SYSTEMATIC EVALUATION OF FACTORS INTERFEARING WITH SOIL COLOR RETRIEVAL FROM SPACE

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ABSTRACT

Correlations between soil color and soil characteristics, such as organic matter and iron content, have promoted many researchers to develop remote sensing techniques for soil color mapping. But although soil color calculation is based on well established physical principles, its estimation from image data is far from being trivial. Problems are due to measurement conditions which may differ significantly from those encountered in laboratory studies. For example, water content, surface roughness, and the amount of dead or living vegetation residues may vary in space and time for a given soil. Since these factors affect soil reflectance, differences in retrieved soil color attributes are inevitable.

In this study, important factors which interfear in soil color mapping from space have been systematically evaluated using laboratory spectra of 55 widely differing soil samples and well established reflectance models. The factors studied have been soil water content, soil roughness, amount of green and senescent vegetations residues, as well as measurement configuration (sun and sensor geometry). The color attributes which have been analyzed are Munsell hue, value and chroma, and CIE-coordinates. Since the soil samples have been developed in different parent materials, regions and soil horizons, we believe that the results will be of some general validity.

1 INTRODUCTION

The mapping of soil color is of importance in agriculture and pedology. For example, there have been many studies revealing strong relations between soil color and organic matter content, respectively, iron oxide characteristics (table 1). Moreover, soil color is used in many modern soil classification systems as a differentiating characteristic for many classes. But unlike other pedologic characteristics, such as particle size distribution which are verifiable by established laboratory procedures, soil color is determined solely by visual comparison with standard soil color charts (since 1951, the use of Munsell's soil color charts is recommended). In these soil color charts, colors are ordered according to hue (tone), value (brightness) and chroma (intensity). Due to their subjective determination, visually determined soil colors are, of course, difficult to analyse quantitatively.

Soil color may be calculated objectively using spectroradiometric devices (e.g. SHIELDS ET AL., 1968; MELVILLE & ALKINSON, 1985; FERNANDEZ & SCHULZE, 1987; ESCADAFAL ET AL., 1989; ESCADAFAL, 1993; MATTIKALLI, 1997). Using tabulated factors (e.g., Wyszecki & Stiles, 1967), the measured bi-direktional reflectance between 380 and 780 nm is simply transferred into CIE (1964) color attributes, which allow in turn to determine Munsell HVC.

Table 1. Selected publications concerning the relation between soil color and soil organic matter content, respectively, iron oxide characteristics

Soil information	Autor(s)
Organic matter content	SHIELDS ET AL. (68); ALEXANDER (69); KRISHNA MURTI & SATYA-NARAYANA (71); MCKEAGUE ET AL. (71); KARMANOV & ROZKHOV (72); PAGE (74); LEGER ET AL. (79); STEINHARDT & FRANZMEIER (79); BLUME & HELSPER (87); FERNANDEZ ET AL. (88); FRANZMEIER (93); SCHULZE ET AL. (93)
Iron oxide content, oxidation level and degree of substituation	SCHWERTMANN & LENTZE (66); SOILEAU & MCCRACKEN (67); ESWARAN & SYS (70); KRISHNA MURTI & SATYANARAYANA (71); MCKEAGUE ET AL. (71); KARMANOV & ROZKHOV (72); TORRENT ET AL. (80); TORRENT ET AL. (83); BARRON & TORRENT (84); KOSMAS ET AL. (86); SCHWERTMANN (93); JARMER & SCHÜTT (98)

Although the spectroradiometric determination of soil color is based on solid physical principles, its remote determination (for example, through hyperspectral imaging) is quite complicated. For instance, atmospheric processes modify the measured spectra throughout the (visible) spectrum. Second, soils are known to be non-lambertian reflectors. Therefore, varying sun elevations and observation geometries may lead to errors in the retrieved soil colors. Moreover, soil water content, surface roughness, and the amount of vegetation residues (either living or senescent) are known to vary in space and time. Thus, it is not surprising that one often observs differences between laboratory measurements and remotely sensed color attributes (e.g. Escadafal 1989).

Since the mentioned factors detoriate also the predictive power of remote soil color (and reflectance) measurements, a systematic laboratory and modeling effort has been undertaken. By spectroradiometric measurements we determined the influence of soil water content on spectral reflectance and soil color. Using well established reflectance models, we further studied the influence of measurement geometry, amount of dead and living vegetation residues, and surface roughness. Atmospheric perturbations have not been studies, since powerful correction algorithms are available.

2 MATERIAL & METHODS

2.1 Soil samples

In total, 55 soil samples have been analyzed for the present study. 38 samples are from the Ap-horizons (german nomenclature) of uncovered agricultural soils with variable geology and morphology (Bitburger Gutland and Ruwertal). 11 soil samples have been taken in 5, respectively, 25 cm depth under forest (Morbach) and 6 soil samples are from Crete. The soil samples represent therefore a grreat variability in soil color, although some soils (e.g., the forest soils) are normally not accessible from remote sensing platforms.

2.2 Reflectance measurements

Bi-directional soil reflectance (380 - 780 nm) has been measured in the laboratory using an ASD Field Spec II spectroradiometer and a lambertian Spectralon reference panel of known reflectivity. To stabilize the measurements of the unsifted samples as much as possible, soil samples have been placed on a slowly rotating device (0.07 rotations sec^{-1}). The integration time of the ASD sensor has been fixed to 26 sec, to intergrate over two complete rotations of the sample holder. During the measurements, the illumination source (halogen lamp) has been positioned in a distance of 50 cm to the soil sample, whereas the 25° ASD fiber optic has been in a distance of 10 cm to the sample.

To parameterize the non-lambertian reflectance behaviour of the soils and to extract the soil-inherent spectral information (i.e. its single scattering albedo), we measured (1) the bi-directional reflectance of air-dried soil samples under two illuminations (30 and 60°) and four view angles (table 2), and (2) soil reflectance for water contents of 0, 10 and 20 % water (two measurement configurations). Attention has been paid to meet exactly the requiered water contents.

Illumination		Sensor	
θz	ϕ	θv	
30	0	0	45
	90		45
	180		45
60	0	0	45
	90		45
	180		45

Table 2. Eight measurement configurations for soil reflectance measurements (air-dried soil samples). The two underligned configurations are used for reflectance measurements under different soil water contents (0, 10 and 20 weight-% H_2O)

2.3 Parameterization and simulation

To analyze the different factors which may influence the quality of the remotely sensed soil colors, we proceeded as follows. In a first step, we separated the soil-inherent spectral information (i.e. its single scattering albedo), from the bi-directional effects of the soil surface (i.e. due to soil roughness and phase function). In a second step, we used well established reflectance models to simulate the influence of surface roughness, respectively, dead and living vegetation residues, on spectral “soil” reflectance. These spectral signatures may then be transferred into soil color attributes.

According to the SOILSPEC model (JACQUEMOUD ET AL., 1992), the bi-directional soil reflectance ($\rho_{s\lambda}$) for a given illumination zenith (θz), observation angle (θv), and relativ azimuth between observer and illumination (ϕ) is formalized by:

$$\rho_\lambda = f(\omega_\lambda, h, b, c, b', c', \theta z, \theta v, \phi) \tag{1}$$

The four phase parameter (b,c,b‘ und c‘) are independent from wavelength, and describe the angular dependence of the reflection component which is scattered only once (the multiple scattering component is assumed to be isotrop; CHANDRASEKHAR 1960). The roughness parameter (h) determines the strength of the hot-spot effect and is also independent from wavelength. Therefore, the spectral variability of the soil reflectance is determined exclusively by its single scattering albedo (ω_λ), which is the ratio of the scattered energy to the total energy either scattered or absorbed by the particle.

Assuming that phase and roughness parameters do not change with soil water content, it is possible to determine the soil-inherent spectral signature of each sample and for different soil water contents. From the eight multi-angle reflectance measurements of the air-dried soil samples (for example in three wavelengths), one simply adjusts in an iterative numerical procedure the eight unknown parameters ($\omega_{\lambda 1}$,$\omega_{\lambda 2}$,$\omega_{\lambda 3}$,h, b, c, b‘, c‘). Using the adjusted phase and roughness parameters, it is then possible to determine the single scattering albedo in the whole spectral range and for each soil water content.

Generally, the SOILSPEC model fits very well the angular and spectral dependence of soil reflectance. This is shown in Figures 1 and 2 for a representative soil sample. In figure 1, measured and fitted bi-directional reflectances at 600 nm are shown in the principle plane for two illumination zenith angles (30 and 60°). For the same soil sample, figure 2 shows the measured and fitted soil reflectances for all wavelengths, measurement geometries, and soil water contents together. Similar results have been obtained for the remaining soil samples (not shown here).

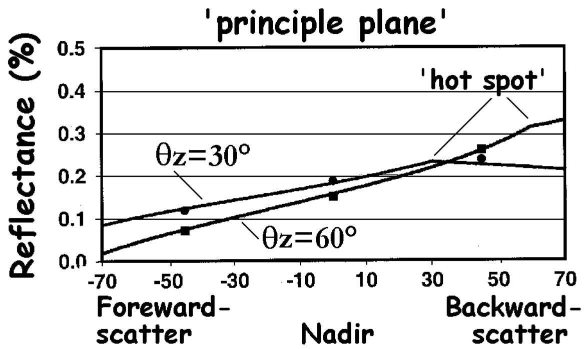

Figure 1. Measured (points) and fitted (lines) reflectances of an air-dried soil sample (ruw22) in the principle plane. The two illumination zenith angles (30 and 60°) are indicated (λ=600 nm)

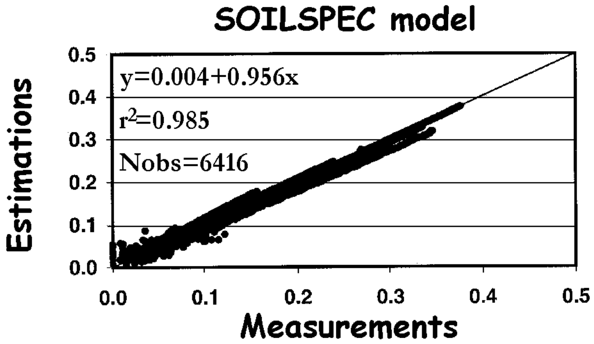

Figure 2. Measured versus estimated soil spectral reflectance (380-780 nm) of soil sample ruw22. All wavelengths, measurement geometries and soil water contents have been put together (n=6416)

For the analysis of vegetation residues on soil spectral reflectance (and soil color) we used the SPECAN reflection model (JACQUEMOUD ET AL. 1995). SPECAN describes with a high accuracy the spectral bi-directional reflectance behaviour of a vegetation cover as a function of the spectral reflectance of the underlying soil (see Eq.1), and a few bio-physical and geometrical parameters.

$$\rho_\lambda = f(\rho_{S\lambda}, Cab, Cw, N, LAI, \theta z, \theta v, \phi) \tag{2}$$

with $\rho_{S\lambda}$ Spectral reflectance of the underlying soil (equation 1)
Cab Leaf chlorophyll (a+b) content ($\mu g/cm^2$)
Cw Leaf water content (cm)
N Leaf structure parameter (N=1.5 for monocotyls, N=2.5 for dicotyls)
LAI Leaf area (one-sided) per unit soil surface (m^2/m^2)

Through careful selection of SOILSPEC and SPECAN parameters, one may therefore simulate the influence of surface roughness, measurement geometry, and vegetation residues (either living or dead) on soil reflectance (table 3).

Table 3. Assigned values of SOILSPEC and SPECAN reflectance models used for the simulation of the reflectance and color behaviour of soil samples. The standard values are underligned

ω_λ	h	b	c	b'	c'	θz	θv (*)	Cab	Cw	N	LAI
all	0.02	1.4	0	0.3	-0.1	0	-50	0	0.1	2	0
soils	0.2					20	-30	30			0.1
	2					40	-10				0.3
	20					60	0				0.5
							10				
							30				
							50				

(*) negative angles = foreward scatter direction; positive angles = backward scatter direction

2.4 Calculation of color attributes

In contrast to its spectral reflectance, soil color is not a soil-inherent property. Soil color is rather the result of human color perception, and depends on (i) the illumination of the object, (ii) its spectral bi-direction reflectance, and (iii) the color sensation of the observer. Therefore, color is determined not only by physical parameters, but also by psychologically and physiologically factors. In color science, one tries to formalize this complex interaction and to develop systems for quantitative desription of colors.

Briefly, a color sensation may be completely reproduced using three primary colors. Beside, red (700 nm), green (546.1 nm), and blue (435.8 nm), three virtuel colors are widely used: X, Y and Z. XYZ of a color (C) are easily calculated using the object reflection (ρ_λ), the illumination characteristics (S_λ), and CIE color-matching functions ($\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$) (figure 3):

$$X = \sum S_\lambda \bar{x}_\lambda \rho_\lambda / \sum S_\lambda \bar{x}_\lambda$$
$$Y = \sum S_\lambda \bar{y}_\lambda \rho_\lambda / \sum S_\lambda \bar{y}_\lambda$$
$$Z = \sum S_\lambda \bar{z}_\lambda \rho_\lambda / \sum S_\lambda \bar{z}_\lambda \qquad (3)$$

Through normalisation by the sum of X, Y, and Z, one obtains x,y, and z, which may easily presented in a 2-dimensional CIE chromacity diagram (figure 4). In such a diagram, the spectral (pure) colors of a given brightness (Y) are located on the spectral locus, respectively, the purple line. All real colors are inside this area and the color with the highest purity are found on its border.

$$x = X/(X+Y+Z);\ y = Y/(X+Y+Z);\ z = Z/(X+Y+Z) = 1-(x+y) \qquad (4)$$

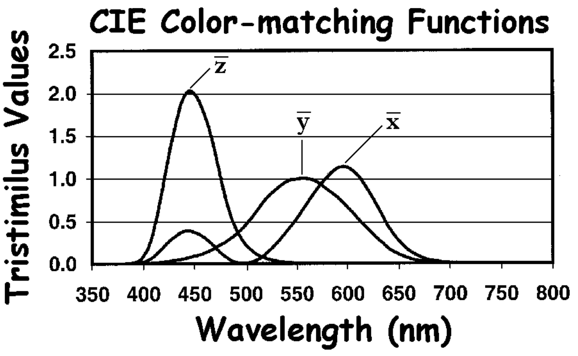

Figure 3. CIE color-matching functions used to calculate CIE XYZ coordinates (data from Wyszecki & Stiles, 1967)

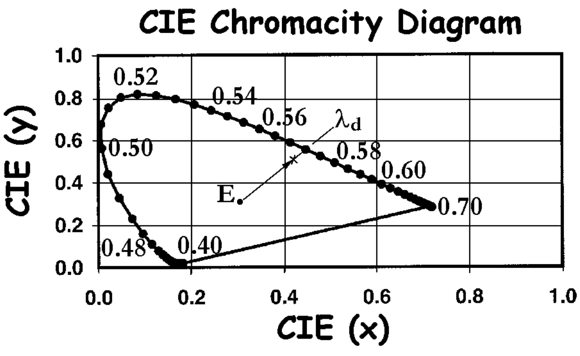

Figure 4. CIE chromacity diagram with spectral locus, purple line, location of the achromatic illumination (E), and Helmholtz dominant wavelength (λ_d)

For a given illumination and object reflexion, the calculation of CIE coordinates is straightforward. However, in the history of soil science, spectroradiometric devices are only recently available. To describe nevertheless soil colors in an unique and reproducible way, pedologist widely used (and still use today) the color system developed by A.H. Munsell in 1905. In this color system, one determines soil color solely by visual comparison with standard soil color charts, which are ordered according to hue, value and chroma (HVC). A typical Munsell color is called, for example, 5Y 5/6. In this example, 5Y is the hue, 5/6 are value, respectively, chroma. To make the Munsell hues suitable for mathematical analysis, we transferred them into a decimal system: A hue of 1 corresponds to 2.5 YR, and a hue of 8 equals 10Y. Colors outside these hue's have not been encountered in this study.

No equation system exists, which allows to calculate directely Munsell colors from CIE coordinates. Only Munsell value and CIE-Y are interchangeable ($Y=value^2$). If a transformation of CIE coordinates into Munsell hue and chroma is required, one must use tabulated data (e.g., WYSZECKI & STILES 1967). To avoid this labor-intensive step, we developed an automatic search routine for the tabulated data.

3 RESULTS & DISCUSSION

For all 55 soil samples, we analyzed the effect of soil water content, surface roughness, and the amount of vegetation residues (either living or death) on soil reflectance and soil color. While the influence of soil water content has been measured directly, the influences of the remaining factors have been simulated using established reflectance models and parameter ranges indicated in table 3.

Observed reflectances of oven-dried soil samples are shown in Figure 5, and in table 4 you will find some statistical properties of the calculated soil colors, revealing a great variability in soil reflectance and soil color.

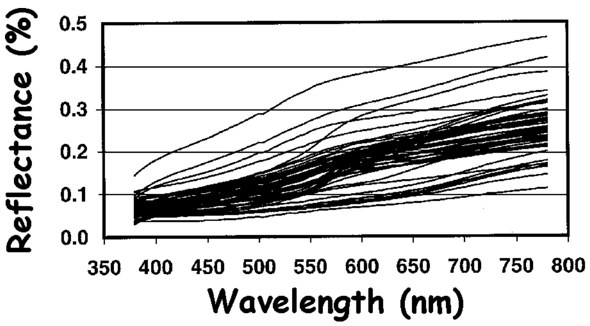

Figure 5. Bi-directional reflectance of oven-dried soil samples (n=55; θz=30°; θv=45°;ϕ=0°)

Table 4. Descriptive statistics of CIE and Munsell attributes. Colors have been calculated from reflectance measurements of oven-dried soils (n=55; θz=30°; θv=45°; ϕ=0°). Note that Munsell coordinates are only in discrete values

Color system	attribut	mean	std.dev.	min	max	range
Munsell	Hue (*)	3.42	0.76	1	4	3
	Value	3.75	0.78	2	6	4
	Chroma	3.11	0.63	2	5	3
CIE (1964)	Y	0.1083	0.0435	0.0434	0.2939	0.2505
	x	0.3963	0.0133	0.3754	0.4336	0.0582
	y	0.3723	0.0066	0.3571	0.3840	0.0269

(*) Munsell-hue=1 corresponds to 2.5 YR and hue=8 corresponds to 10Y

3.1 Soil water content

The dependence of soil reflectance on soil water content is shown exemplarily in Figure 6. Independent from wavelength, reflectance decreases exponentially with soil water content from 0 to 20%. This decrease in soil reflectance, even outside the water absorption bands, is due to the so-called "trapping effect". Similar effects have been noted for all other soil samples (not shown here). For the soil samples analyzed, the decrease of soil reflectance leads to a strong decrease in Munsell value (by one or two units) (Figure 7). Hue remains in most cases constant, with some soil samples showing an increase, some other a decrease in hue. At the same time, many samples exhibit a decrease in Munsell chroma (by one unit). The influence of soil water content on soil brightness is more pronounced if the soil surface is smooth, especially at small sensor zenith angles.

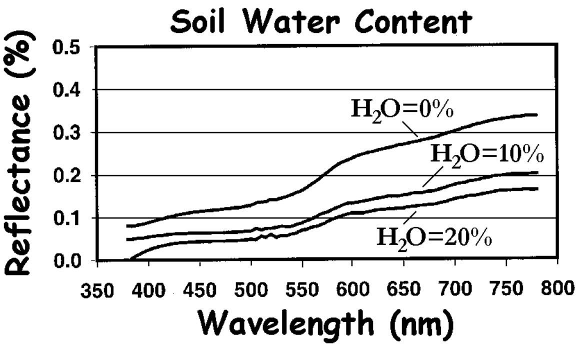

Figure 6. Influence of soil water content on soil reflectance (soil sample *ruw22*). Measurements have been performed in the backscatter direction (θz=30° and θv=45°)

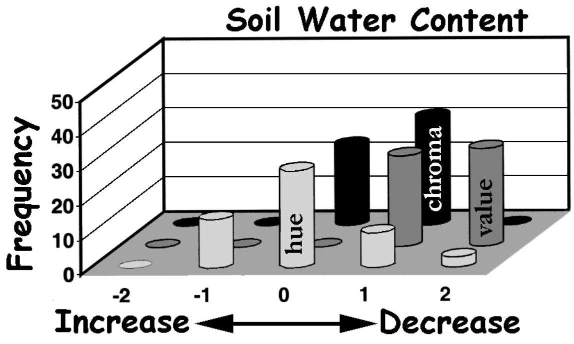

Figure 7. Simulated deviations of Munsell HVC when soil water content increases from 0% to 20%. Results have been obtained using measured reflectance spectra of 55 soil samples

Analysis shows that CIE-$Y_{oven\text{-}dried}$ and CIE-Y_{wet} are linearily related to each other, with slope and intercept being functions of the soil water content (H_2O in % weight). These dependencies lead to the following relationship between $Y_{oven\text{-}dried}$ and Y_{wet} (r^2=0.88; Nobs=55):

$$Y_{wet}=10^{-6}(-0.29\ H_2O - 11.44\ (H_2O)^2)+Y_{oven\text{-}dried}\ (1-0.0588\ H_2O + 0.0016\ (H_2O)^2) \quad (5)$$

3.2 Surface roughness

The influence of a decreasing surface roughness on soil reflectance has been simulated using the SOILSPEC model (equation 1), by increasing the roughness parameter from h=0.02 to h=20. Results of the simulation are shown in Figure 8 for a typical soil sample. Due to decreasing shadows, soil reflectance increases throughout the visible range when the soil becomes smoother.

The effects of a decreasing surface roughness on Munsell color coordinates (Figure 9) are much the same like those of an increasing soil water content (Figure 7), just opposite. More detailed analysis shows that the influence of the surface roughness increases with increasing phase angle between observer and illumination.

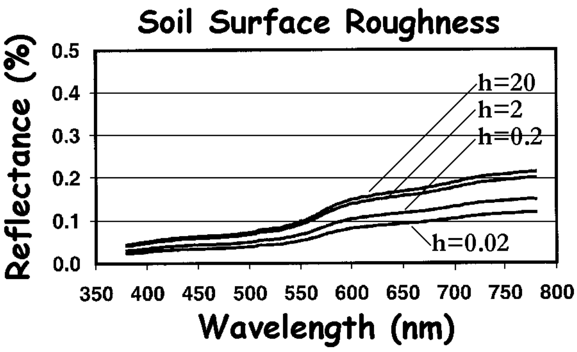

Figure 8. Influence of soil surface roughness on soil reflectance. Reflectance behaviour has been simulated using the SOILSPEC reflectance model and the measured single scattering albedo of the soil sample (*ruw22*). h=20 corresponds to a smooth surfacea, and h=0.02 to a rough soil surface

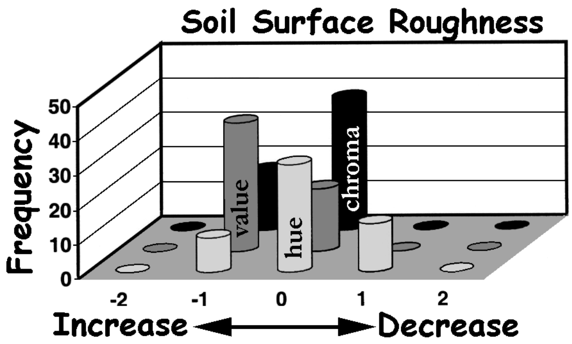

Figure 9. Simulated deviations of Munsell HVC when soil roughness changes from rough (h=0.02) to smooth (h=20). Results have been obtained using measured single scattering albedos of 55 soil samples and SOILSPEC reflectance model

3.3 Vegetation residues

When analyzing remotely sensed images, one is rarely sure that no vegetation residues remain on the soil surface. This is especially true for greater pixel sizes. Already small amounts of living (Figure 10), or dead vegetation residues (Figure 11) change the "soil" reflectance dramatically. In contrast to the soil water content and the surface roughness, one observes this time distinct spectral features.

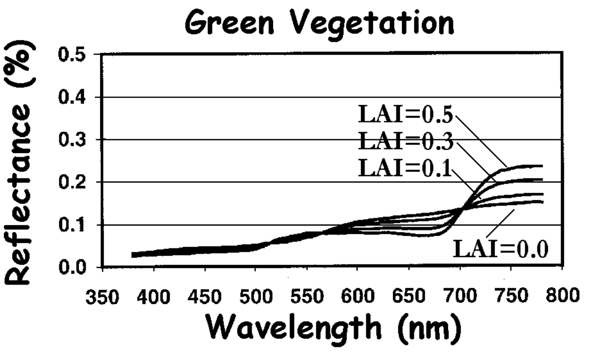

Figure 10. Influence of LAI_{green} on soil reflectance. Reflectance behaviour has been simulated using the SPECAN reflectance model and the measured single scattering albedo of soil sample *ruw22*. To model leaf optical properties of green leaves, the leaf chlorophyll content has been set to 30 $\mu g/cm^2$

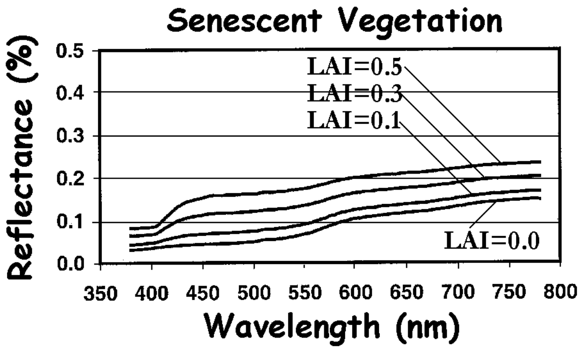

Figure 11. Influence of $LAI_{senescent}$ on soil reflectance. Reflectance behaviour has been simulated using the SPECAN reflectance model and the measured single scattering albedo of soil sample *ruw22*. To model leaf optical properties of senescent leaves, the leaf chlorophyll content has been set to zero

In the case of green vegetation residues, these spectral changes lead to a strong increase in Munsell hue (by one or even two units), when LAI is increased from 0 to 0.3 (Figure 12). A more detailed analysis shows that the effect of green vegetation residues on Munsell hue is even more pronounced for wet soils and elevated solar zenith angles. On the contrary, green vegetation residues hardly change Munsell value and chroma.

Even more pronounced are the effects of senescent vegetation residues on soil color (Figure 13). Munsell hue may increase or decrease in an unpredictable way. Since the overall brightness of the "soil" increases with increasing vegetation residues, Munsell value increases, whereas chroma decreases.

A more detailed analysis reveals that the influence of senescent vegetation residues on Munsell hue and value depends on soil water content and solar zenith angle. The deviation of Munsell hue increases with increasing solar zenith angle and for very wet, respectively, very dry soil conditions. The error in Munsell value increases both with increasing solar zenith angle and increasing soil water content.

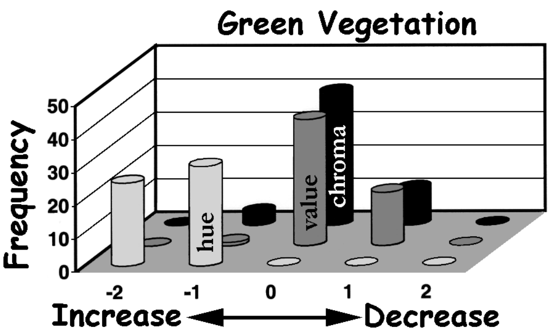

Figure 12. Simulated deviations of Munsell HVC when vegetation cover increases from 0 to LAI_{green}=0.3. Results have been obtained using measured single scattering albedos of 55 soil samples and SPECAN reflectance model. The leaf chlorophyll content (Cab) has been set to 30 $\mu g/cm^2$

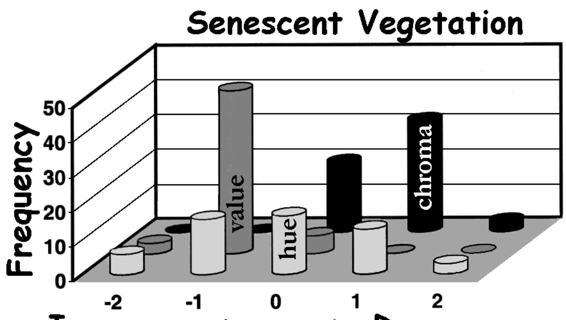

Figure 13. Simulated deviations of Munsell HVC when vegetation cover increases from 0 to $LAI_{senescent}$=0.3. Results have been obtained using measured single scattering albedos of 55 soil samples and SPECAN reflectance model. The leaf chlorophyll content (Cab) has been set to zero

4 CONCLUSION

Through multi-angle reflectance measurements, soil-inherent spectral single scattering albedos of 55 soil samples have been determined. With these spectral signatures and well established reflectance models (i.e. SOILSPEC and SPECAN) it has been possible to analyze different factors which interfear with soil color retrieval from space.

All factors (i.e. soil water content, soil surface roughness, green and senescent vegetation residues) lead to significant changes in Munsell and CIE color coordinates. The strength of the dependencies, however, depend on factor, color attribute and measurement configuration.

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