM2 (Sherman and Waite, 1985). For the same reason as above and unlike the "classical" soil color components, the good result obtained for RI4(XS) sug-

Table 4. Linear Correlation Coefficient (*r*) Matrix between Landsat TM–SPOT HRV Radiometric Indices and Helmholtz–Munsell Parameters[a]

	BI(TM)	*SI(TM)*	*HI(TM)*	*CI(TM)*	*RI(TM)*	*BI(XS)*	*CI(XS)*	*RI3(XS)*	*RI4(XS)*
V	$\underline{0.87}$°	−0.37°	−0.6°	−0.49°	$\underline{-0.77}$°	$\underline{0.87}$°	−0.45°	$\underline{-0.81}$°	$\underline{-0.78}$°
C	0.07	$\underline{0.85}$°	0.12	$\underline{0.71}$°	0.09	0.12	$\underline{0.73}$°	0.22	0.03
H	−0.29	0.34°	$\underline{0.77}$°	0.54°	0.52°	−0.28	0.56°	0.59°	0.55°
RI(MUN)	−0.45°	0.59°	0.68°	$\underline{0.75}$°	$\underline{0.79}$°	−0.43°	$\underline{0.76}$°	$\underline{0.85}$°	$\underline{0.79}$°
Y%	$\underline{0.99}$°	−0.36°	−0.58°	−0.5°	−0.73°	$\underline{0.97}$°	−0.46°	−0.78°	−0.73°
Pe%	−0.12	$\underline{0.94}$°	0.15	$\underline{0.78}$°	0.33	−0.7°	$\underline{0.79}$°	0.43°	0.25
λd	−0.37°	0.42°	$\underline{0.92}$°	0.66°	0.47°	−0.36°	0.65°	0.6°	0.50°
RI(HL)	−0.66°	0.43°	0.63°	0.6°	$\underline{0.98}$°	−0.65°	0.61°	$\underline{0.96}$°	$\underline{0.99}$°

[a] Sample number=124; ° significant at the 99% level; underlined values correspond to the best relationships for each radiometric indices.

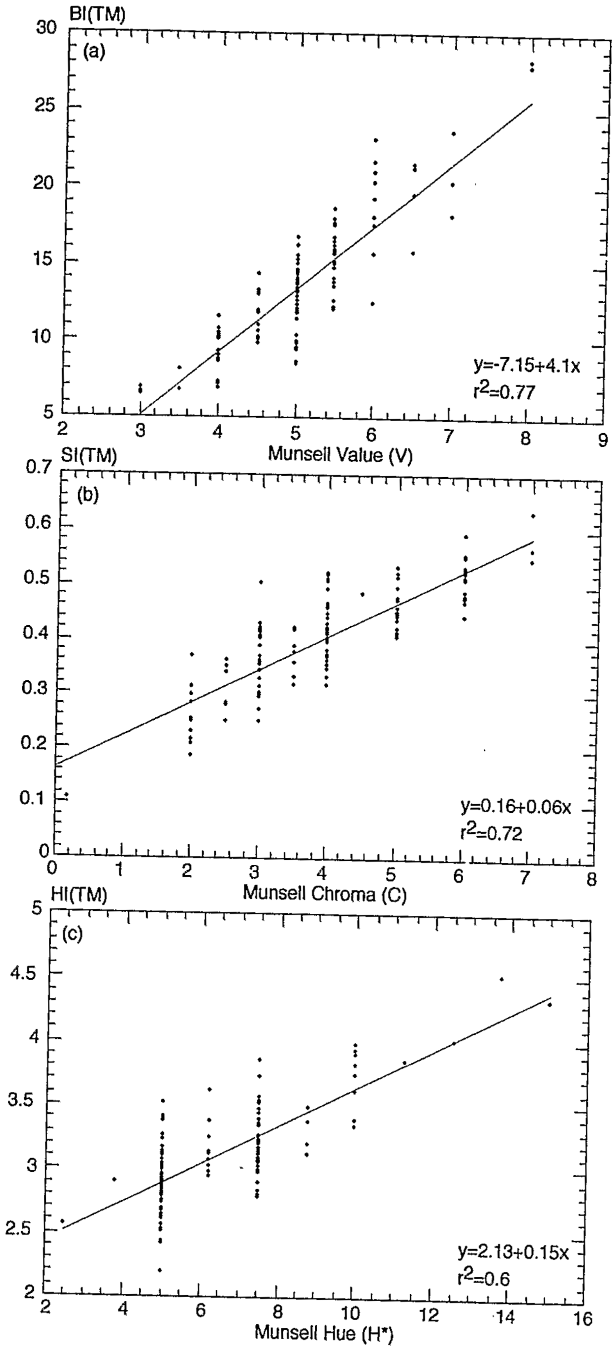


Figure 5. Relationships between selected radiometric indices of Landsat TM and Munsell parameters *V*, *C*, and *H*. (*)Original Munsell Hue codes are converted according to the following numeric system: 10R=15; 2.5YR=12.5; 5YR=10; 7.5YR=7.5, 10YR=5; 2.5Y=2.5 (see text).

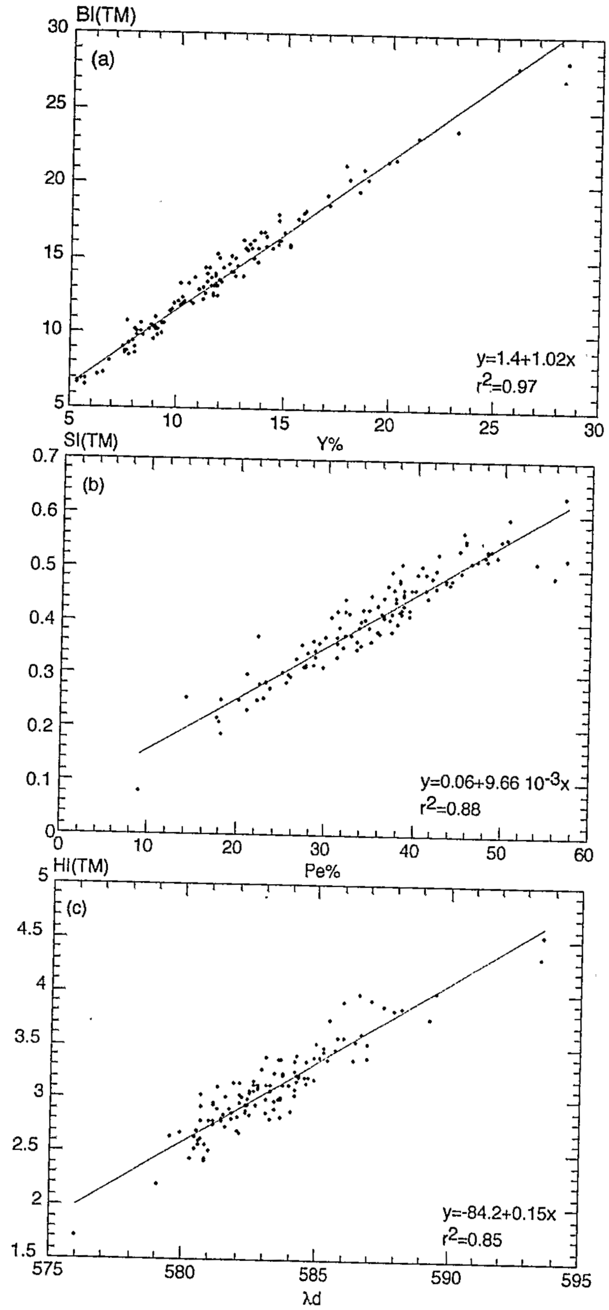


Figure 6. Relationships between selected radiometric indices of Landsat TM and Helmholtz parameters Y%, Pe%, and λd.

gests that blue data are not so useful to follow soil redness variations.

A summary of the best relationships between soil color and radiometric indices is given in Table 5 showing the regression equations and the r^2 coefficients.

DISCUSSION AND CONCLUSION

Differences in measurement precision explain to a great extent the poor results of Munsell data compared to Helmholtz data. Reflectance data corresponds to a continuous physical measure and for one sample its precision depends mainly on the noise generated by the sensing device. In return, using a visual estimation, the three-dimensional space of Munsell color is simplified in a dis-

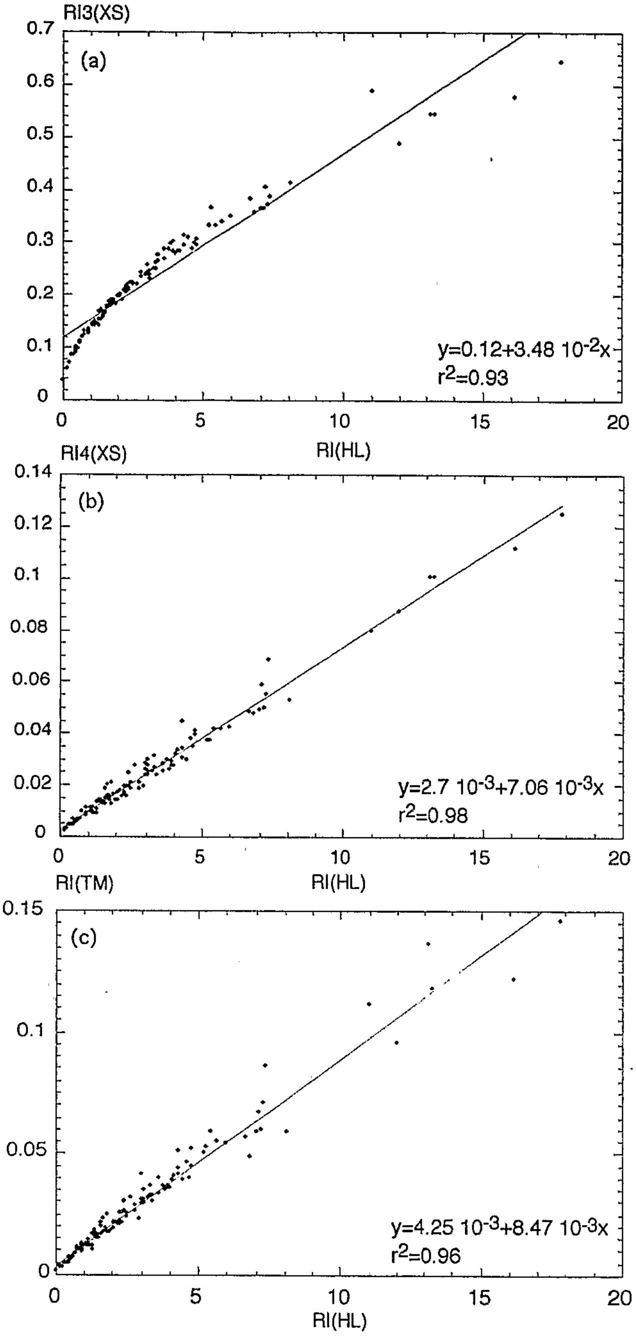


Figure 7. Relationships between the redness indices obtained from the combination of simulated satellite bands [RI3(XS), RI4(X), RI(TM)] and the redness index calculated from the Helmholtz parameters, RI(HL).

crete system consisting of a limited number of chips that each represents a small fraction of this volume. A perfect match between the soil sample color and the chip read is therefore almost never achieved, 2% of probability according to the Soil Survey Staff (1975). Visual measurement may also be influenced by variables independent of soil sample properties, for example, operator's color

Table 5. Selected Linear Regression Equations between Radiometric Indices and Soil Color Parameters

Equation	r^2
BI(TM)=1.4+1.02 Y%	0.97
SI(TM)=6.34×10^{-2}+9.67×10^{-3} Pe%	0.88
HI(TM)=−84.2+0.15λd	0.85
RI(TM)=4.23×10^{-3}+8.5×10^{-3} RI(HL)	0.96
BI(XS)=1.94+1.09 Y%	0.95
RI4(XS)=2.7×10^{-3}+7.06×10^{-3} RI(HL)	0.98

vision ability, operator's fatigue and psychological state, effect of contrast between the target color and its environment, and illumination conditions (Shields et al., 1966; Melville and Atkinson, 1985). A recent study reports that the total agreement of several soil scientists on the Munsell value, chroma, and hue of 41 samples was reached only 52% of the time (Post et al., 1993). To reduce these effects, various solutions have been proposed such as the interpolation between color chips, the calculation of an average color from several observer readings, the use of a complete Munsell color chart, and the definition of a rigorous measurement procedure (Kelly and Judd, 1976; Torrent et al., 1983). Nevertheless, in the daily field practice, the measurement conditions usually available are those that we have voluntarily retained in this work (Soil Survey Staff, 1975).

The significant improvement of the relationships between indice and Helmholtz data is an important observation suggesting that the indices, that is, BI, SI, HI, and RI may be useful for improving soil color remote sensing. Build as simple band ratios, these indices constitute a rapid and easy method to discriminate soil color in arid regions. Validation of the linear models obtained for the best radiometric indices has been performed on an other set of 36 samples, originated from the same geographical zone and taken from similar soil types. The same sample treatment procedure was followed and diffuse reflectance spectra were acquired with a Varian/Cary 2300 spectrophotometer according to a method described elsewhere (Bédidi et al., 1992). The equations presented in Table 5 were inverted to predict the sample color [Y%, Pe%, λd, RI(HL)] from their reflectance. Model performances are given in Table 6. Correlation coefficients (r) between predicted values and measured values are similar to those obtained during the model development phase (i.e., more than 0.9). The average prediction error of the different color components is less than 10% with a standard deviation varying from 2% to 8%. The degree of precision is compatible with the quality of the relationships previously established. The radiometric indices allows us therefore to predict Helmholtz parameters with an acceptable accuracy. Besides the limitations due to the radiometric indices themselves, errors may

Table 6. Performance of Radiometric Indices for Soil Color Prediction[a]

Prediction	*Predictor*	*r(°)*	*Mean Error %*	*STD Error(°°)*
Y%	BI(TM)	0.98	2.7	2.3
Pe%	SI(TM)	0.97	8.7	7.7
λd	HI(TM)	0.92	8.5	6.2
RI(HL)	RI(TM)	0.97	7.1	4
Y%	BI(XS)	0.98	3.8	3.5
RI(HL)	RI4(XS)	0.96	5.3	4.4

[a] (°)Linear correlation coefficient *r* between predicted and measured components; (°°)standard deviation of the % error.

have been introduced by the different nature of reflectance data used to define and to validate the linear regressions. In the first case, reflectance was measured with a specific viewing and illumination direction while in the second one, hemispherical reflectance were acquired by the Varian/Cary 2300 instrument. Because of the nonlambertian soil behavior, significant reflectance differences may be expected if the observation and illumination configuration changes (Baret et al., 1993). Errors may also be increased by sample size changes (i.e., some tens of cm^2 for the ASD to a few cm^2 for the Cary), inducing variations of sample roughness or compaction effects.

Since color depends only on visible light, only such spectral domain were used for indice construction. As expected from colorimetric law definitions, comparison of results from SPOT and TM shows that a knowledge on blue reflectance variability is needed to elaborate a comprehensive soil color model. In the case of the SPOT instrument, an indirect and synthetic information on soil color might be retrieved from red and green reflectance data, due to a redness index. However, in the case of soils, Mattikalli (1997) demonstrated that the high dependence between visible and near-infrared wavelengths can be used to relate the Munsell parameter to green, red, and near-infrared reflectance data of Landsat MSS.

It should be first recalled that the results of this study are only valid for the soil types represented in the investigated region. Further studies are required to examine the usefulness of the radiometric indices on other soil types and colors (i.e., more specific for temperate and tropical environments). Secondly, the results presented here are for data acquired in laboratory conditions and on disturbed soil samples of reduced size. This approach is fundamental to determine the optimal potentiality of different currently available spectral configurations with a view to extract soil surface color from remotely sensed images. However, applied to a real set of data recorded from space instruments, the indices may yield different results because of the basic differences existing between laboratory and satellite data. Therefore, it may be important to convert exoatmospheric luminance values measured by space sensors into ground reflectance data. Attention should be given to correct images for atmospheric effects, particularly sensitive in the short wavelength of the visible range, using available technics and models (Chavez, 1988; Tanré et al., 1990). Illumination variations due to Sun angle and rugged topography can be reduced using a digital elevation model (Civco, 1989; Meyer et al., 1993). Misinterpretation of soil color may also be induced by some changes in soil surface conditions within an image. For the case of bare or sparsely vegetated surfaces, these confusions concern mainly roughness or hydric state variations of soil surface. The reasoned choice of the image acquisition date is certainly a first reply to solve these difficulties. The period of soil tillage is more suitable to observe homogeneous roughness conditions while a dry season should be preferred to lower the risk of soil moisture variation. However, image calibration for moisture and roughness variations remains highly desirable and may be endowed by the results of the ongoing research efforts on bidirectional reflectance (Deering et al., 1990; Jacquemoud et al., 1992) and by the complementary techniques of microwave remote sensing (Ulaby et al., 1978; Chanzy, 1993).

This work reports an original application of Helmholtz parameters under laboratory conditions for further color research in the remote sensing field. These measures of color can be equally obtained for soils preserved in their natural environment and under natural light. The acquisition of finely resolved reflectance spectra in the field (i.e., 1–5 nm/band) is today greatly facilitated by the growing availability of portable, light, and maniable spectroradiometers (e.g., GER and ASD instruments). Once a sampling strategy for collecting reflectance data in the field is defined (e.g., point, toposequence, or pixel simulation), the color of the soil surface can be calculated using the colorimetric equations presented in the method section. Unlike the human eye used in the Munsell color chart method, spectroradiometers have the capacity to integrate and average the light flux reflected by the different components of the soil surface. As a result, the average color [λd, Pe%, Y% and RI(HL)] of a complex mineral surface, including aggregate, crust, gravel, block, and rocky outcrops, can be directly worked out from its reflectance spectra. Such data take into account most of the soil surface and are more representative of what is really seen by the satellite. Potential applications may involve further studies to reduce soil color effect on the accuracy of vegetation indices (Huete, 1988; Bannari et al., 1995). The development of airborne imaging spectrometers recording hyperspectral data (Vane and Goetz, 1993) makes possible in the near future the automatic calculation of dominant wavelength or purity images. In this context, useful applications may arise from recent laboratory research using these parameters to investigate soil properties (Bédidi et al., 1992; Malengreau et al., 1996). The use of this system of soil color quantification deserves to be developed and should be encouraged in the remote sensing community.

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